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Vol. 62 • No. 5

May 2019

Microwave Journal

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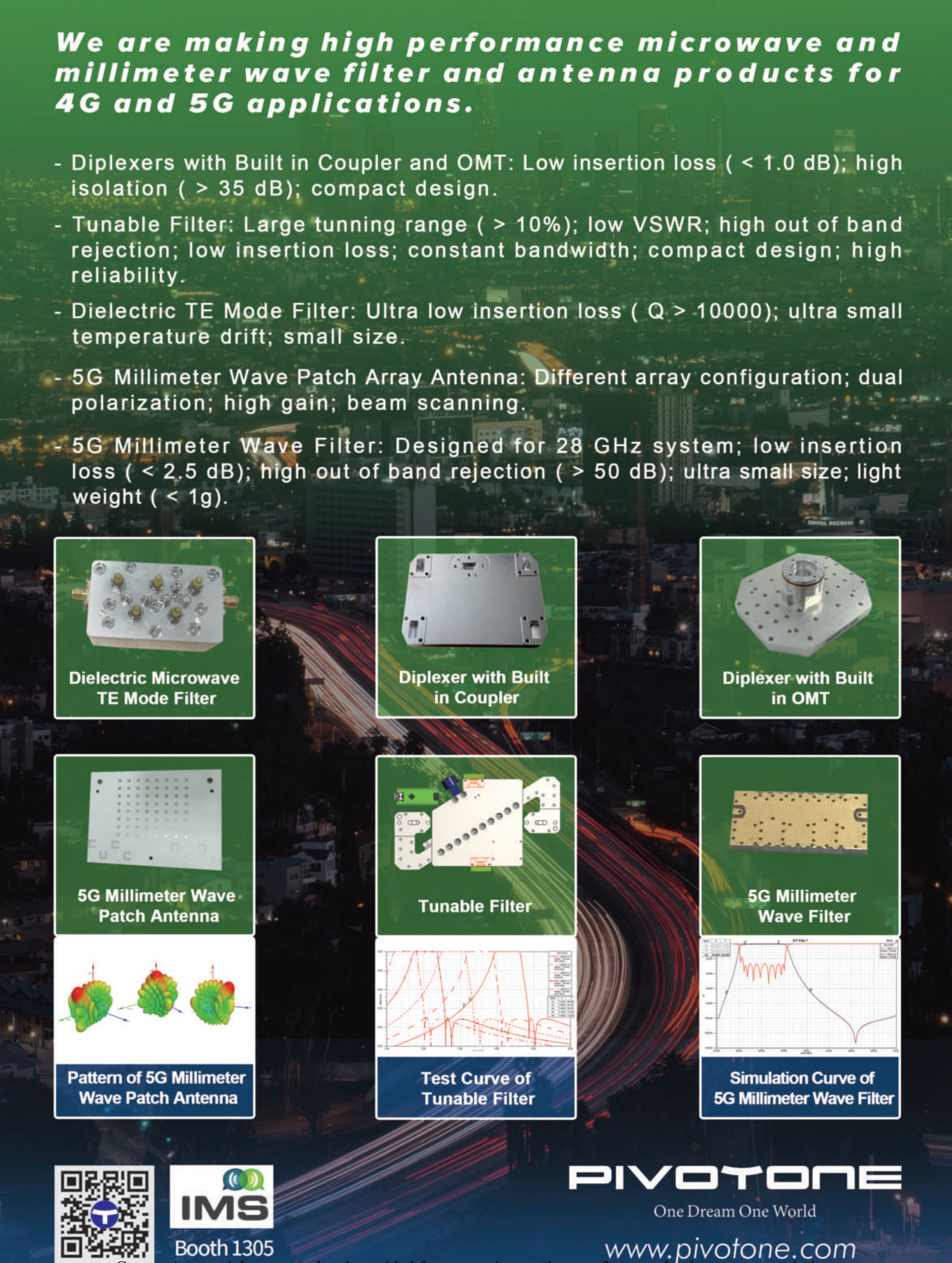

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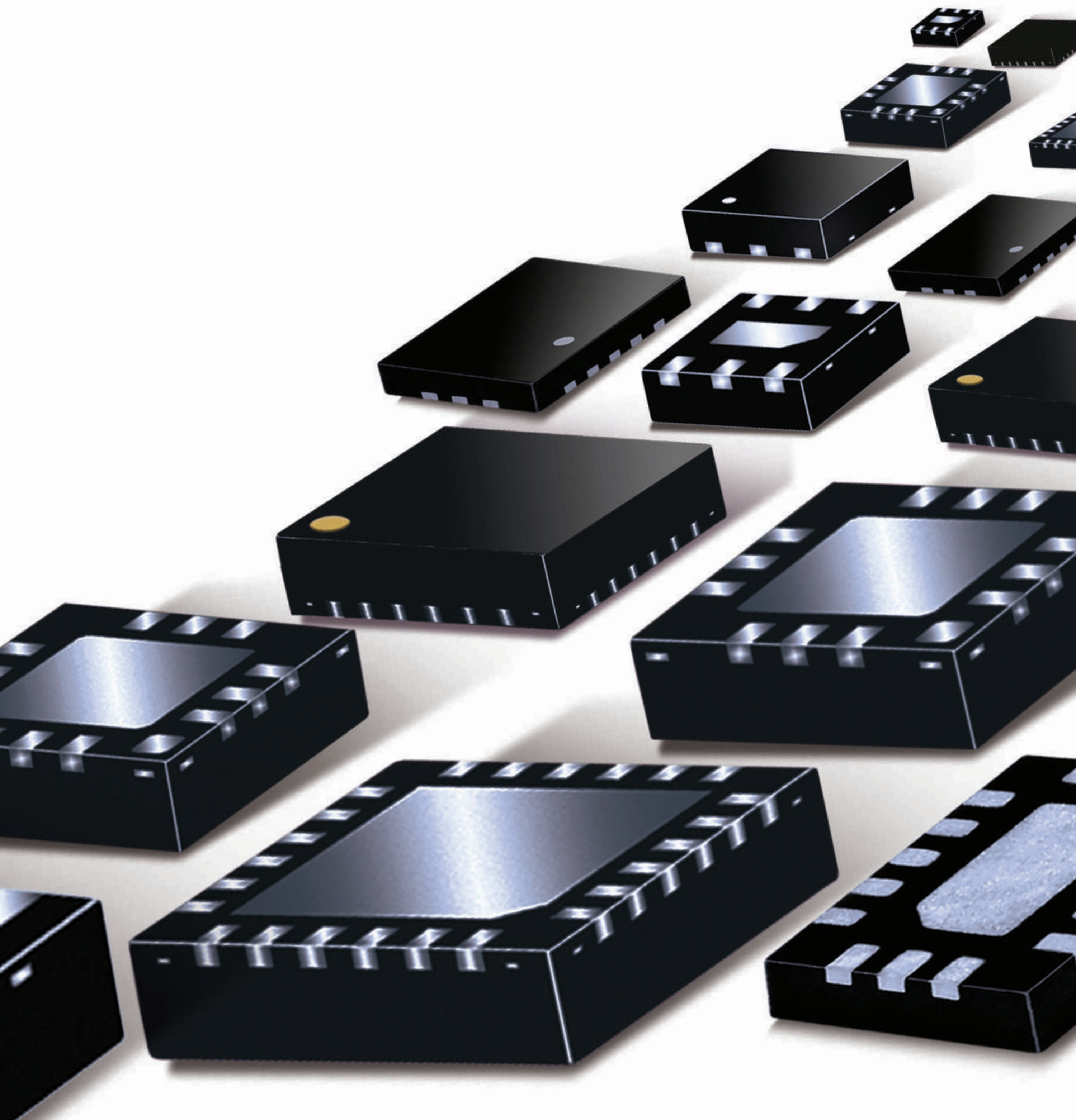

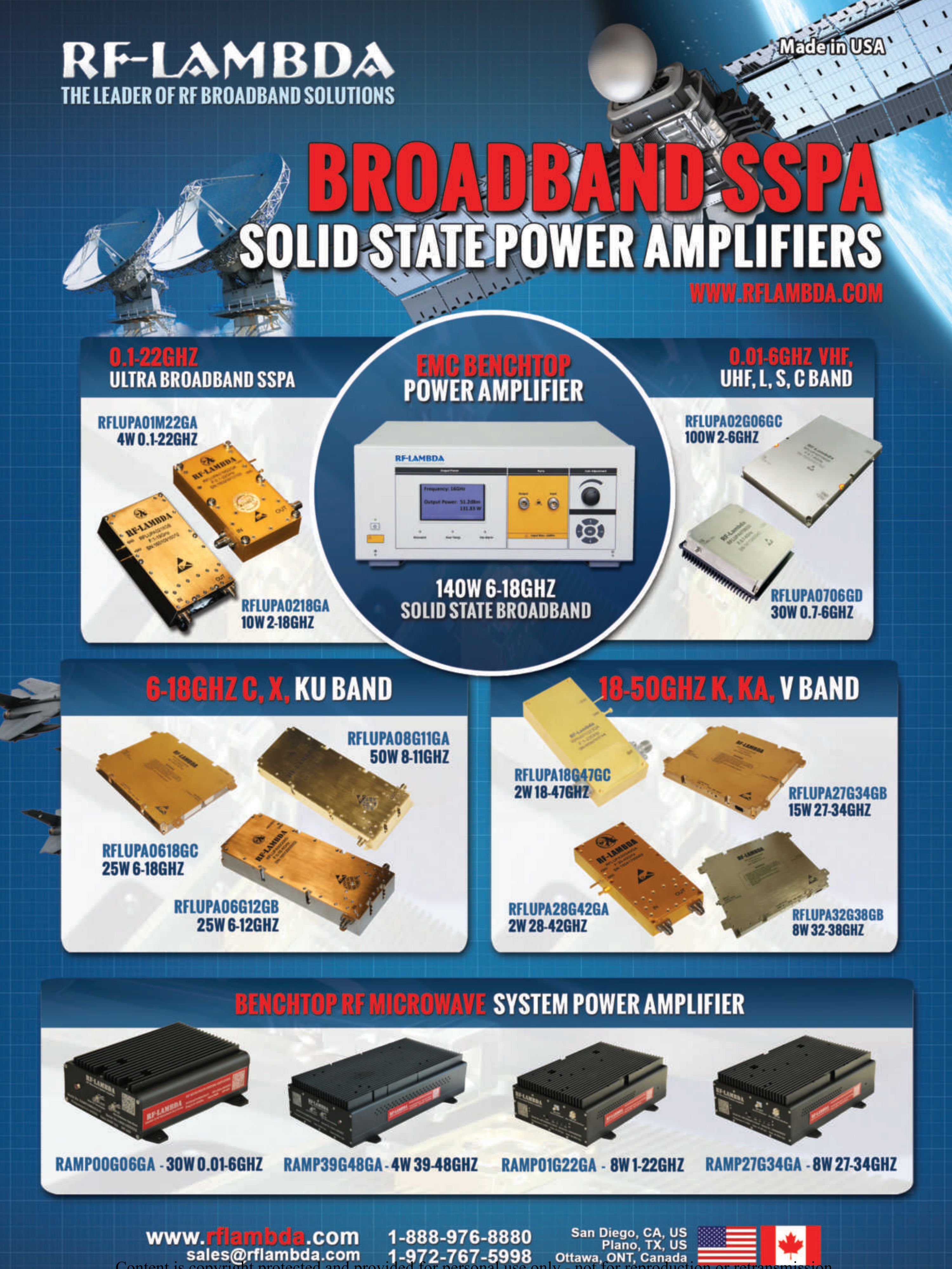
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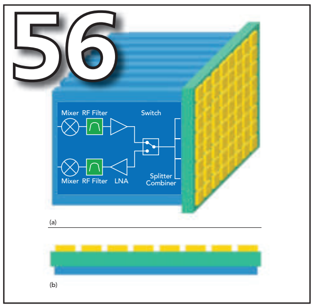

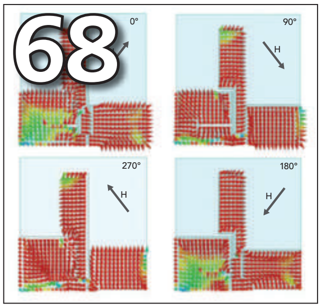

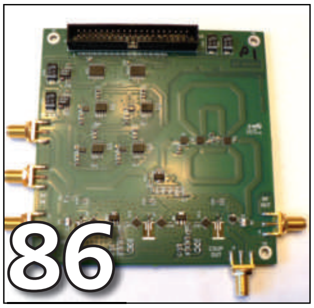

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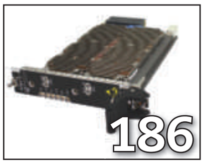

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Microwave Journal (USPS 396-250) (ISSN 0192-6225) is published monthly by Horizon House Publications Inc., 685 Canton St., Norwood, MA 02062. Periodicals postage paid at Norwood, MA 02062 and additional mailing offices.

POSTMASTER: Send address corrections to Microwave Journal, PO Box 1028, Lowell, MA 01853 or e-mail mwj@e-circ.net.com. Subscription information: (978) 671-0446. This journal is issued without charge upon written request to qualified persons working in the RF & microwave industry. Other subscriptions are: domestic, $120.00 per year, two-year subscriptions, $185.00; foreign, $200.00 per year, two-year subscriptions, $370.00; back issues (if available) and single copies, $10.00 domestic and $20.00 foreign. Claims for missing issues must be filed within 90 days of date of issue for complimentary replacement.

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Executive Interviews

With IMS2019 taking place in Boston, *Microwave Journal* interviewed two executives from contrasting companies headquartered in the area. One with a long history of close to 70 years in the RF/microwave industry, **MACOM**, and the other a new wireless Internet startup, **Starry Inc.**

John Croteau, president and CEO of **MACOM,** discusses the company's recent evolution to diversify into RF/microwave and optical applications plus an update on their GaN on Silicon technology and other product innovations.

Joe Lipowski, Starry co-founder and CTO, discusses the business model and technology behind the mmWave ISP startup and how Starry's service compares to 5G fixed wireless access.

Web Trivia

While working for Raytheon in 1946, who discovered the microwave oven when a candy bar melted in his pocket while standing in front of a magnetron source?

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https://ims-ieee.org/

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SMi
MILITARY SPACE USA
June 11-12 2019
Los Angeles

Los Angeles, Calif.

Featuring high level briefings from senior leadership across industry, government and allied partner states, Military Space USA will provide a holistic overview of developments in the fourth domain, including how organizational efforts such as "SMC 2.0" are facilitating and delivering the space supremacy that is demanded by the warfighter.
www.smi-online.co.uk/defence/northamerica/conference/milspace-usa

26-27

SMi
MilSatCom USA

Arlington, Va.

MilSatCom USA conference, in its 4th annual year, is set to provide a refined focus on the U.S. communications market and address how these critical programs are developing. The two-day event will explore the resiliency of systems, their integration to ground terminals, as well as wider efforts to optimize bandwidth utilization via international partnerships.
www.smi-online.co.uk/defence/northamerica MilSatCom-USA

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Microwaves bridging Smart Cities
2019 IEEE Asia-Pacific Microwave Conference

APMC 2019 will cover the entire scope of microwave and mmWave engineering, including RF/microwave/THz, antennas and propagation and EMC/EMI. Prospective authors are invited to submit original papers on their latest research results on topics including Active Devices and Circuits, Passive Components, Systems, Antennas and Propagation and Emerging areas.
http://apmc2019.org/

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May 3

IEEE IMARC 2019
May 31

Asia Pacific Microwave Conference 2019
June 30

Radio & Wireless Week 2020
July 24

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MAY

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May 21–22 • Pasadena, Calif.
www.spacetechexpo.com/

JUNE

IEEE MTT-S IMS 2019
June 2–7 • Boston, Mass.
https://ims-ieee.org/

Military Space USA 2019
June 11–12 • Los Angeles, Calif.
www.smi-online.co.uk/defence/northamerica/conference/Milspace-USA

MilSatCom USA 2019
June 26–27 • Arlington, Va.
www.smi-online.co.uk/defence/northamerica/MilSatCom-USA

JULY

SEMICON West 2019
July 9–11 • San Francisco, Calif.
www.semiconwest.org/

IEEE EMC+SIPI 2019
July 22–26 • New Orleans, La.
www.emc2019.emcss.org/

AUGUST

ESC Silicon Valley 2019
August 27–29 • Santa Clara, Calif.
http://escsiliconvalley.com/

SEPTEMBER

PCB West 2019
September 9–11 • Santa Clara, Calif.
www.pcbwest.com/

EDI CON Online
September 10–12
www.ediconoline.com

EuMW 2019
September 29–Oct. 4 • Paris, France
www.eumweek.com

OCTOBER

AMTA 2019
October 6–11 • San Diego, Calif.
https://amta2019.org/

2019 IEEE International Symposium on Phased Array Systems and Technology
October 15–18 • Waltham, Mass.
http://array2019.org

ITC 2019
October 21–24 • Las Vegas, Nev.
www.telemetry.org/

NOVEMBER

BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium 2019 (BCICTS 2019)
November 3–6 • Nashville, Tenn.
www.bcicts.org

IEEE COMCAS 2019
November 4–6 • Tel Aviv, Israel
www.comcas.org/

Global MilSatCom 2019
November 5–7 • London, U.K.
www.smi-online.co.uk/defence/uk/global-milsatcom

Space Tech Expo Europe 2019
November 19–21 • Bremen, Germany
www.spacetechexpo.eu/

DECEMBER

IEEE IMARC 2019
December 5–7 • Mumbai, India
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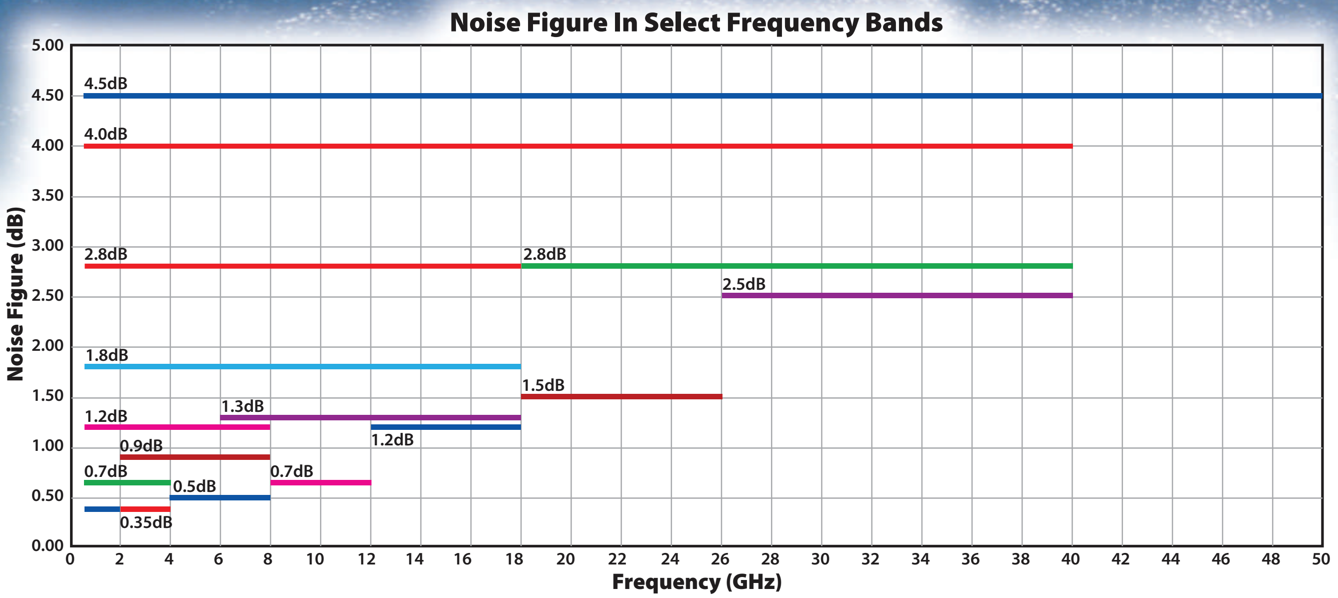

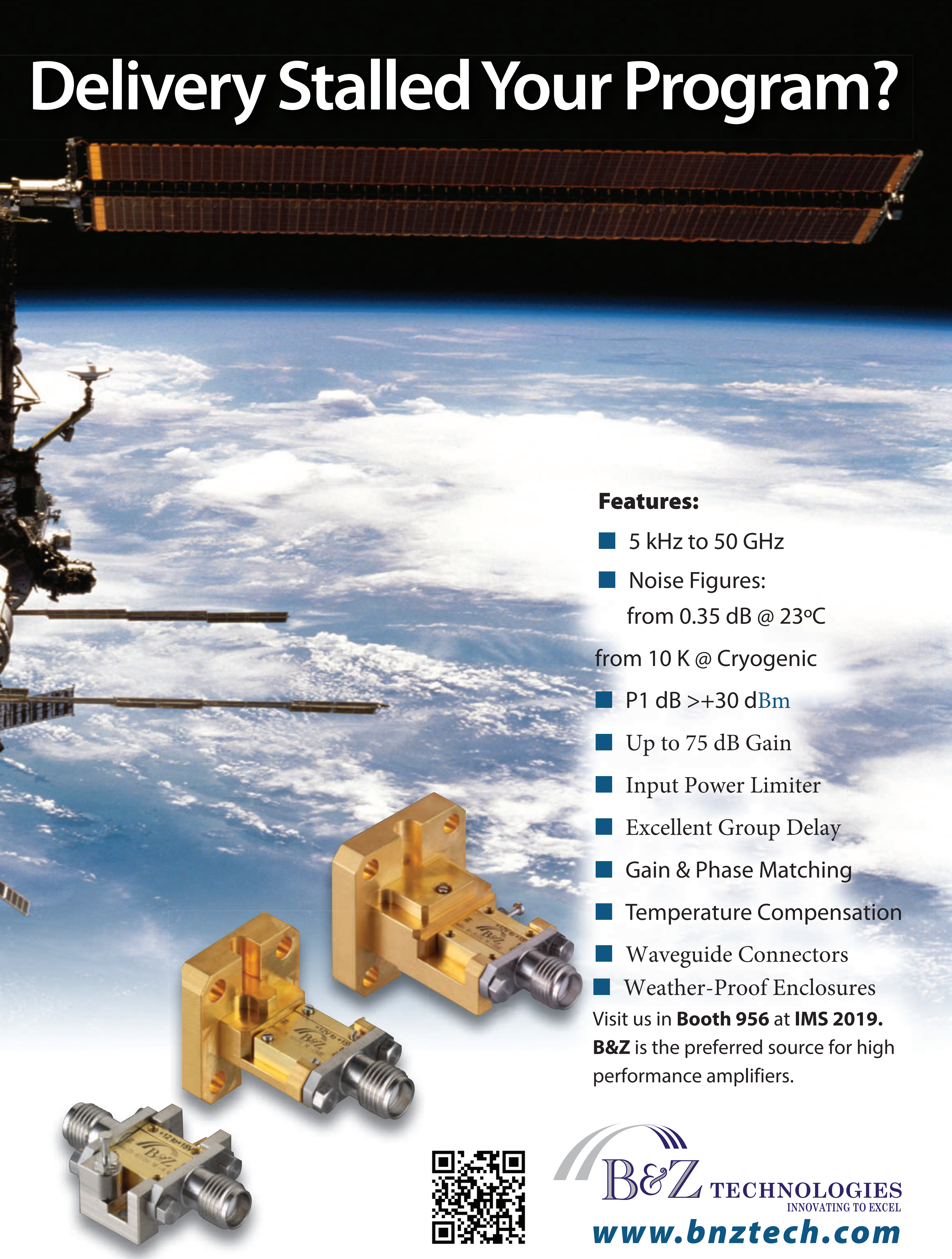
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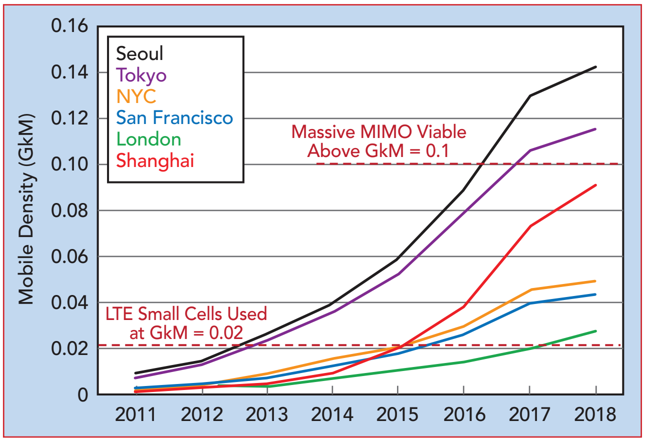
mmWave Will Be The Critical 5G Link

Joe Madden
Mobile Experts, Campbell, Calif.

Over the past 30 years, the mobile network has become a critical part of life, and the use of mobile services is starting to reach incredible levels of demand. This year, 30 Exabytes will fly over worldwide mobile networks every month. And the demand will continue to rocket upward by roughly 50 percent each year. About 15 percent of adults in the U.S. use LTE full-time, leaving Wi-Fi turned off (they say that managing Wi-Fi hotspots can be annoying). A whole generation of young people consumes 50 GB of mobile video each month, relying on "unlimited plans." The signs are clear that data demand will continue to grow rapidly.



▲ **Fig. 1** **Benchmarking data for Mobile Traffic Density (Gbps/km^2/MHz or GkM).**

Mobile Experts tracks the demand for mobile data with multiple mobile operators worldwide and their Traffic Density tracking metric measures the level of traffic in a busy sector, during busy hours, in terms of Gigabits per second, per square kilometer, per MHz of spectrum (GkM). In order to understand how advanced networks should handle extreme demand in some cities, the GkM is compared between different operators, and an assessment can be made whether small cells, massive MIMO or mmWaves will be necessary to accommodate the traffic (see ***Figure 1***).

Traffic density in GkM has been rising steadily for years, and is most pronounced in locations such as subway stations in Tokyo and Seoul, where thousands of people stand close together, all watching video. The statistical rise in density has been remarkably smooth as new apps and video content become available on mobile platforms.

Above a traffic density level of 0.02 GkM, small cells were observed to be universally adopted by mobile operators. In other words, the macro network saturated above 0.02 GkM, and small cells became a more economical way to add capacity. More recently, networks have reached levels of density above 0.1 GkM, making massive MIMO necessary to continue increasing capacity.

We are now starting to see some signs that density levels in the range of 0.15 to 0.2 GkM will saturate the OFDM network. There will be ways to push through this barrier as well, but moving beyond 0.2 GkM in the 1 to 3 GHz bands will get very expensive, requiring large numbers of very low-power radio nodes.

Adding 5G spectrum to the mobile network can actually reduce the traffic density. As an example, one of the leading Korean networks should experience a drop in GkM with their recent introduction of 100 MHz at 3.5 GHz. An additional 800 MHz of spectrum at 28 GHz will reduce their traffic density in key hotspots to much more manageable levels as shown in ***Figure 2***.

Therefore in many ways the operators can be viewed as using 5G spectrum to manage the density of their traffic. When high density makes adding capacity expensive, adding more spectrum is the best option.

mmWAVES TO THE RESCUE

After the convenient licensed bands below 5 GHz are used up, mobile operators start to look to mmWave spectrum as an opportunity to get significant bandwidth. The U.S. is a prime example where wide blocks of C-Band spectrum are not available so mobile operators have invested heavily in 28 and 39 GHz mmWave bands.

In fact, the large U.S. mobile networks, in key urban pockets, are running out of capacity below 6 GHz. During special events such as the Super Bowl, the traffic density is in the range of 0.12 GkM and above in the U.S. Mobile Experts modeled the demand for mobile data in four segments of the U.S. network (dense urban, urban, suburban and rural) and estimated the total capacity of the mobile network including macro base stations, small cells, CBRS, LAA and the impact of massive MIMO below 6 GHz. Even with a fully utilized heterogeneous network with maximal capacity, demand in dense urban pockets will exceed capacity in 2023 as shown in ***Figure 3***. Note that the numbers shown in the Figure 3 represent the total demand and capacity for all dense urban sites in the U.S., so the extreme high-density locations such as Times Square will experience demand higher than capacity in the 2021 to 2022 timeframe. Extrapolating the trends in traffic density benchmarks, the dense urban sites in New York City should reach daily peak-hour density levels in the range of 0.1 GkM or higher by 2022.

HOW mmWAVE LINKS CAN BE USEFUL

Many experienced RF engineers have reasonable doubts about using mmWave radio links in a mobile environment. After all, the mmWave link depends on a narrow beam in order to achieve a reasonable link budget. Any clutter in the RF channel can disrupt the narrow beam.

Handovers in a mobile 5G mmWave network have been demonstrated in test systems in Seoul and at speeds above 200 km/hr on a racetrack, so the 5G frame structure lends itself to handovers in extreme Doppler shift conditions.

However, the mobile operators will not be using the 5G mmWave link as a standalone (SA) radio channel initially. Instead, an LTE carrier at 1 to 2 GHz will be used as the primary link, with control signaling taking place on the more reliable lower band. Then, the mmWave link will come into play when it is available to download or upload large amounts of data. In this way, the mmWave radio will add throughput as a carrier aggregation layer, boosting speed when it is available but not essential to the continuity of the link for handovers. At some point, operators may decide to use 5G mmWave as a SA mobile network, but today none of the active operators are planning to operate 5G mmWave independently.

RF IMPLEMENTATION—INFRASTRUCTURE

The mmWave base station will look dramatically different than LTE base stations below 6 GHz. At a

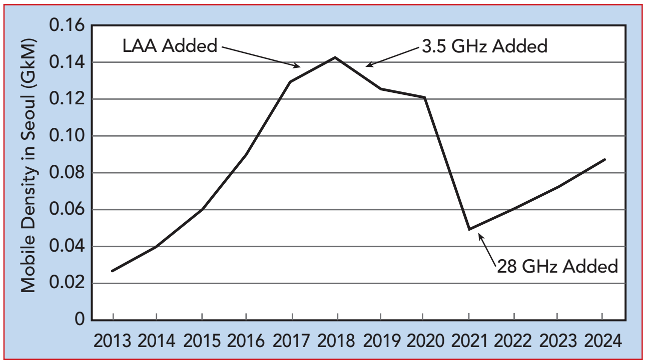


Fig. 2 Changes in traffic density with addition of 5G spectrum.

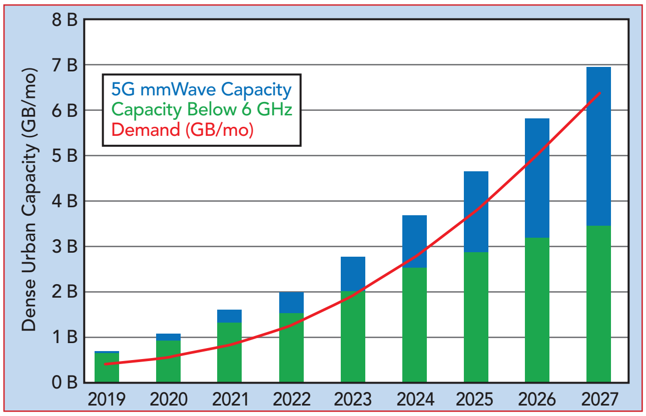


Fig. 3 Demand vs. capacity for dense urban mobile networks in U.S.

fundamental level, the mmWave radio suffers from the lower power amplifier efficiency in the 24 to 40 GHz bands, so the level of conducted output power will be much lower than lower frequency mobile radios. The primary limitation is the level of heat dissipation possible in a passively cooled radio unit at the towertop. Given a limit of about 250 W of heat in a small enclosure, the conducted RF power will be very low, below 10 W in any configuration.

As a result, systems engineers have turned to massive MIMO architectures with at least 64 antennas, in order to use high antenna gain. Initial products have utilized between 64 and 256 antenna elements per beam, to achieve between 25 and 30 dBi of antenna gain. In this way, the low conducted power can achieve linear EIRP in the range of 60 dBm. Each beam also carries multiple streams. Massive MIMO base stations are configured with dual-polarized antenna arrays, so that each beam can operate with 2×2 MIMO.

Multiple beams can be supported from a radio unit by constructing the array with multiple panels. From a manufacturing point of view, OEMs are settling into the use of panels with a set number of elements (examples range from 64 to 256 elements per panel). Then, the product can be scaled up and down to support different levels of capacity. One example in the field now uses four 256-element panels for a total of 1024 antenna elements, supporting four beams and 2×2 MIMO in each beam.

Note that the configuration of beams and streams is not set based on hardware. The OEM can choose to

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HUBER+SUHNER AG 9100 Herisau/Switzerland change the configuration in software, assuming that the antenna elements are equipped with analog phase shifter and variable gain components that can be individually controlled. In almost all prototypes, this "hybrid beamforming" approach is used today, as full digital beamforming at very wide bandwidths can be costly in terms of processing power and dollar cost.

Currently, SOI and SiGe semiconductor technologies are used in many base stations in order to achieve high levels of integration and low-cost. GaN also holds great potential for lower power dissipation at high levels of EIRP, using the higher inherent linearity/power of GaN devices to achieve 60 dBm or higher with fewer antenna elements.

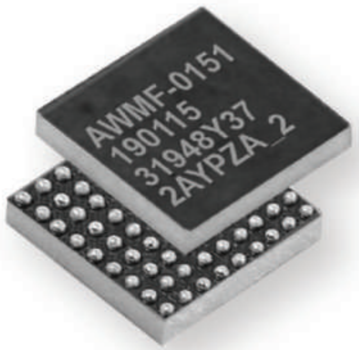
Based on PA efficiency data and size/efficiency of heatsinks for live demonstrations at MWC Barcelona 2019, the DC power consumption of multiple mmWave arrays was estimated as shown in ***Figure 4***. It appears that GaN has a significant advantage in terms of raw efficiency of a linear power amplifier at 28 GHz. However, all major OEMs have chosen to use SOI or SiGe so far, to take advantage of higher levels of integration, larger wafers and the resulting lower cost profile.

Over the next five years, significant adjustments are expected to occur to the balance between narrow beams (for long range) and wide beams (for better mobility). The optimal tradeoff in a dense urban network is not well understood today, and is likely to break into specific configurations to handle trains/buses/moving vehicles differently than pedestrian users. In particular, the large SOI-based arrays are expected to support the applications that cover dense urban pockets, where both vertical and horizontal steering are required and pedestrian speeds are typical. Other applications with higher mobility and less vertical steering are likely to move toward GaN devices.

The physical integration of the RF front-end will also be critical. Very tight integration will be necessary in the 24 to 40 GHz bands to keep insertion losses low, so either LTCC or 3D glass structures will be used to embed the active die and passive elements (see ***Figure 5***).

In the Radio Unit (RU), one convenient arrangement is to use an RFIC device for four antenna elements. From a simple geometric point of view, one RFIC for beamforming (phase and amplitude adjust) can be positioned between four antenna elements, using short traces and vias to route the mmWave signal (see ***Figure 6***)

One open question concerns the use of filters in the mmWave front-end. Currently, no bandpass filters are used at the front-end, and during field trials the spectrum was clean enough to rely on the natural rolloff of the patch antenna and distributed antenna feed to provide out-of-band rejection. In the future, spectrum auctions and multi-operator deployment suggest that interference will arise. In fact, with high EIRP and very narrow beams, the interference will be intense when it unexpectedly pops up. Recent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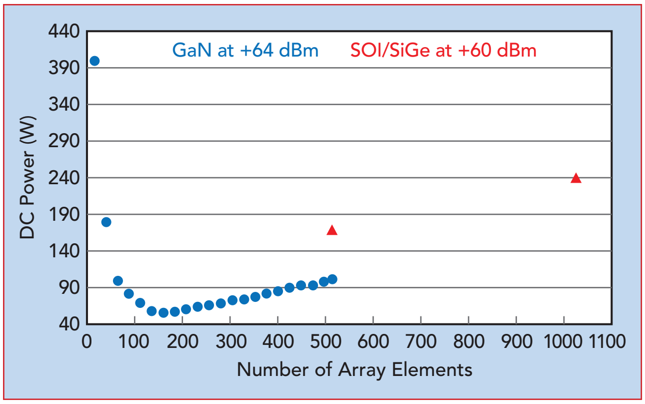

Fig. 4 Comparison of power dissipation in GaN, SOI and SiGe arrays.

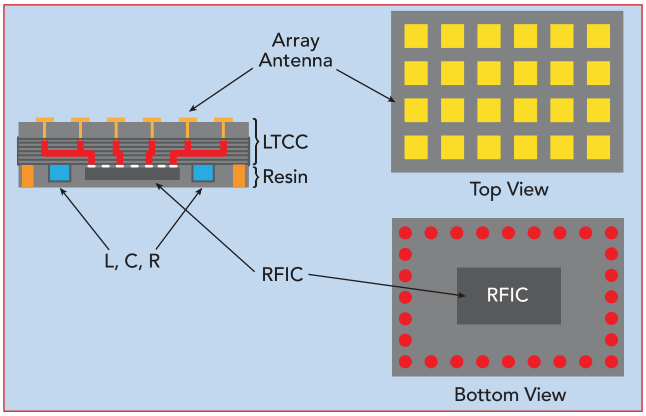

Fig. 5 A diagram representing physical packaging/integration for mmWave front ends (source: pSemi).

analysis indicates that filters will be introduced into the packaging over the next three years.

RF IMPLEMENTATION—CPEs

In fixed wireless, the Customer Premises Equipment (CPE) is a key part of the system. Initial deployments of 5G mmWave networks rely on high antenna gain and high EIRP from the CPE in order to support the necessary capacity. CPE RF front-ends today are constructed using a method that is similar to the network infrastructure, with a panel of antenna elements supported by beamforming RFICs, up-/down-conversion and then baseband processing. A typical CPE uses 32 dual-polarized antenna elements, supporting 2×2 MIMO with about 20 dBi gain from the antenna system.

Because the CPE is always connected to prime power, the PA efficiency is not a crippling limitation, and the CPE can often achieve high gain and high transmit power (linear EIRP in the range of 40 dBm).

RF IMPLEMENTATION—HANDSETS AND OTHER MOBILE DEVICES

The biggest challenge facing the 5G mmWave link will come from the user's hand blocking the antennas on a smartphone. In the 28 GHz band, the user's hand is likely to attenuate the signal by at least 30 to 40 dB,

effectively killing the link altogether. There can be multiple strategies to avoid this issue:

1. Multiple antenna sub-arrays on each handset. All 5G mmWave handset prototypes demonstrated over the past year utilize multiple sub-arrays, placed on both sides of the smartphone.
2. Foldable handsets are coming to market such as Samsung's Galaxy Fold and Huawei's Mate X. Because a foldable handset would be much larger than a human hand in the unfolded position, the placement of antennas could be more exposed.
3. Mobile hotspots can be used instead of mmWave links directly to the smartphone. This avoids the hand issue altogether, but may incur greater interference in the unlicensed bands. Importantly, the space and battery size constraints of the smartphone do not apply here, so the number of antennas can be increased to achieve much higher EIRP.

The physical implementation on a handset is limited for cost and space reasons to a few sub-arrays, an RFIC and the modem/beamforming processing. To make this arrangement economical, each mmWave sub-array includes an up-/down-converter to shift the mmWave signal down to an IF frequency at roughly 4 to 6 GHz (see ***Figure 7***). This enables the signals to travel through the PCB to a centralized RF transceiver.

Each mmWave subarray currently uses four dual-polarized patch antennas, each with a transmit/receive switch, low noise amplifier (LNA) and power amplifier (PA) closely integrated using RF-SOI. Each amplifier can only produce about 15 dBm linear power, so as many as eight antennas would be used to reach EIRP levels somewhere above 20 dBm. Three-dimensional beamforming on the smartphone platform is challenging, especially with a cluttered environment with metal surfaces and human hands in very close proximity. Even with eight antennas engaged, prototyping so far suggests antenna gain of only about 5 dBi.

For that reason, we expect much higher performance with hotspot products that utilize 32 antennas or more, achieving gain in the range of 20 dBi in the antenna system (15 dBi from the array and 5 dBi from the patch antenna itself). This type of product should be able to reach roughly 35 dBm linear EIRP or

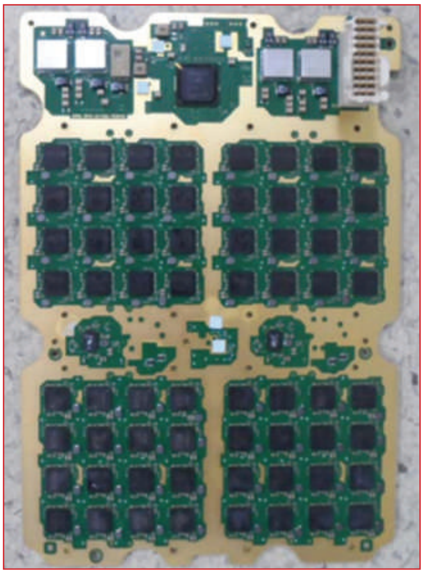

Fig. 6 **A typical panel with 4 sections, 64 256 dual-polarized antennas total (Source: FCC filing).**

higher. From a system point of view, roughly 35 dBm or higher will be an important level to reach since the 5G link requires a closed loop with TDD channel feedback in order to maintain a continuous connection.

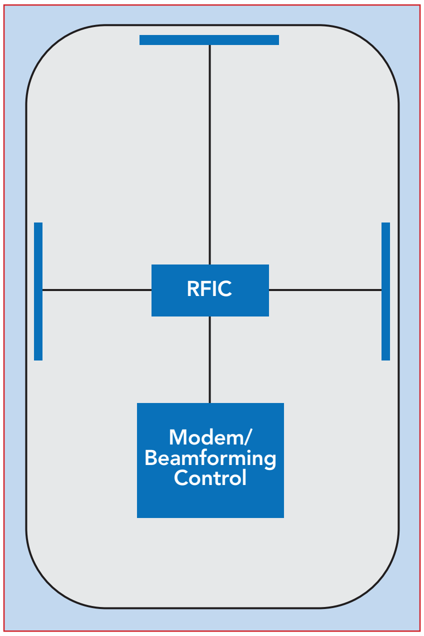

Fig. 7 Layout of three mmWave sub-arrays on a handset.

Lower EIRP from the client device means a shorter range for the link, and would require the network operator to deploy larger numbers of cell sites in order to blanket a neighborhood with coverage. In short, low transmit power from the client devices would make the 5G business case unworkable for the mobile operator.

COMMERCIAL STATUS

Base station deployment is underway in earnest for the U.S. market this year, and the South Korean market is not far behind. Recent forecasts indicate that more than 600,000 radio heads will be deployed by 2024.

Commercial fixed-wireless services have already been launched in a handful of U.S. cities, with CPEs supported by major OEMs today. A few CPEs have appeared from the ODM community with poor performance, but we expect those to improve quickly to support healthy growth. In the next few years, the fixed-wireless application will account for millions of users.

This generation of technology is also unique in that handsets are coming out very quickly, and smartphones will be available before the network is launched in most countries. The first 5G mmWave handset has already been released (the 5G Moto MOD), and at least eight other mmWave handsets will be released in the second half of 2019.

SUMMARY

5G mmWave radio links are more complex, more expensive and less reliable than LTE connections at 1 to 2 GHz. But mmWave bands will be necessary to keep up with rising demand, so the industry is currently pouring money into deployment of base stations and development of client devices. Initial fixed-wireless performance with CPEs has been surprisingly solid. The migration to mobile 5G usage will be tricky, with tradeoffs on beamwidth, link budget, mobility and cost coming into play. But there is one clear conclusion: 5G mmWave will be a significant part of future mobile networks.■

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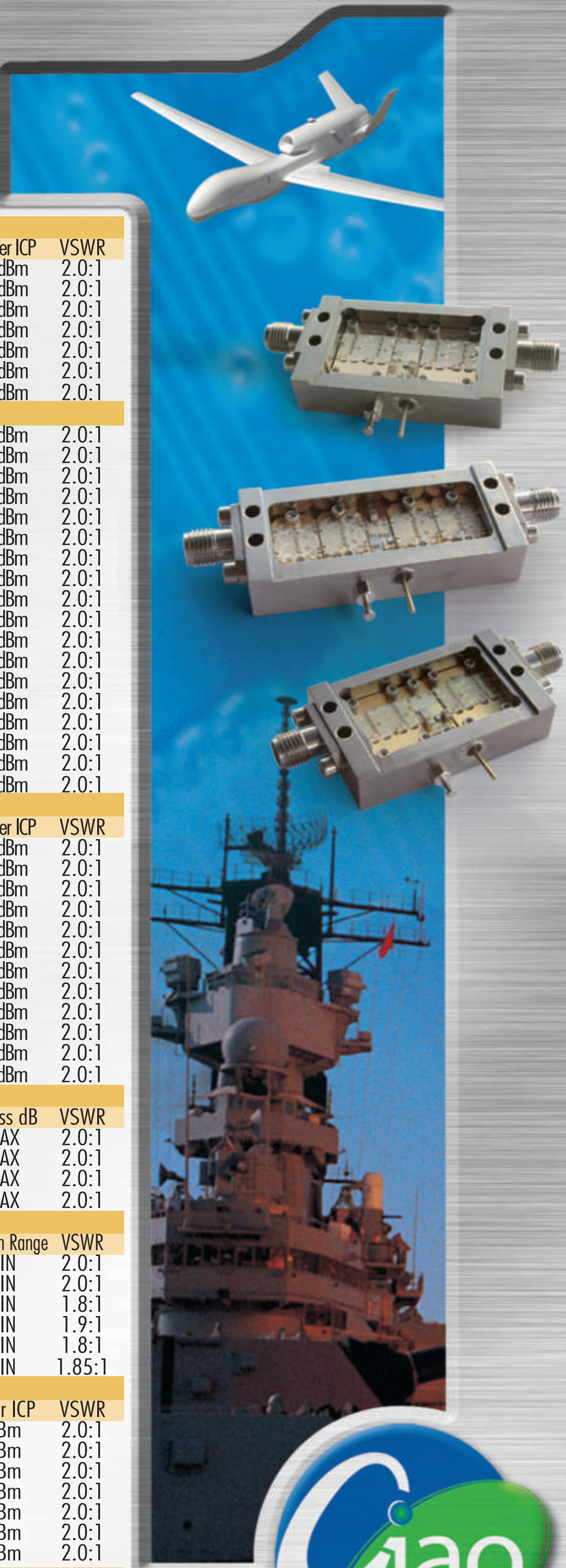

OCTAVE BAND LOW NOISE AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2110	0.5-1.0	28	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA12-2110	1.0-2.0	30	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA24-2111	2.0-4.0	29	1.1 MAX, 0.95 TYP	+10 MIN	+20 dBm	2.0:1
CA48-2111	4.0-8.0	29	1.3 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA812-3111	8.0-12.0	27	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA1218-4111	12.0-18.0	25	1.9 MAX, 1.7 TYP	+10 MIN	+20 dBm	2.0:1
CA1826-2110	18.0-26.5	32	3.0 MAX, 2.5 TYP	+10 MIN	+20 dBm	2.0:1

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2111	0.4 - 0.5	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA01-2113	0.8 - 1.0	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3117	1.2 - 1.6	25	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3111	2.2 - 2.4	30	0.6 MAX, 0.45 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3116	2.7 - 2.9	29	0.7 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA34-2110	3.7 - 4.2	28	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA56-3110	5.4 - 5.9	40	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA78-4110	7.25 - 7.75	32	1.2 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA910-3110	9.0 - 10.6	25	1.4 MAX, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA1315-3110	13.75 - 15.4	25	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3114	1.35 - 1.85	30	4.0 MAX, 3.0 TYP	+33 MIN	+41 dBm	2.0:1
CA34-6116	3.1 - 3.5	40	4.5 MAX, 3.5 TYP	+35 MIN	+43 dBm	2.0:1
CA56-5114	5.9 - 6.4	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6115	8.0 - 12.0	30	4.5 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6116	8.0 - 12.0	30	5.0 MAX, 4.0 TYP	+33 MIN	+41 dBm	2.0:1
CA1213-7110	12.2 - 13.25	28	6.0 MAX, 5.5 TYP	+33 MIN	+42 dBm	2.0:1
CA1415-7110	14.0 - 15.0	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA1722-4110	17.0 - 22.0	25	3.5 MAX, 2.8 TYP	+21 MIN	+31 dBm	2.0:1

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA0102-3111	0.1-2.0	28	1.6 Max, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA0106-3111	0.1-6.0	28	1.9 Max, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-3110	0.1-8.0	26	2.2 Max, 1.8 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-4112	0.1-8.0	32	3.0 MAX, 1.8 TYP	+22 MIN	+32 dBm	2.0:1
CA02-3112	0.5-2.0	36	4.5 MAX, 2.5 TYP	+30 MIN	+40 dBm	2.0:1
CA26-3110	2.0-6.0	26	2.0 MAX, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA26-4114	2.0-6.0	22	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA618-4112	6.0-18.0	25	5.0 MAX, 3.5 TYP	+23 MIN	+33 dBm	2.0:1
CA618-6114	6.0-18.0	35	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA218-4116	2.0-18.0	30	3.5 MAX, 2.8 TYP	+10 MIN	+20 dBm	2.0:1
CA218-4110	2.0-18.0	30	5.0 MAX, 3.5 TYP	+20 MIN	+30 dBm	2.0:1
CA218-4112	2.0-18.0	29	5.0 MAX, 3.5 TYP	+24 MIN	+34 dBm	2.0:1

LIMITING AMPLIFIERS

Model No.	Freq (GHz)	Input Dynamic Range	Output Power Range Psat	Power Flatness dB	VSWR
CLA24-4001	2.0 - 4.0	-28 to +10 dBm	+7 to +11 dBm	+/- 1.5 MAX	2.0:1
CLA26-8001	2.0 - 6.0	-50 to +20 dBm	+14 to +18 dBm	+/- 1.5 MAX	2.0:1
CLA712-5001	7.0 - 12.4	-21 to +10 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1
CLA618-1201	6.0 - 18.0	-50 to +20 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	Gain Attenuation Range	VSWR
CA001-2511A	0.025-0.150	21	5.0 MAX, 3.5 TYP	+12 MIN	30 dB MIN	2.0:1
CA05-3110A	0.5-5.5	23	2.5 MAX, 1.5 TYP	+18 MIN	20 dB MIN	2.0:1
CA56-3110A	5.85-6.425	28	2.5 MAX, 1.5 TYP	+16 MIN	22 dB MIN	1.8:1
CA612-4110A	6.0-12.0	24	2.5 MAX, 1.5 TYP	+12 MIN	15 dB MIN	1.9:1
CA1315-4110A	13.75-15.4	25	2.2 MAX, 1.6 TYP	+16 MIN	20 dB MIN	1.8:1
CA1518-4110A	15.0-18.0	30	3.0 MAX, 2.0 TYP	+18 MIN	20 dB MIN	1.85:1

LOW FREQUENCY AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure dB	Power-out @ P1-dB	3rd Order ICP	VSWR
CA001-2110	0.01-0.10	18	4.0 MAX, 2.2 TYP	+10 MIN	+20 dBm	2.0:1
CA001-2211	0.04-0.15	24	3.5 MAX, 2.2 TYP	+13 MIN	+23 dBm	2.0:1
CA001-2215	0.04-0.15	23	4.0 MAX, 2.2 TYP	+23 MIN	+33 dBm	2.0:1
CA001-3113	0.01-1.0	28	4.0 MAX, 2.8 TYP	+17 MIN	+27 dBm	2.0:1
CA002-3114	0.01-2.0	27	4.0 MAX, 2.8 TYP	+20 MIN	+30 dBm	2.0:1
CA003-3116	0.01-3.0	18	4.0 MAX, 2.8 TYP	+25 MIN	+35 dBm	2.0:1
CA004-3112	0.01-4.0	32	4.0 MAX, 2.8 TYP	+15 MIN	+25 dBm	2.0:1

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Collaboration Vital to DARPA's CODE for Success

On a brisk February morning in the Yuma, Ariz. desert, a swarm of unmanned aerial vehicles (UAV) equipped with DARPA's Collaborative Operations in Denied Environment system (CODE) successfully carried out mission objectives, even when communications were offline and GPS was unavailable.

One-by-one, six RQ-23 Tigersharks lifted off, fitted with an array of sensors onboard. Next to the runway at the U.S. Army's Yuma Proving Ground, the mission team inside a small operations center tracked the aircraft and as many as 14 additional virtual planes on an aerial map. The capstone demonstration paired program performer Raytheon's software and autonomy algorithms and Johns Hopkins University Applied Physics Laboratory's White Force Network to create a realistic, live/virtual/constructive test environment. During four demo runs, the team activated a variety of virtual targets, threats and countermeasures to see how well the Tigersharks could complete their objectives in suboptimal conditions.

"Exactly how the aircraft continue to work together in degraded conditions is the most challenging aspect of this program," said Scott Wierzbanowski, program manager for CODE in the Tactical Technology Office. "Current procedures require at least one operator per UAV in the field. Equipped with CODE, one operator can command multiple aircraft; and in a denied environment, the aircraft continue toward mission objectives, collaborating and adapting for deficiencies." Before, if operators lost communications with a UAV, the system would revert to its last programmed mission. Now, under the CODE paradigm, teams of systems can autonomously share information and collaborate to adapt and respond to different targets or threats as they pop up.

"CODE can port into existing UAV systems and conduct collaborative operations," said Wierzbanowski. "CODE is a government-owned system, and we are working closely with our partners at the Air Force Research Laboratory and Naval Air Systems Command to keep each other informed of successes and challenges, and making sure we don't replicate work. In the end, our service partners will leverage what we've done and add on what they need."

RQ-23 (DARPA Photo)

The Tigersharks employed in the demo are surrogate assets for CODE. Each has about one-tenth the speed and performance of the aircraft planned for integration, but shows traceability to larger platforms. Constructive and virtual threats and effects presented by the White Force Network are appropriately scaled to the Tigersharks' capabilities.

"It's easy to take the CODE software and move it from platform to platform, both from a computer and vehicle perspective. It could be a manned aircraft, unmanned aircraft or a ground vehicle," said J.C. Ledé, technical advisor for autonomy with the Air Force Research Laboratory. "The concept for CODE is play-based tactics, so you can create new tactics relatively easily to go from mission to mission."

Market Study Shows Increased Role of Radar in Combat

The radar market has evolved from a threat indication system to an active protection system, the evolutions in the radar technology market has helped increase systems capabilities. The integration of platforms in modern battlefield systems have increased the role of radar in combat. Applications areas include C4ISR, air defense systems and electronic warfare (EW).

Mobile Radar (Source: ASD News)

R&D areas include MIMO, the MIMO to achieve compound resolution and operate at several frequencies without interference, cognitive radar technology based on machine learning and Bayesian approaches. R&D activities in the military radar market are focused on three aspects, improved situational awareness, higher safety to troops and assets and reduced troop fatigue.

The military radar market is expected to grow at a CAGR of around 2.7 percent from $12.37 billion in 2018 to $16.21 billion in 2027. The skewness of the market towards developed economies is high; North American and European markets account for nearly 70 percent of the total. This is predominantly due to modernization programs, air platform upgrades and NATO spending. Emerging economies in APAC have helped this region to grow at a higher CAGR compared to the global market. There are also a few indigenous programs which act as drivers in the APAC market.

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The highest growth is expected in airborne platforms. This is driven by AESA radar replacement and growth in the unmanned aerial vehicle (UAV) segment.

Wrath of the UAVs

The successful unmanned aerial vehicle (UAV) missions in the early 1970s and 1980s led to an explosive growth in the UAV market in the following decades. The U.S. Department of Navy had reported that at least one UAV was airborne throughout Desert Storm. The beginning of this century witnessed a new phase in the combat UAV market with its first recorded kill in Kandahar. This UAV was a MQ-1 Predator, piloted from Virginia, a Hellfire missile was used in the mission and it resulted in elimination of two targets. The success of this mission resulted in a new phase of warfare led by UAVs piloted a few thousand kilometers away in the U.S.

Thirteen years later, census revealed that a single Predator squadron had flown over 4,300 missions and dropped over 1,000 bombs between August 2013 and August 2014. The U.S. government has claimed that more than 70 percent of the Al-Qaeda leadership were eliminated using UAVs. The most important advantage is that it replaces systems like cockpit, armor and environmental controls with satellite control systems, sensors and ground control stations.

Predator (Source: ASD News)

The superiority of combat UAVs in cost and endurance compared to a fighter is expected to drive the replacement of around 30 percent of the existing U.S. fighter aircraft in the next few years. The cost of the MQ-1 Predator is around $5 million, which is approximately one-twentieth of the cost of an F35 and one-tenth of the cost of a Super Hornet. The second aspect is endurance; a fighter aircraft would need to be refueled approximately every two hours, the UAV can accomplish 12-hour missions without need for such refueling. Global Hawk has an endurance of around 35 hours. It is estimated that the U.S. DoD has an arsenal of 10,000 UAVs that can be used for surveillance and combat. The Raven is the most widely used surveillance UAV in the world and the Predator is the most commonly used combat UAV. Though the technology for autonomous decision firing systems is being developed, it is expected that the final decision to fire (except defensive fire) would remain at the discretion of a human at least for the next few years.


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Cliff Drubin, Associate Technical Editor

Wi-Fi Still Dominates, G.hn and MoCA Trying to Carve Out a Place

As the device count per household grows and use of multimedia and smart home applications increases, so does the demand for reliable high-capacity home networks. While Wi-Fi dominates the home network market, demand for wired home networking devices supporting high throughput is on the rise. ABI Research expects that Multimedia over Coax Alliance (MoCA) 2.5 or G.hn specification network node shipments will reach eight million units in 2019.

"Wi-Fi networks are highly penetrated in today's broadband homes due to the convenience of wireless connectivity. Newer Wi-Fi standards and devices such as Wi-Fi mesh systems do improve the coverage and throughput of home networks, however, wired connectivity can improve the stability and throughput, especially while using bandwidth-intensive applications," noted Khin Sandi Lynn, an industry analyst at ABI Research. The G.hn standard can support home networking data rates up to 2 Gbps over coaxial, power lines, optical fiber or telephone wiring, while the MoCA 2.5 standard can support up to 2.5 Gbps speed over coaxial cables.

> Wired connectivity can improve stability and throughput.

There is growing interest from service providers in both technologies to deploy this as an efficient backbone for residential Wi-Fi networks. Taiwanese service provider Chunghwa Telecom recently announced the launch Gh.n adapters to its FTTx subscribers. Operators including China Telecom, China Unicom and UK Liberty Global have also joined HomeGrid Forum in support of G.hn technology.

MoCA home networking adoption is mainly concentrated in North America, however, the MoCA continues to eye growth in Europe and the Asia-Pacific, particularly since 2017, with the introduction of MoCA Access 2.5, which added broadband access specifications based on MoCA 2.5. Companies including InCoax from Sweden, Teamly Digital from France and ZTE have announced MoCA Access 2.5 solutions.

Wi-Fi is certainly the preferred home network connectivity, however, there is significant market potential for wired networking devices supporting high capacity or to complement Wi-Fi installations. The increasing use of live video streaming, gaming and VR applications is likely to boost demand for 100 percent reliable coverage of home networks. Service providers can take advantage of advanced home networking devices and integrate with Wi-Fi offerings to optimize the customer experience. ABI Research forecasts that advanced home networking node shipments will reach 39 million units in 2023.

Bluetooth Low Energy Market to Triple by 2023

Bluetooth Low Energy (BLE) devices are forecasted to reach over 1.6 billion annual shipments by 2023 according to ABI Research. Increasing opportunities in smart home, beacons and asset tracking, emerging IoT applications, alongside growth in existing key markets and the emergence of audio over BLE will enable the technology to achieve a CAGR of 27 percent between 2018 and 2023, tripling in size.

"BLE has witnessed tremendous growth since its introduction in 2010 because continued technical enhancements have ensured that the technology can take advantage of opportunities across an ever-increasing number of verticals and use cases," said Andrew Zignani, senior analyst at ABI Research. "BLE's ubiquitous support in mobile devices, combined with its ability to support mesh networking, beacon functionality and, most recently, centimeter level location accuracy with the introduction of Bluetooth 5.1 and radio direction finding (RDF), is enabling BLE to be increasingly leveraged within smart consumer devices, larger scale home and commercial building automation environments and RTLS deployments with more stringent accuracy requirements," says Zignani.

> BLE technology is leveraging opportunities across an increasing number of verticals and use cases.

In addition to these recent enhancements, from 2020 onward, Bluetooth is anticipated to enable high-quality audio streaming over BLE, providing a boost for the existing headset market and the emerging True Wireless audio device market. "Late last year, and more recently during CES 2019, Dialog Semiconductor demonstrated an audio over BLE proof of concept utilizing their SmartBond SoCs. From 2020, we expect the Bluetooth audio market to take advantage of upcoming enhancements to better support truly cable-free earbud experiences while enhancing the battery life and user experience, though it may take some time for the standardization process to translate to wider mobile and ecosystem support," Zignani explained. Meanwhile, BLE chipset providers continue to innovate to provide further im-

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provements in power consumption, further extending battery life and enabling support for battery-free devices via energy harvesting.

"Together, Bluetooth's existing and upcoming enhancements will provide an enormous opportunity for the likes of Nordic Semiconductor, Dialog Semiconductor, Silicon Labs, Texas Instruments, Microchip, Cypress, STMicroelectronics, Atmosic, NXP, CEVA and Imagination, among several other IC and IP providers who are heavily invested in the Bluetooth and BLE ecosystem," Zignani concluded.

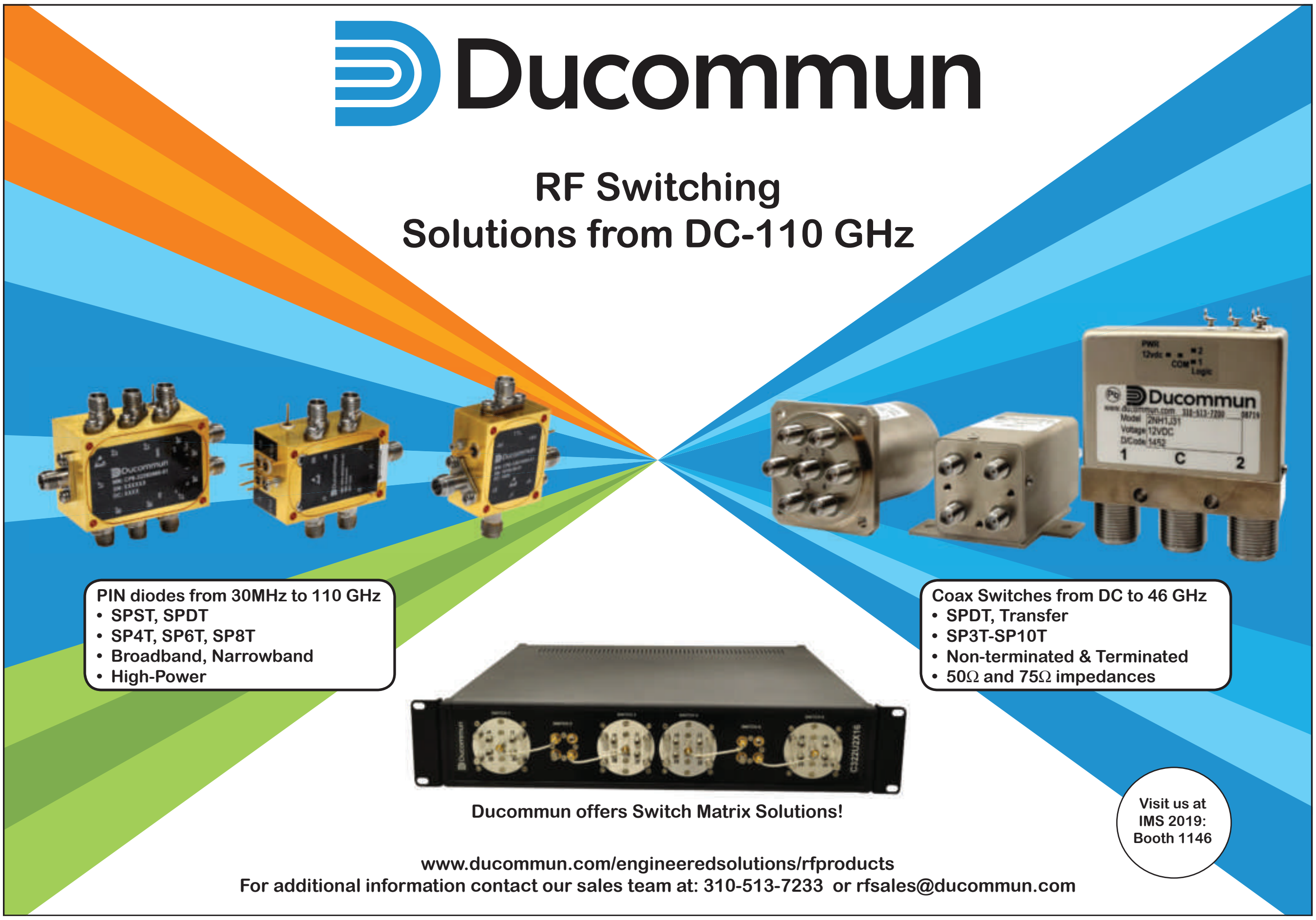
LTE Achieves 4B Connections Worldwide

In the fourth quarter of 2018, LTE technology reached nearly four billion connections worldwide representing 47 percent of all cellular technologies and providing 4G wireless access to services and applications to a large portion of the world's population. 5G Americas announced LTE's continued momentum for the fourth quarter of 2018 in North America, Latin America and throughout the world according to data from Ovum.

North America's market share for LTE at 82 percent exceeds all other world regions at the fourth quarter of 2018; the next highest world regions are Oceania; Eastern and South Eastern Asia with LTE share of 67 percent, followed by Western Europe at 52 percent. Latin America and the Caribbean had significant growth of LTE market share to 40 percent, up from 29 percent at the end of 2017. Market share represents the percentage of mobile wireless connections that are LTE technology versus all other mobile cellular technologies.

> The global deployment success of LTE provides the foundation for future 5G networks.

"While the 5G market reality and innovation are upon us, the number of LTE connections continue to grow on 637 commercial networks worldwide, as well as the evolution to advanced LTE networks for the IoT, Gigabit LTE speeds and new methods for spectrum use and sharing," stated Chris Pearson, president of 5G Americas.



Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Rohde & Schwarz has acquired the complete security scanner business unit of **Camero-Tech** and founded a new R&D company, named **SeemPulse Ltd.** With this acquisition, Rohde & Schwarz further expands its portfolio to complement its existing security scanner product lines.

Harris Corp. and **Elbit Systems Ltd.** announced the signing of a definitive agreement under which Elbit Systems of America LLC (ESA) will acquire Harris' Night Vision business for $350 million in cash. The transaction is conditioned on completion of Harris' previously announced proposed merger with L3 Technologies Inc., as well as customary closing conditions including receipt of regulatory approvals. Proceeds from the divestiture are expected to be used to pre-fund the L3 Harris pension and return cash to shareholders. Headquartered in Roanoke, Va., the Night Vision business is a premier developer, producer and supplier of night vision technology for the U.S. and allied military and security forces and for the federal homeland security market.

ON Semiconductor Corp. and **Quantenna Communications Inc.** announced that they have entered into a definitive agreement for ON Semiconductor to acquire Quantenna for $24.50 per share in an all cash transaction. The acquisition consideration represents equity value of approximately $1.07 billion and enterprise value of approximately $936 million, after accounting for Quantenna's net cash of approximately $136 million at the end of fourth quarter of 2018. The acquisition significantly enhances ON Semiconductor's connectivity portfolio with the addition of Quantenna's industry leading Wi-Fi technology and software capabilities.

Dialog Semiconductor plc announced that it has signed a definitive agreement to acquire **Silicon Motion Technology Corp.**'s mobile communications product line, branded as FCI. FCI is a global leader in mobile TV systems on a chip (SoC) in T-DMB and ISDB-T, with RF tuner-demodulator SoC solutions for smartphones, tablets and automotive portable navigation devices (PND). The acquisition provides Dialog with a rich portfolio of complementary connectivity-based products that includes ultra-low-power Wi-Fi SoC and modules, mobile TV SoCs and mobile communication transceiver integrated circuits (IC).

Renesas Electronics Corp. and **Integrated Device Technology Inc. (IDT)** jointly announced the successful completion of Renesas' acquisition of IDT, following approvals by IDT shareholders and the relevant regulatory authorities. Together with IDT, Renesas will now deliver an even broader range of leading-edge technology and embedded solutions by combining IDT's RF, high performance timing, memory interface, real-time interconnect, optical interconnect, wireless power and smart sensors with Renesas microcontrollers, SoCs and power management ICs. This combined portfolio enables the creation of new classes of products and solutions in fast-growing, data-economy applications across different verticals, including industrial, infrastructure and automotive segments, for customers and partners across the globe.

NSI-MI Technologies announced the addition of **Frequensys Limited** to the NSI-MI team. Frequensys Limited, an RF consultant and equipment supplier based in Sheffield, U.K., will be now known as **NSI-MI UK**. NSI-MI UK will offer all NSI-MI system solutions, backed by a strong presence in the U.K. This expansion of resources and experience will bring European customers high quality, cost-effective products and systems. NSI-MI UK will retain all current staff members as they have an unrivalled track record and experience in all things RF. NSI-MI UK will also continue to offer and support the existing products and brands previously offered by Frequensys Limited, ensuring continuity and support to all existing customers.

Singapore Technologies Engineering, through its European subsidiary wing, has entered into a conditional share purchase agreement to acquire 100 percent ownership in **Newtec Group NV**, an established Belgium-based SATCOM solutions company. They have offered €250 million (SGD$383 million) on a cash-free and debt-free basis for the proposed acquisition, subject to closing adjustments.

COLLABORATIONS

The **NFC Forum** and the **LoRa Alliance** have signed a liaison partnership agreement. The agreement focuses on technical cooperation, use case exploration and the potential to promote the use of NFC in combination with LoRaWAN for IoT applications. According to Paula Hunter, executive director of the NFC Forum, the liaison with the LoRa Alliance advances the NFC Forum's goal of expanding the use of NFC to help connect, commission and control the predicted 36 billion IoT devices in use by 2020. NFC is now welcoming opportunities to partner with complementary technologies to better address emerging market needs.

NEW STARTS

KNN Microwave LLC is a newly established low noise microwave amplifier company with 40 years of combined experience, based in Atlanta. Their main product is ultra low noise amplifiers for frequency range of 100 MHz to 40 GHz. They also provide desktop amplifiers with options such as various frequency bands, noise figures, power output and input limiters.

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Teledyne Defense Electronics (TDE), a new Teledyne brand representing the combined capabilities of 11 Teledyne companies, unveiled a new website that provides a "single source" on the web for accessing its comprehensive high tech offerings for global markets. With well over 100 highly-engineered product lines and service offerings spanning defense, commercial and industrial markets, TDE targets the majority of its products and technologies towards the needs of airborne, EW, energetics, missiles, radar, SATCOM, space and test & measurement markets. Visitors to the new website will find access to the product lines by whichever method they choose: by market, by technology type or by alphabetical listings.

CONTRACTS

Lockheed Martin (LM) received a $1.13 billion contract from the **U.S. Army** for Lot 14 production of Guided Multiple Launch Rocket System (GMLRS) rockets and associated equipment. The contract calls for the production of more than 9,500 GMLRS Unitary and Alternative-Warhead (AW) rockets, more than 300 low-cost Reduced-Range Practice Rockets (RRPR) and integrated logistics support for the U.S. Army and international customers. Work will be performed at LM facilities in Camden, Ark.; Dallas and Lufkin, Texas; and Ocala, Fla., and will be completed by July 2021.

Defence Secretary **Gavin Williamson** has signed a $1.98 billion deal to purchase five E-7 aircraft. The E-7 fleet will replace the current Sentry aircraft and ensure the continued delivery of the **U.K.'s Airborne Early Warning and Control (AEW&C)** capability. Named "Wedgetail" by the Australian Department for Defence, the E-7 aircraft can fly for long periods of time and manage the battlespace from the sky. The new fleet will be able to track multiple airborne and maritime targets at the same time, using the information it gathers to provide situational awareness and direct other assets such as fighter jets and warships.

The **U.S. Army** has awarded **Northrop Grumman Corp. (NGC)** a $713 million contract for the production of Integrated Air and Missile Defense (IAMD) Battle Command System (IBCS) for the first phase of Poland's WISLA air and missile defense program. Under this foreign military sales contract for WISLA, NGC will manufacture IBCS engagement operations centers and integrated fire control network relays and deliver IBCS net-enabled command and control for four firing units. The IBCS engagement operations centers will be integrated with IBCS battle management software that maximizes the combat potential of sensors and weapon systems. IBCS engagement operations centers and network relays will be transported by Polish Jelcz vehicles.

Raytheon Co. Integrated Defense Systems (IDS) was awarded a $402,658,015 fixed-price-incentive (firm target) modification to previously-awarded contract N00024-14-C-5315 to exercise options for Air and Mis-

sile Defense Radar Program (AMDR) low-rate initial production (LRIP). This modification will provide for three AMDR LRIP units. The LRIP units will be deployed on DDG 51 Flight III-class ships. Work will be performed in Marlborough, Mass., and is expected to be completed by March 2023. Fiscal 2019 shipbuilding and conversion (U.S. Navy) funding in the amount of $402,658,015 will be obligated at time of award and will not expire at the end of the current fiscal year.

CACI International Inc announced it has won a $71 million task order to provide sensor systems acquisition services to the **U.S. Army Program Executive Office (PEO) Soldier**. This five-year contract represents new work in CACI's surveillance and reconnaissance market area. CACI will provide acquisition, engineering, quality assurance, test, logistics and operations management services to the PEO Soldier's Project Manager, Soldier Sensor and Lasers (PM SSL). PM SSL equips soldiers with products for enhanced vision and targeting capabilities in day, night and all-weather conditions; and systems that precisely locate and designate enemy targets. CACI will assist the Army with technology maturation, production, deployment and sustainment of new mobility and targeting systems.

Mercury Systems Inc. announced it received a $25 million follow-on order from a leading defense prime contractor for integrated RF, mixed-signal and FPGA processing subsystems for an advanced electronic support application. The order was booked in the company's fiscal 2019 third quarter and is expected to be shipped over the next several quarters. The company offers an industry-leading portfolio of microelectronics solutions simultaneously addressing the analog, digital and mixed-signal domains for the most sophisticated EW programs demanded by U.S. military forces. Designed in accordance with OpenVPX™ architectures, Mercury's highly ruggedized integrated subsystems provides the assurance of agile, cost-effective future upgrades to address the continuously-evolving threat environment of tomorrow.

PEOPLE

Qualcomm Inc. announced that **George Davis** has decided to leave the company after a six-year tenure, during which he served as CFO and was a member of Qualcomm's Executive Committee, to become Intel's new CFO. As part of the transition plan, Qualcomm's Board of Directors have unanimously approved the appointment of **David Wise**, SVP and treasurer, as interim CFO during the search for a permanent replacement. Wise joined Qualcomm in 1997 and has held a variety of roles in finance, and corporate development and strategy since that time.

Keysight Technologies Inc. announced that **Marie Hattar**, Keysight's chief marketing officer (CMO), has been named as one of the 2019 Top 50 Most Powerful Women in Technology by the National Diversity Council. Hattar is responsible for Keysight's brand and

Around the **Circuit**

▲ *Marie Hattar*

global marketing efforts. She drives Keysight's corporate positioning, messaging and communications to both internal and external audiences. Hattar has more than 20 years of marketing leadership experience spanning the security, routing, switching, telecom and mobility markets.

REP APPOINTMENTS

Basingstoke-based RF and microwave component specialist **Link Microtek** has signed a representation agreement with manufacturer **L3 Narda-ATM**, which is based in Long Island, N.Y. Under the terms of the deal, Link Microtek will handle the U.S. firm's entire range of waveguide and coaxial components in the U.K. and Ireland. Formerly known as Advanced Technical Materials Inc., prior to its acquisition by L3 Technologies early in 2016, L3 Narda-ATM manufactures waveguide components such as transitions, adapters and couplers, together with a variety of coaxial products, including attenuators, phase shifters, power dividers, couplers and terminations.

PLACES

On April 2, **EDI CON China 2019** announced the winners and presented the trophies to company representatives in its second annual EDI CON China Product Innovation Awards. The ceremony was presided over by Winson Xing, editor *Microwave Journal China*, and Carl Sheffres, publisher of *Microwave Journal* and exhibition manager. The EDI CON China Product Innovation Awards honor products introduced in the last year that have had the greatest impact on the industry, providing the tools necessary to bring on the next-generation of electronic design innovations. A panel of *Microwave Journal* and *Signal Integrity Journal* editors selected the finalists and winners from nominated products.

The **Electronic Design Innovation Conference (EDI CON)** announced that this year, in conjunction with *Microwave Journal* and *Signal Integrity Journal*, it will host an online, interactive event for high frequency and high speed design engineers on September 10-12, 2019. The interactive technical sessions will occur at no cost to attendees, and sponsors will have the opportunity to present workshops and keynote sessions as part of the daily schedule. For more information, visit www.ediconoline.com.

INVITED PAPER

Approaching the 5G mmWave Filter Challenge

Key specifications for mmWave filtering and available options

Peter Matthews
Knowles Precision Devices

In the world of LTE, developers are very familiar with the available filtering technologies that work, namely surface acoustic wave (SAW) and bulk acoustic wave (BAW) filters. These filters cover a range of frequencies up to 6 GHz, come in small sizes and offer good performance-to-cost trade-offs, making them the dominant off-chip approaches in mobile devices today. Unfortunately, analogous filtering options for the mmWave spectrum have issues regarding viability, performance, size and availability, while research teams helping to write 5G standards have yet to provide information on what filters will be required, where they need to be placed in the base station and what performance metrics they must meet.

CONSIDERATIONS

The obstacles to and advantages for using the mmWave spectrum are both widely-publicized and well-understood. High frequencies suffer from range limitations and path loss through air, objects and buildings. However, mmWave signals require much smaller antennas, which can be tightly packed together to create single, narrowly focused beams for point-to-point communication with greater reach. Frequency bands around 28, 38 and 72 GHz are the main candidates for 5G mmWave, having demonstrated directional antenna, beamforming and beam tracking performance in multipath environments.[1-2]

The focus has now shifted to solving the practical issue of how to build an actual mmWave-capable base station and implement high performance RF filtering. Fortunately, mmWave technology has been employed for decades in various fields and functions. For example, it has a long history in military, aerospace and SATCOM applications such as K-Band inter-satellite communication and ranging and Ka-Band high-resolution radar.

In other industries, the automotive field is using both 24 GHz in short-range and 77 GHz in long-range radar-based advanced driver assistance systems (ADAS) to scan a vehicle's environment for driver support or automated driving. In the U.S., 36 to 40 GHz is currently licensed for high speed microwave data links between a cellular base station and a base station controller; and, the unlicensed 60 GHz band is used in short range data connections and IEEE 802.11ad WiGig for high bandwidth streaming.


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FILTER REQUIREMENTS

Chief concerns of industry leaders include:

- **Quality and Performance:** Can the filter perform accurately, repeatably and reliably across thousands of units?
- **Time-to-Market:** 5G deployment is nearly at hand, so do we have a solution that is available today for rapid prototyping and product development?
- **Ease of Integration:** Will the new filter solution be relatively straightforward to implement into existing technology? Can it be easily adapted for use with various wireless standards and frequencies?

Specific filter performance metrics must address the following:

- **Percent Bandwidth:** The filter technology must not limit the radio access system bandwidth.
- **Selectivity:** High selectivity enables designers to make good use of available bandwidth.
- **Insertion Loss:** Power is a system cost driver and on the receiver side, insertion loss impacts the overall noise figure of the receiver.
- **Size and Packaging:** In phased arrays, the antenna elements must be sufficiently close together to avoid generating grating lobes; a half wavelength spacing for mmWave frequencies amounts to only a few millimeters. As shown in ***Figure 1***, phased arrays often used in mmWave applications use a plank architecture, in which the gold areas indicate the antennas mounted on a printed circuit board (PCB) (green area) and the blue areas indicate the circuit "planks" extending 90 degrees from array (where space for filters is already very limited). Base station manufacturers, however, are now looking into flat panel architectures where the circuitry is implemented on the back side of the antenna PCB, requiring even denser spacing for filtering and other functional blocks.
- **Temperature Stability:** In order to make efficient use of available bandwidth, the filter must meet its specifications over a range of temperatures. Small-scale systems may be deployed in exposed environments that experience extremes in temperature and temperature variation. Further, overall size reduction in

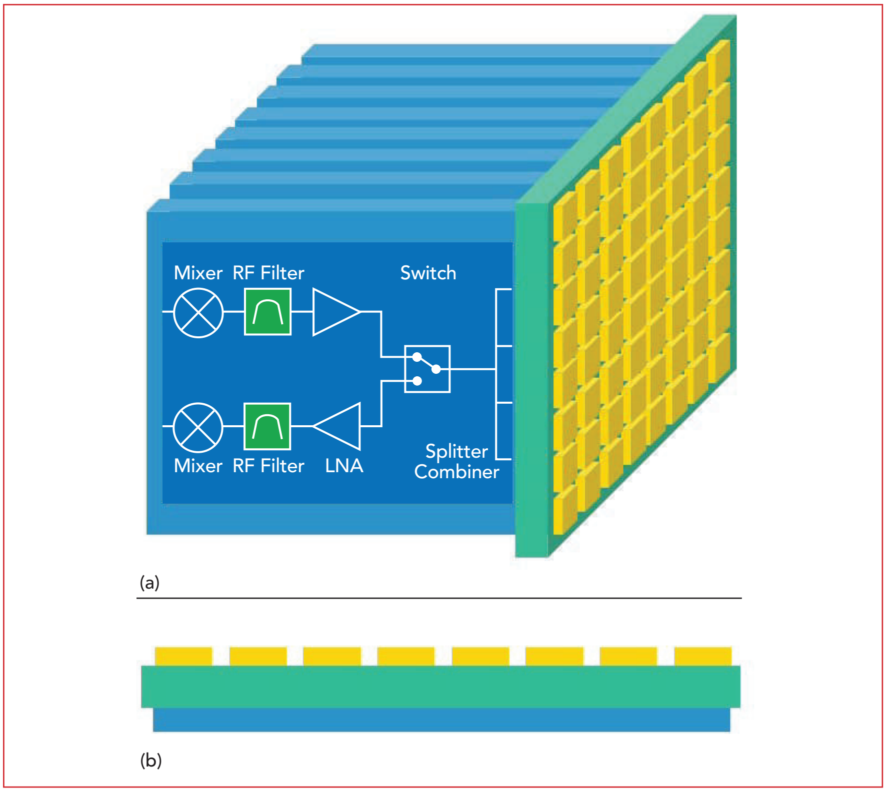
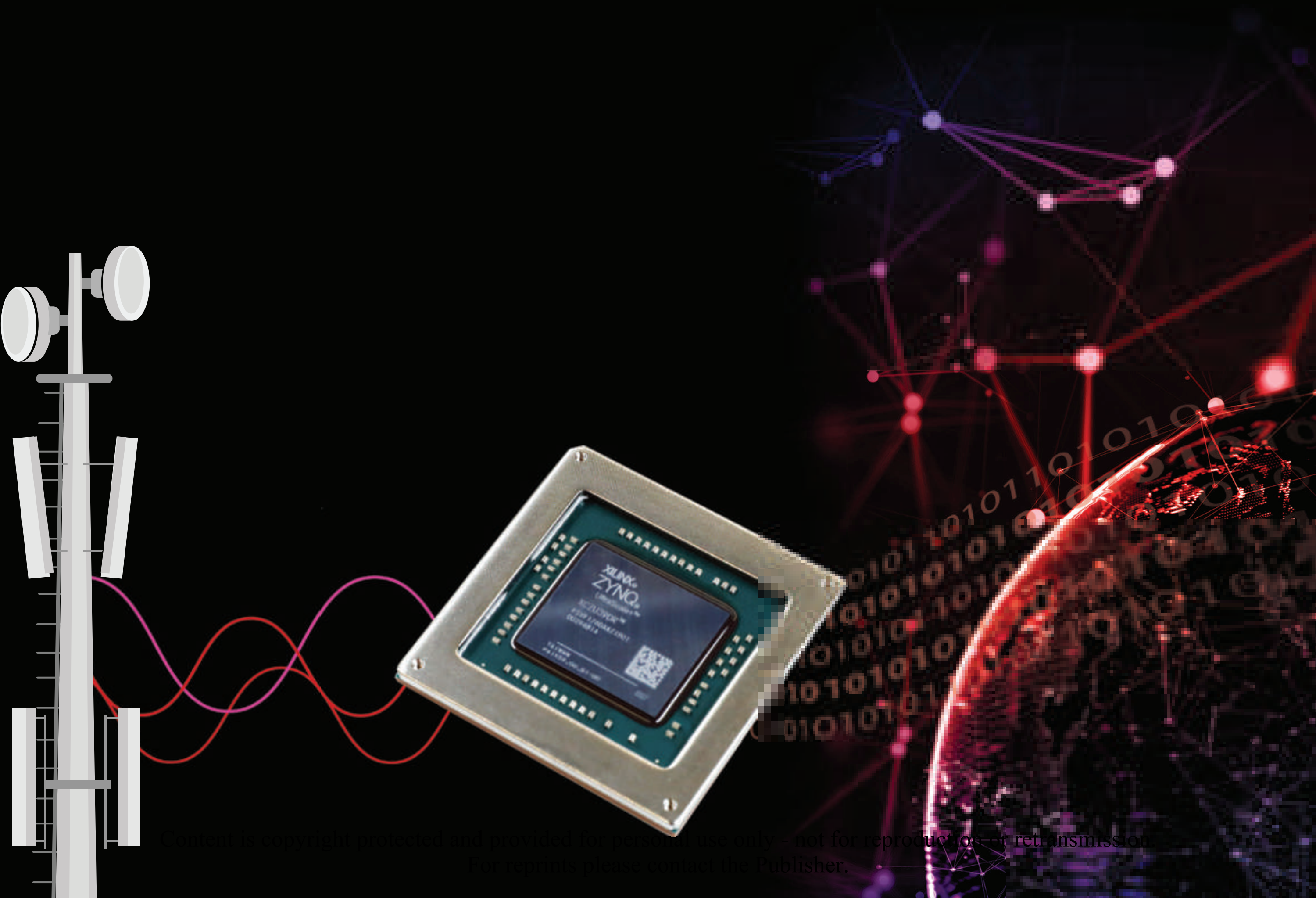


Fig. 1 **Alternative array architectures: plank (a) and flat panel (b).**



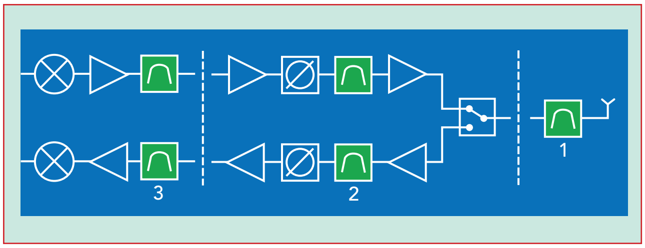


Fig. 2 Potential radio filter locations.

TABLE 1
TYPICAL SAW AND BAW FILTER PERFORMANCE

Performance Goals	Typical SAW/BAW Performance
Low Insertion Loss	< 3 dB
Excellent Rejection	> 30 dB out of band
Broad Bandwidth	Up to 100 MHz
Small Size	~9 mm^2
Good Temperature Stability	~3 ppm/°C

systems leads to densely populated boards, where heat from surrounding components can affect filter stability.

- **Power Handling:** The ability of the filter to withstand large amounts of transmit RF power is mostly a concern in traditional macro-cell use cases below 3 GHz. In mmWave 5G use cases, the transmit power is spread over the individual array elements and the transmit range is reduced as well.
- **Filter Placement:** As shown in ***Figure 2***, there are several practical locations: at the antenna element (Position 1), behind the amplifiers closest to the antenna (Position 2) and on the high frequency side of the mixers (Position 3). It should be noted that the dashed lines represent potential 1:N branching in a beam forming architecture, and that Figure 2 shows a simplified single path from mixer to antenna. The advantage of the Position 1 implementation is that linearity and bandwidth design constraints for the subsequent blocks is eased, potentially reducing overall system cost. Filtering placed at Position 1 suppresses noise far from the channel of interest across a wide frequency range, making wideband suppression and very low insertion loss key performance features. Given that each sub-array has its own filter, small size and low cost are important.

SOLUTIONS

SAW and BAW filters have long dominated the off-chip filtering market in mobile devices because of their excellent performance specs, tiny footprints and affordable prices compared to other options. Unfortunately, the nature of their design—using interdigital transducers (IDT) to process signals as acoustic waves—exhibits degradation in selectivity at frequencies greater than 6 GHz, making SAW and BAW technology unfeasible for mmWave applications. Nevertheless, it is worth noting their performance metrics (see ***Table 1***) as a benchmark for potential mmWave filter solutions.

Emerging SAW/BAW Alternatives

Given the successful use of SAW and BAW technologies at lower frequencies, researchers are naturally looking into developing an acoustic equivalent for mmWave applications.

The Film bulk acoustic resonator (FBAR) filter is a form of BAW filter that can reportedly operate from 5 to 20 GHz,[3] which is applicable for LTE but still below desired mmWave ranges. Resonant Inc. is developing a so called XBAR™ technology that seeks to outperform FBARs, but currently it is only available as licensable intellectual property for manufacturers to complete development.

The use of substrate integrated waveguides (SIW) offers another approach where researchers seek to create small waveguide cavity filters for use in PCB and on-chip applications. While attractive for its wideband properties, good isolation and lower losses, challenges for mmWave include radiation leakage between plated through-holes (PTH), difficulties designing SIW transitions and

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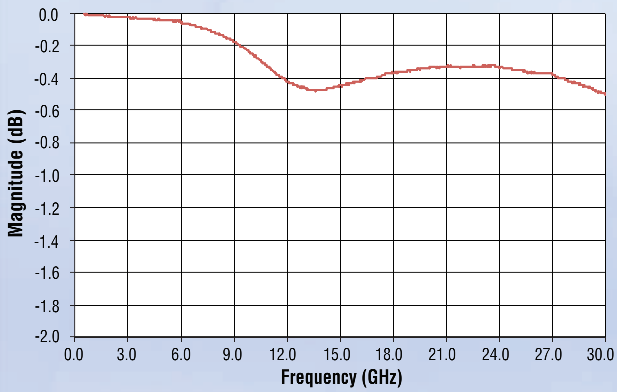
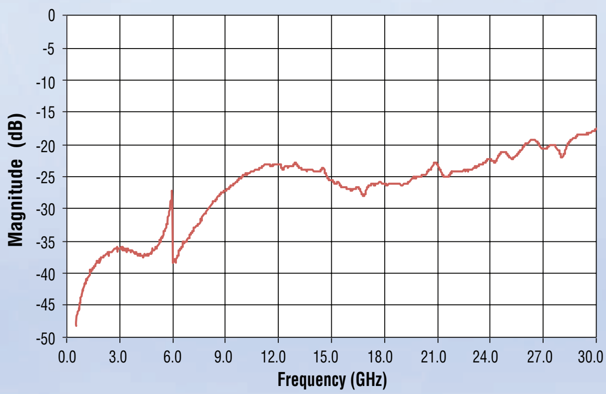


531Z Return Loss (S11)



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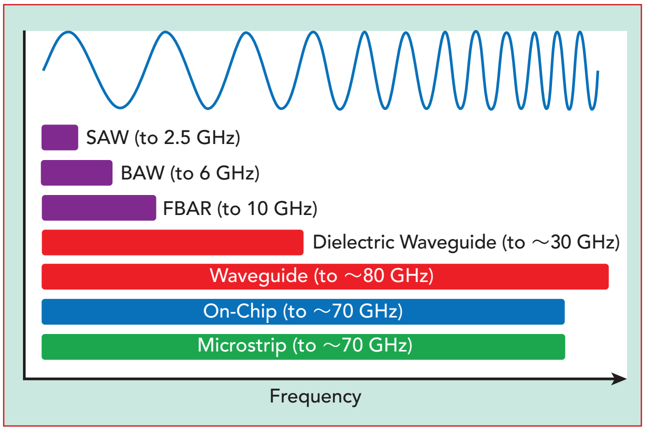

Fig. 3 Frequency ranges of common filter technologies.

dimensional variations in the PTH side walls (which are detectable at mmWave frequencies).[4]

Micro-Electro-Mechanical Systems (MEMS) offers the potential for tiny, tunable RF filters created using conventional semiconductor fabrication processes. The methodology is interesting due to its dimensional accuracy, high component density and low-cost at high volumes;[5] however, current designs are still in the research phase or are limited to the sub-mmWave ranges.

Proven Approaches

Figure 3 summarizes the frequency ranges of today's commonly available filters. At higher mmWave frequencies, acoustic filtering is not as practical, so many developers have turned to electromagnetic (EM) solutions. For mmWave applications at 20 GHz and higher there are dielectric and cavity waveguide, on-chip and microstrip (or planar thin film) filters.

Waveguide filters are hollow or dielectric filled cavities within metal tubes that act as BPFs, blocking certain wavelengths while allowing others to pass. Characterized by high-power handling and low loss, waveguide filters are widely used for mmWave frequencies from 20 to 80 GHz in military, radar, satellite and broadcasting markets. Unfortunately, waveguides typically have dimensions in the centimeter range (see *Figure 4*). A $\lambda/2$ array element spacing at 28 GHz in free space is 5.35 mm. Until manufacturers are able to sufficiently reduce waveguide sizes while still meeting electrical performance requirements, this solution may not be practical for an array antenna system.

On-chip filters using semiconductor technologies are attractive because of the compact circuits, tight tolerances, and the capability for integration with other devices to form system on a chip (SoC) solutions. Yet, significant performance issues regarding Q-factor, losses and noise figure (NF) occur with the production of on-chip devices having reduced dimensions for mmWave frequencies.

Challenges arise from various factors, including the physical characteristics of the semiconductor material and the cost of implementation. For example, GaN circuits are made as thin as possible to increase heat dissipation; however, filter Q is

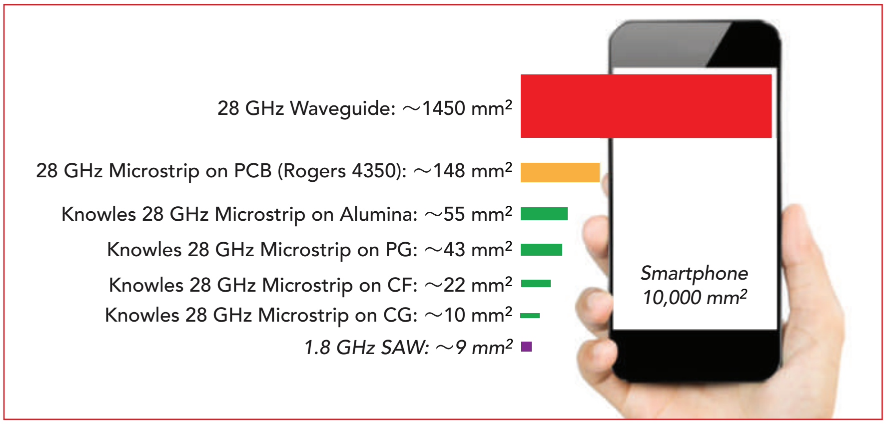

Fig. 4 Sizes of mmWave filters compared to typical SAW filters.

TechnicalFeature

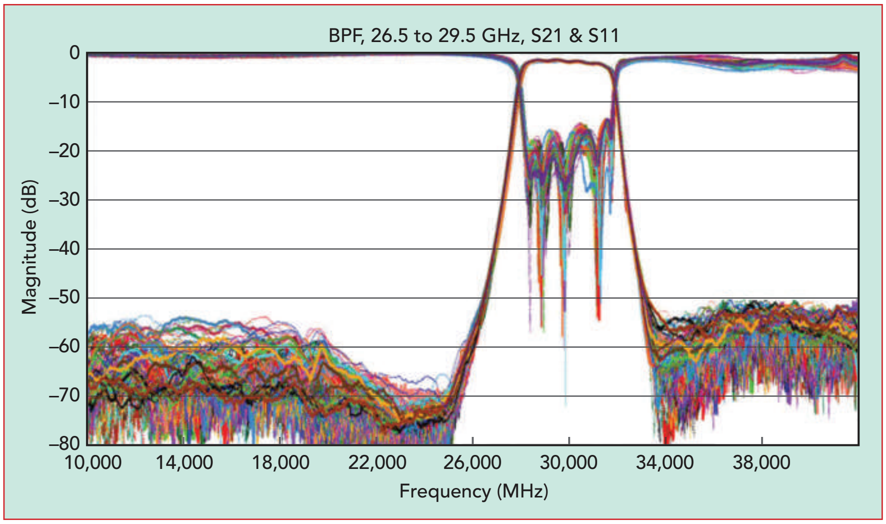

Fig. 5 Repeatability of Knowles Precision Devices 28 GHz SMT single-layer microstrip filters, using 100 samples without tuning.

TABLE 2

COMPARING SAW/BAW FILTER PERFORMANCE WITH SMT MICROSTRIP

Performance Goals	*Typical SAW/ BAW Performance (< 6 GHz)*	*SMT Microstrip Performance (> 20 GHz)*
Low Insertion Loss	< 3 dB	< 3 dB
Excellent Rejection	> 30 dB out of band	> 50 dB out of band
Broad Bandwidth	< 100 MHz	3 GHz
Small Size	~9 mm^2	< 9 mm^2
Good Temperature Stability	~3 ppm/°C	~3 ppm/°C

proportional to dielectric substrate thickness, so the high-power advantage of using GaN devices works in opposition to integrating filters with high Q. In addition, a filter structure in GaN occupies valuable real estate on the wafer that would be better allocated to active devices. Building on-chip high Q filter structures to serve in a front-end application is currently impractical.

Microstrip filters have been considered for mmWave applications but are commonly dismissed for various performance issues. Note that there are at least three different form factors:

- Microstrip on PCB
- Microstrip in a multilayer, low temperature co-fired ceramic (LTCC) package
- Microstrip in a small form factor, single-layer package

Microstrip filters printed on PCB are appealing because of their simple construction, but high performance PCB solutions generally reach centimeter-range sizes, which are much larger than the sub-wavelength dimensions required for mmWave antennas. Variations caused by the PCB manufacturing processes also limit performance, resulting in higher insertion loss and lower suppression values.

Another option is surface mount technology (SMT). SMT assembly has been long used in commercial systems and is now being adopted in mmWave military systems for potential cost savings. Unlike chip and wire solutions, SMT filters have standardized form factors to reduce overall assembly time, and require no post-tuning. ***Figure 5*** shows the performance repeatability of 100 SMT BPFs, measured in the 26.5 to 29.5 GHz range without tuning.

LTCC filters come in a SMT form factor and are similar to multilayer capacitors, in which multiple layers of very thin ceramic tape are printed with different passive elements and then stacked together to prevent

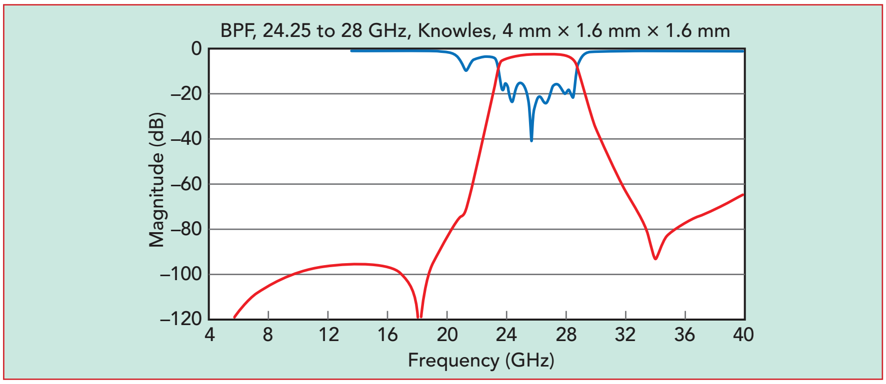

Fig. 6 Performance of a Knowles Precision Devices 26 GHz single-layer 6.4 mm^2 microstrip BPF.

substrate warping. Prototypes of LTCC technology for mmWave applications are being developed, potentially offering a method of including both filters and antennas on the same component with a very small footprint. Unfortunately, since the metal coatings are screen printed, dimensional precision is not as high as other thin film solutions and the unpolished substrate can lead to high losses.[6] Plus, suppression is generally limited to 30 dB and below.

Another type of SMT filter assembly is single-layer microstrip, which is printed with distributed transmission lines to create high performance resonant structures. With a careful choice of filter topology and dielectric materials, high rejection, low loss filters that are temperature stable from −55°C to 125°C can be produced. These filters provide performance similar to their lower frequency SAW and BAW counterparts (see ***Table 2***). High performance and small form factor devices are possible within the constraints of 5G New Radio (NR) systems. ***Figure 6*** shows the functionality of a low loss 26 GHz filter with greater than 50 dB of suppression that fits in a 4 mm × 1.6 mm footprint. This size is significantly smaller than half a wavelength, enabling integration in both plank and planar architectures.

CONCLUSION

The timeline for delivering mainstream 5G communications is getting tighter, and determining the appropriate RF filtering for 20 GHz and above is a fundamental issue. 5G systems require filters with high percentage bandwidths, good selectivity and excellent temperature stability in compact packages. In order to accelerate time-to-market, developers are seeking established solutions, such as waveguide and microstrip filters, that have long been used in the satellite, radar and broadcasting industries.■

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Compact CPW-Fed Dual-Band Linearly and Circularly Polarized Monopole Antenna for WiMAX and WLAN

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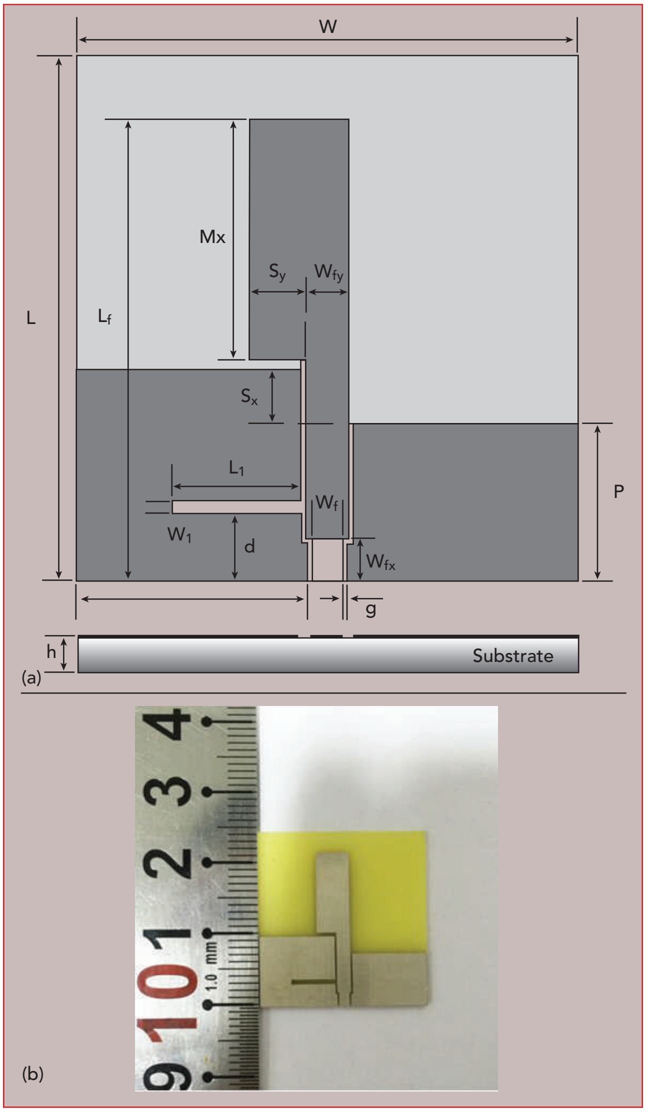
China Mobile Ltd., Shenzhen, China

A compact dual-band linearly and circularly polarized monopole antenna employs an inverted L-shape and an asymmetric ground plane fed by a coplanar waveguide (CPW). The inverted L-shape strip produces an orthogonal component in the ground plane and monopole distinct from its original linear polarization (LP). By embedding a slit on the ground plane, this antenna achieves a broad impedance bandwidth and circular polarization (CP). Measurements demonstrate a 10 dB bandwidth of 92.7 percent from 3.3 to 9 GHz and a 3 dB axial ratio (AR) bandwidth of 57.1 percent from 5 to 9 GHz, capable of covering the 5.725 to 5.85 GHz WLAN band. Meanwhile, LP is also obtained covering the 3.3 to 3.7 GHz WiMAX band. Compared with other recent work, wider axial ratio and impedance bandwidth, as well as a simpler, more compact structure are the key features.

CP radiation has been widely used in the fields of communication, radar and electronic countermeasures.[1-3] To achieve CP, several printed monopoles have been proposed.[4-10] Augustin and Denidni LP designed a multi-band coplanar monopole antenna with a trapezoidal structure.[4] Wang and Hisao[5] used an asymmetrical ground plane to excite CP at 1.57 GHz with a simple CPW ground plane width adjustment. Ghobadi and Dehmollaian[6] introduced CP operation with two arms of different lengths in a simple printed monopole. Others used slots in the ground plane,[7] four notch slots,[8] feed positioning with U- and E-shaped slots,[9] slotted monopoles,[10] S-shaped slots,[11] inverted L-slits on the ground and feed networks composed of three Wilkinson power dividers.[12] These are examples of the various techniques proposed for fabricating CP monopole antennas.

Due to the narrow CP bandwidths of these approaches, several wideband CP monopole antennas were introduced.[13-16] Kumar and Harish[13] described a slot monopole antenna with a power division network. It achieved a 30 percent AR bandwidth by adjusting the size of the slot; yet it was large in size with a complex geometry. By parallel-aligning an inverted L-shaped strip and cutting an inverted L-shaped slot on the ground



▲ Fig. 1 **Final CPW-fed planar monopole antenna configuration (a) and prototype (b).**

TABLE 1

OPTIMIZED ANTENNA DIMENSIONS

Dimension	Size (mm)	Dimension	Size (mm)
L	25	d	3.25
W	24	W_1	0.6
h	0.8	M_x	11.5
P	7.5	g	0.2
W_f	1.5	L_1	6.25
L_f	22	W_{fx}	2
S_x	2.5	W_{fy}	2
S_y	2.75		

plane,[14] a CP bandwidth larger than 30 percent was achieved. Broadband CP radiation could be also produced by moon-shaped[15] or chifre-shaped[16] monopole antennas. However, most of the broadband CP monopole antennas with slots and stubs or embedded complex structures[13-18] are large in size.

In this article, a novel compact dual-band LP and CP monopole antenna with an inverted L-shaped monopole and an asymmetric ground plane for WiMAX and WLAN applications is described.

ANTENNA CONFIGURATION

The final CPW-fed monopole antenna geometry is shown in ***Figure 1***. The antenna is printed on an FR4 substrate with a dielectric constant of 4.4 and loss tangent of 0.02. An asymmetric ground plane with a slit etched on the left is introduced to excite broadband CP and obtain a good impedance match. To obtain a wider impedance bandwidth, an impedance matching structure is employed at the base of the asymmetric ground and the monopole radiator. Broadband CP is obtained with two adjacent CP modes combined by adjusting the size of the inverted L-strip and length of the slit etched on the ground plane. To maximize the 3 dB AR bandwidth while maintaining the return loss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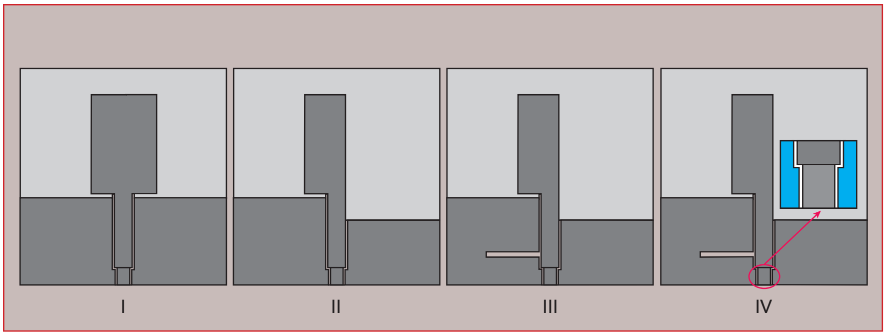


Fig. 2 Monopole antenna prototype designs.

better than 10 dB, the dimensions of the inverted L-strip, the slit length and CPW feed line were optimized in HFSS (see **Table 1**).

Shown in **Figure 2** are four prototypes built during the process of validating the design. S_{11} and AR are compared in **Figures 3a** and **3b**, respectively. Due to weak radiation in the vertical direction, CP is difficult to generate in a traditional monopole. This is illustrated by the electric field vectors in **Figure 4a**. The vertical electric field vectors of the two ground planes are in opposite directions, resulting in small vertical components. Therefore, linear horizontal polarization with a large value of AR is shown in Figure 3b (antenna II).

In general, CP is generated by two orthogonal E vectors with equal amplitudes and a 90 degree phase difference. It is defined as

$$E = E_{Hor} + e^{j\delta}E_{Ver} \quad (1)$$

where E is the instantaneous electric field vector, E_{Hor} and E_{Ver} denote the respective electric field vectors in the horizontal and vertical planes and δ is the phase difference. If the amplitudes of E_{Hor} and E_{Ver} are equal and δ = ±90 degrees, the polarized wave is right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP).[18] The AR can be used to represent the characteristics of the polarization. The AR is defined as RHCP or LHCP[19-20] and is expressed as

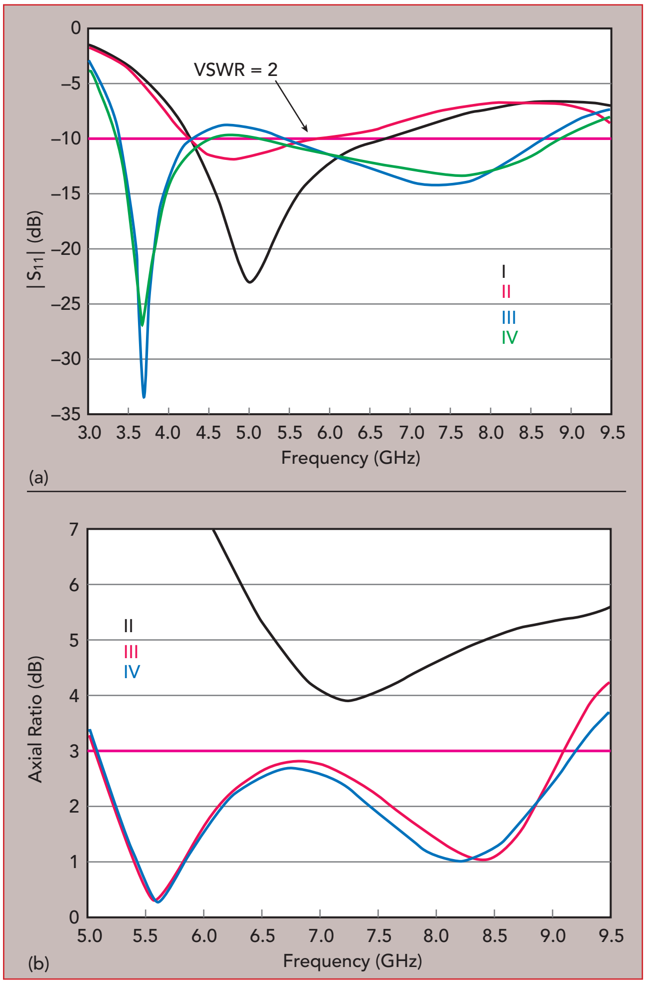
$$AR = 20\log\left|\frac{\rho+1}{\rho-1}\right| \quad (2)$$

$$\rho = \left|\frac{E_{RHCP}}{E_{LHCP}}\right| \quad (3)$$

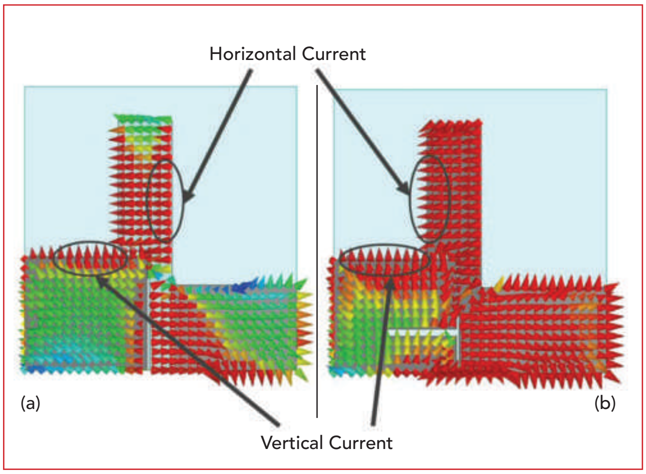
LP, CP and elliptical polarization (EP) are three types of polarization. For perfect LP, the AR is infinite; for perfect CP, the AR is 0 dB; EP is considered to lie between LP and CP. Because a perfect CP wave with AR = 0 dB is ideal, CP is typically defined as an AR value of less than 3 dB.

The asymmetric ground plane with an inverted L-strip feed generates E_{Hor} and E_{Ver}, but it excites EP. So, an asymmetric ground plane with a horizontal slit on the left ground

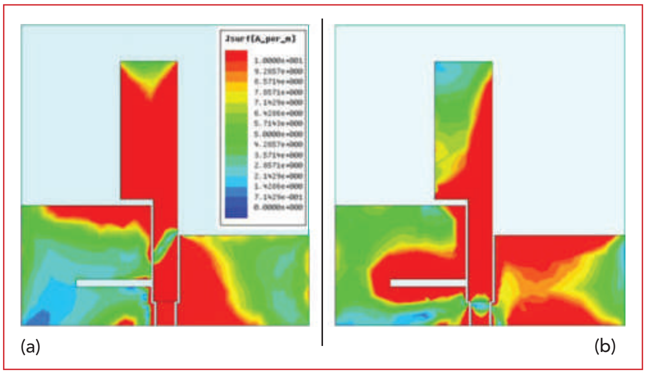
plane is employed to generate two orthogonal modes with a 90 degree phase difference. Using this method, the amplitudes of E_{Hor} and E_{Ver} are almost equal and exhibit a 90 degree phase difference, exciting CP (see antennas III and IV in Figures 3b and 4b). As shown in ***Figure 4b***, a vertically polarized component is produced by an asymmetric ground plane that produces vertical magnetic field vectors in the right ground plane. To achieve a wider impedance matching bandwidth, a matching structure is introduced, which results in the improvement seen in Figure 3a (antenna IV).



▲ Fig. 3 **Simulated $|S_{11}|$ (a) and AR (b) of the prototype antennas.**



▲ Fig. 4 **Simulated electric field distributions: antenna II at 5 GHz (a) and antenna III at 5.6 GHz (b).**



▲ Fig. 5 **Surface current distribution after HFSS optimization, at 0 degrees (a) and 90 degrees (b).**

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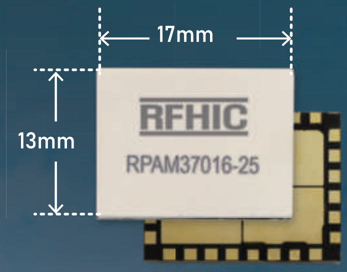

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Psat	50dBm(100W)	50dBm(100W)
Gain	27dB	27dB

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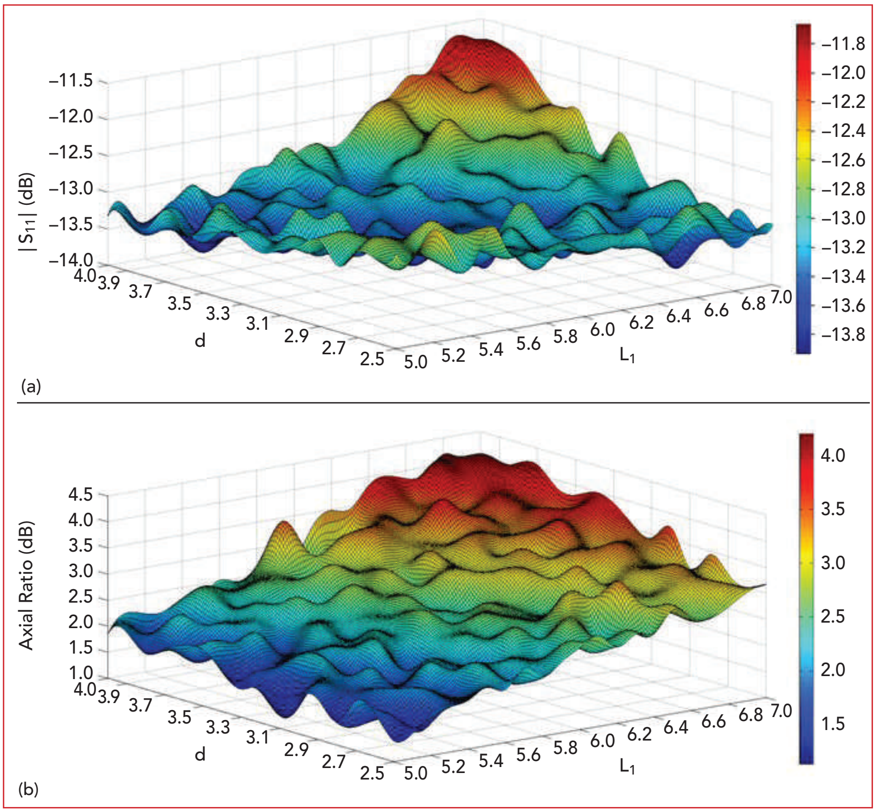


Fig. 6 $|S_{11}|$ (a) and AR (b) vs. L_1 and d.

PARAMETRIC STUDY

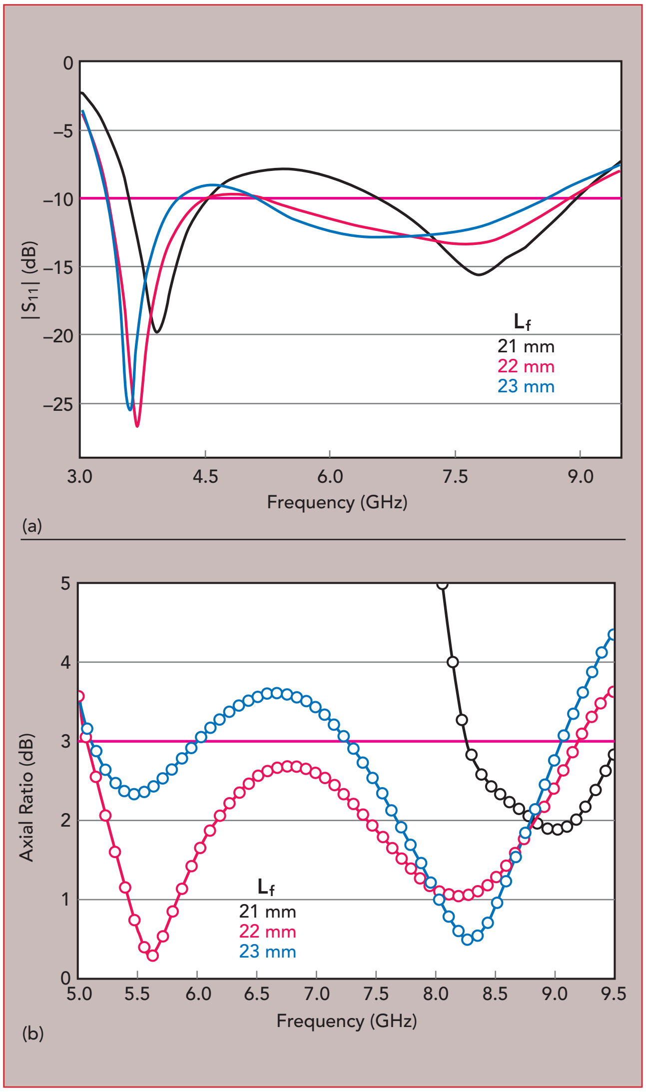
CP depends mainly on the dimensions of the inverted L-strip, height of the ground plane and length of the slit. ***Figure 5*** shows the surface current distribution for each of the orthogonal polarizations after HFSS optimization, with the optimized dimensions listed in Table 1.

Figure 6 shows the effects of L_1 and d on antenna impedance match and AR, as simulated in MATLAB at 7 GHz. Simulation and analysis show that the best impedance and AR properties occur for L_1 = 6.25 mm and d = 3.25 mm. S_{11} and AR curves for various L_f values are shown in ***Figure 7***. An improved impedance match and a downward shift of the S_{11} minima is observed as L_f is varied from 21 to 23 mm. Meanwhile, for L_f greater or less than 22 mm, CP is degraded. The best S_{11} and AR performance occurs at around 22 mm. The S_{11} and AR curves for various S_y values are displayed in ***Figure 8***. When S_y is increased, the second resonance of the reflection coefficient curve shifts upward in frequency. The first and the second CP mode shift upwards as well, widening the AR bandwidth. To achieve good performance in both the reflection coefficient and the AR, a tradeoff must be made selecting S_y; the best S_{11} and AR properties occur for an S_y value of approximately 2.75 mm.

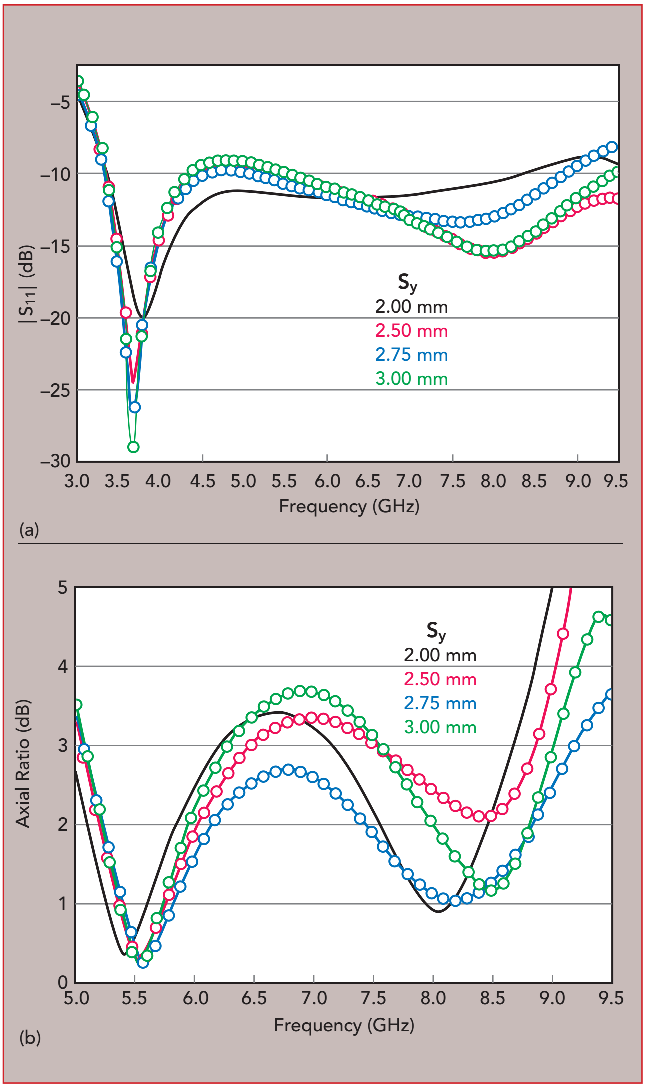
Figure 9 shows the patch's simulated magnetic field vectors at 5.6 GHz for four instants of time, as the field rotates from 0 to 270 degrees. As time increases, the magnetic field vectors rotate clockwise, indicating LHCP for $z > 0$, which is the upper half space. RHCP would be observed for $z < 0$, or the lower half space.

SIMULATION AND MEASUREMENT

The antenna was simulated using HFSS and fabricated with the optimized dimensions shown in Table 1. Simulated and measured antenna S_{11} and AR vs. frequency are shown in ***Figure 10***. Measured and simulated impedance bandwidths are 92.7 percent (3.3 to 9 GHz). CP bandwidths are 57.1 percent, from 5 to 9 GHz at a center frequency of 7 GHz. This performance can



▲ Fig. 7 $|S_{11}|$ (a) and AR (b) vs. L_f.



▲ Fig. 8 $|S_{11}|$ (a) and AR (b) vs. S_y.

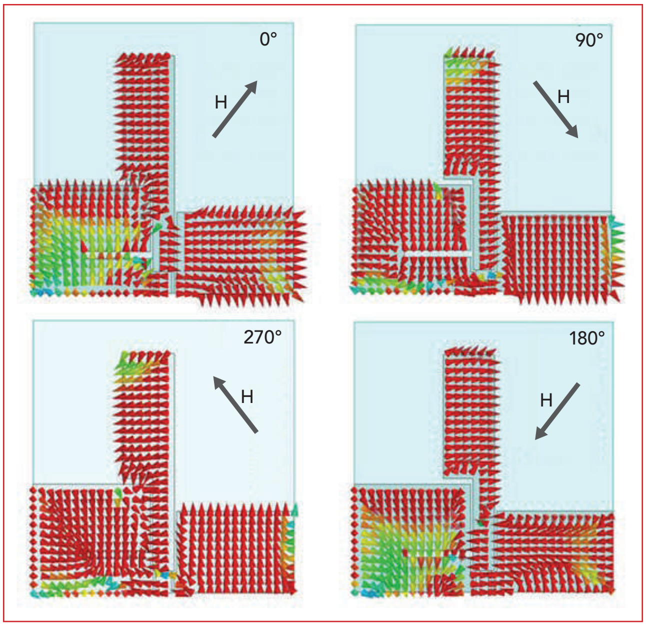


Fig. 9 H-field distribution with rotation at 5.6 GHz.

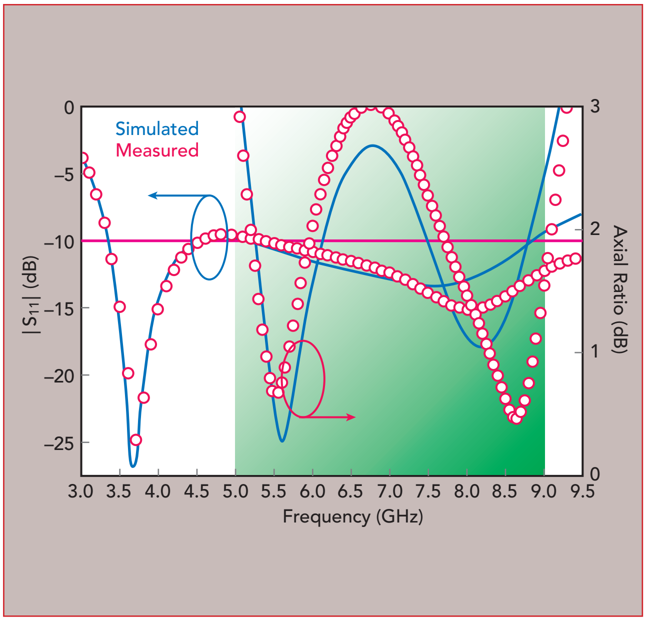


Fig. 10 Simulated and measured $|S_{11}|$ and AR vs. frequency.

provide full coverage of the 5.725 to 5.85 GHz WLAN band. LP is obtained, as well, covering the 3.3 to 3.7 GHz WiMAX band. Excellent agreement is observed between simulation and measurement except for mismatches attributed to poor quality SMA connectors and fabrication tolerances.

Numerical and experimental radiation patterns of the antenna at 3.7, 5.6 and 8.3 GHz for the xoz and yoz planes are plotted in ***Figure 11*** and are in close agreement. When operating at the lower frequency, the antenna radiates with a slot-like pattern for vertical polarization; at the upper frequencies, it radiates with patch-like patterns of RHCP/LHCP polarization. LHCP and RHCP patterns depend on the point of observation, whether it is from the +Z direction (upper hemisphere) or −Z direction (lower hemisphere). The gain and efficiency over frequency are plotted in ***Figure 12***.

CONCLUSION

A compact dual-band LP and CP monopole antenna exhibits a broad 3 dB AR bandwidth by combining an inverted L-strip and a horizontal slit, with two adjacent CP modes coupled together. A 10 dB impedance bandwidth of 92.7 percent (3.3 to 9 GHz) and a 3 dB AR bandwidth of 57.1 percent (5 to 9 GHz) was demonstrated and shows good agreement with measured data.■

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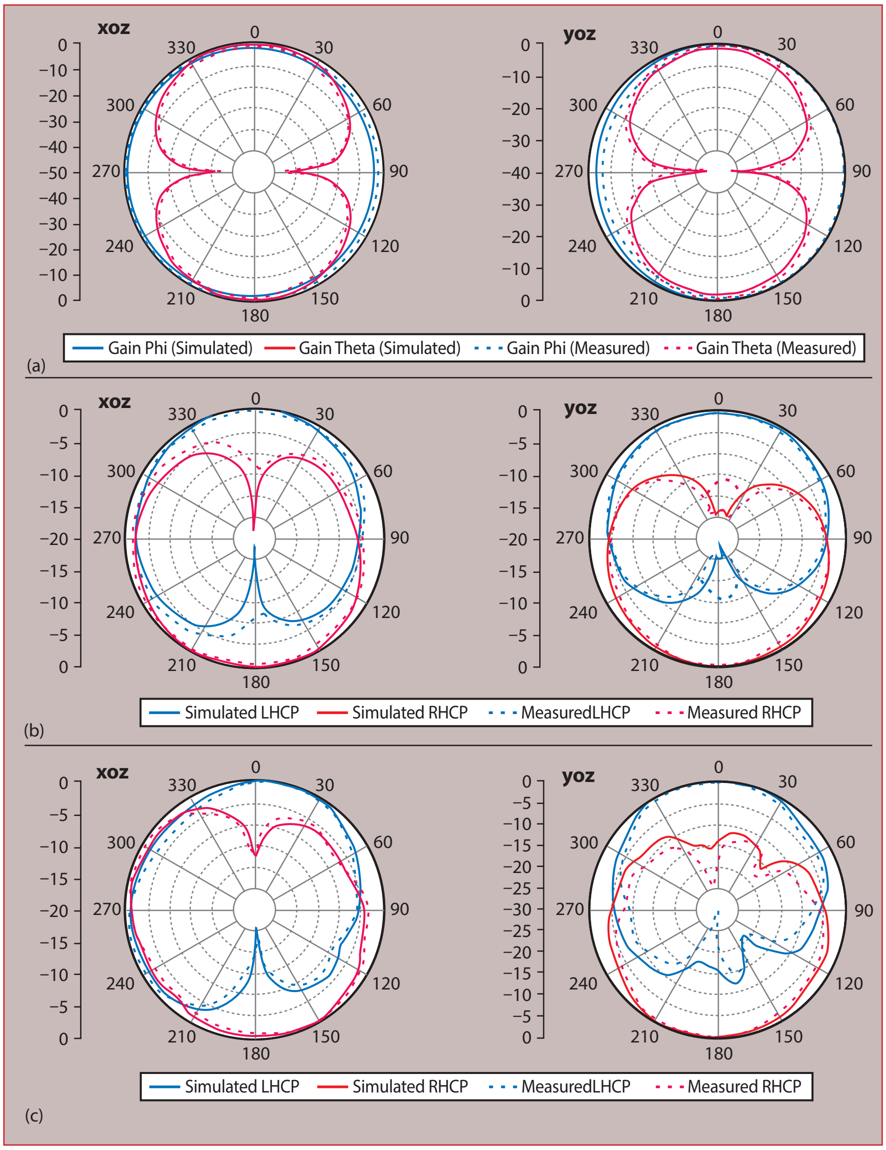

Fig. 11 Simulated and measured radiation patterns at 3.7 (a), 5.6 (b) and 8.3 GHz (c).

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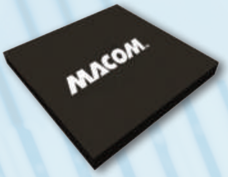

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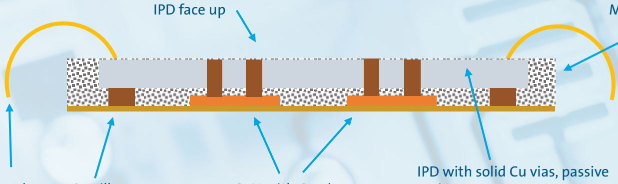

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MAMF-011133	2.3 – 5.0	2	0.4 @ 3.5 GHz	1.3 @ 3.5 GHz	34	43	34	6x6
MAMF-011119	2.3 – 5.0	1	0.4 @ 4.2 GHz	1.3 @ 4.2 GHz	33	41	31	6x6
MAMF-011069	1.8 – 3.9	2	0.5 @ 2.6 GHz	1.2 @ 2.6 GHz	33	–	32	5x5
MAIA-011004	0.4 – 5.0	1	0.21 @ 3.5 GHz	1.1 @ 2.7 GHz	34	50	36	5x5

LNAs for sub 6 GHz 5G

Part Number	Frequency (GHz)	Vd (V)	Id mA	Noise Figure (dB)	Gain (dB)	OP1dB(dB)	OIP3 (dBm)	Package (mm)
MAAL-011078	0.7 – 6.0	3	50	0.35	20 @ 3.5 GHz	16	30	2x2
MAAL-011134	0.7 – 6.0	5	79	0.50	20 @3.5 GHz	20	35	2x2
MAAL-010706	1.4 – 4.0	4	60	0.85	15 @ 2.5 GHz	19	35	2x2

Switches for sub 6 GHz 5G

Part Number	Frequency (GHz)	Type	Type	IL (dB)	Isolation (dB)	Max Pin (dBm)	Vcc	Package (mm)
MASW-000822	0.05 – 6.0	SPDT	R	0.4 @ 3.8 GHz	21 @ 3.8 GHz	40	5/12	3x3
MAMF-007921	DC – 7.0	SPDT	R	0.6 @ 2 GHz	>20 @ 2 GHz	40	3	2x2
MAMF-011070	0.05 – 6.0	SPDT	R	0.4 @ 3.5 GHz	43 @ 2.7 GHz	51	5	5x5

DVGA for sub 6 GHz 5G

Part Number	Frequency (GHz)	Vd (V)	Output P1dB (dBm)	Gain (dB)	Att Range (dB)	Package (mm)
MAAM-011287	3.3 – 5.0	5	25	18	15 in 1dB steps	4x4
MAAM-011292	2.3 – 2.7	5	25	18	15 in 1dB steps	4x4

GaN Doherty PA Solutions for sub 6 GHz 5G

Part Number	Frequency (GHz)	Vd (V)	Pout Avg (W)	Gain (dB)	PAE @ Pout Avg (%)	Package (mm)
*MAGB-102527-050A0P	2.5 – 2.7	28	6	28	48	5X7
*MAGB-103436-040S0M	3.4 – 3.6	28	5	28	42	5X7
*MAGB-102527-055A0P	2.5 – 2.7	TBD	8	15	52	–
*MAGB-102527-010B0P	2.5 – 2.7	28	1	15	20	–
*MAGB-103438-040A0P	3.4 – 3.8	28	6	15	42	–
*MAGB-103438-010A0P	3.4 – 3.4	28	1	15	20	–

Integrated HMIC for mmWave 5G

Part Number	Frequency (GHz)	Function	Rx Gain (dB)	Rx Gain (dB)	Rx Gain (dB)	Tx P1dB (dBm)	Package (mm)
MAMF—011099	24.25 – 29.5	HMIC	25	3.5	28	27	6.5.x6.5

Drivers, PAs and LNAs for mmWave 5G

Part Number	Frequency (GHz)	Function	Tx Psat (dBm)	Tx Gain (dB)	Tx PAE (%)	Rx Gain (dB)	Rx NF (dB)	Package (mm)
MAAM-011112	20-37	Driver	20	24	–	–	–	3x3
MAAP-011298	27-31.5	PA	33.5	26	26	–	–	5X5
MAAP-011289	28-30	PA	35	23	23	–	–	5X5
MAAL-011129	18-31.5	LNA	–	–	–	20 @ 28 GHz	2.3 @ 28 GHz	2X2

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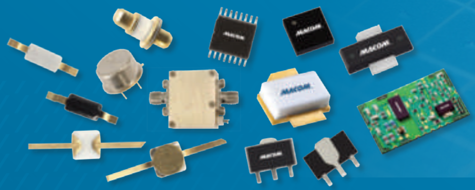

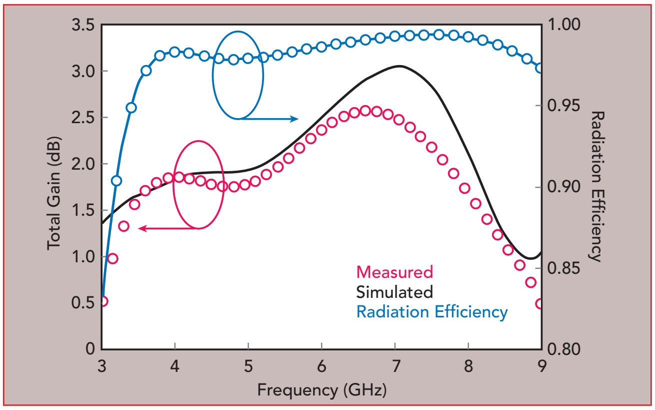

Fig. 12 Simulated and measured antenna gain and efficiency vs. frequency.

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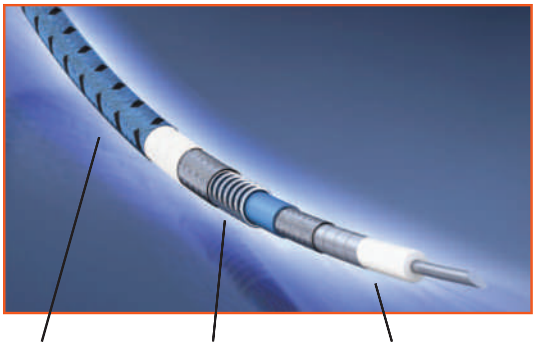

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INVITED PAPER

A New Generation of Integratable Frequency Agile Bandpass Filters

Fred Schindler, John Nielsen, Dennis Rosenauer and Tom Raschko
Anlotek Ltd.

A new filter technology has been developed that is tunable in frequency, with variable bandwidth and the capability to operate at RF through mmWave frequencies. These filters exploit new innovations in regenerative resonance circuits that result in high stability and controllable Qs in the thousands. Further, the self-calibration circuitry ensures ease of configuration in a wide range of applications. A multipole filter has been demonstrated with variable bandwidth and tunable passband. The demonstrated filter has a bandwidth of 2.8 MHz (0.16 percent) centered at 1.75 GHz and is comprised of three dominant poles with Qs on the order of 1900. The core of this filter technology is a regenerative resonator, denoted as the ATL3. Three ATL3s have been combined to realize an agile multipole Chebyshev bandpass filter. An important feature of the ATL3 architecture is orthogonal control of center frequency and bandwidth (Q) that results in superior stability and ease of control. This technology is compatible with semiconductor integration and an ideal candidate for 5G systems, IoT and a wide range of military systems.

A 3-pole tunable bandpass filter has been demonstrated, denoted as the MP3, which consists of three regenerative resonators. ***Figure 1*** shows a measurement of the MP3, tuned for a nominal 3 MHz bandwidth, centered at 1758 MHz. The passband ripple is less than 0.8 dB. Since the filter is comprised of three independent electronically adjustable poles, the passband ripple and transition steepness are programmable. ***Figure 2*** shows an example where the bandwidth is varied, from a nominal 3 to 4

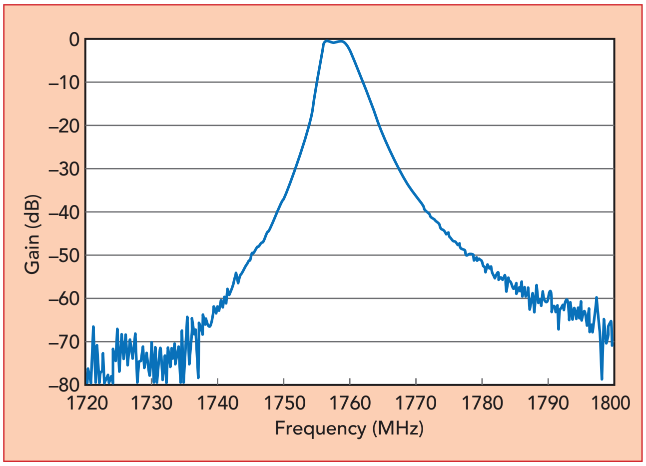

Fig. 1 MP3 agile filter, tuned for a 3 MHz bandwidth.

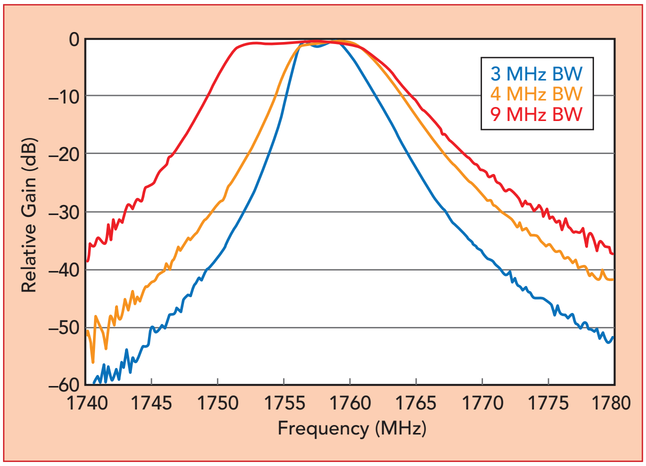

Fig. 2 MP3 agile filter, tuned for varying bandwidth.

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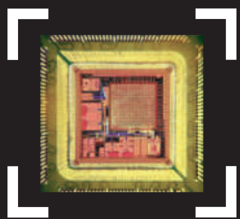

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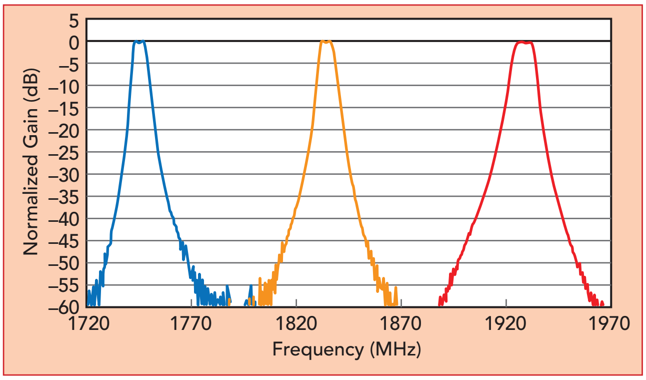

Fig. 3 MP3 agile filter, tuned across a 10 percent frequency range and with a 5 MHz bandwidth.

and 9 MHz. Low ripple is maintained. Note that the gain in Figure 2 is normalized. The poles feature Q enhancement via regeneration, as explained in more detail later in this article.

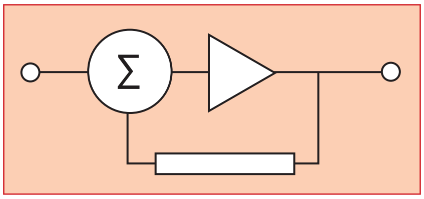

Fig. 4 Basic regenerative circuit.

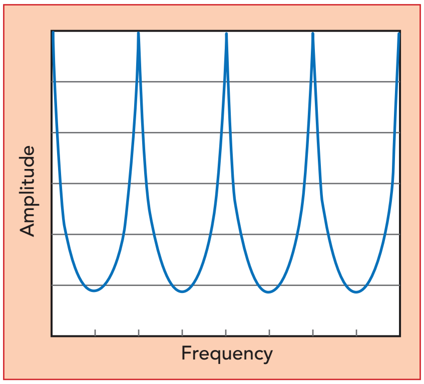

Fig. 5 Response of the basic regenerative circuit in Figure 4.

Bandwidth can be adjusted by moving the frequency of the poles and by adjusting Q. The MP3 can implement a third-order bandpass filter of arbitrary pole placement. Hence any Chebyshev filter type can be realized with the usual trade-off of ripple versus transition steepness. In the other extreme, a Butterworth type filter can be implemented with maximally flat passband, but less transition steepness.

The poles may also be moved together in frequency, which allows the filter to be tuned up and down in frequency. ***Figure 3*** shows an example of the filter tuned over a 10 percent bandwidth, 185 MHz, from 1745 to 1930 MHz. The range of frequency tunability is 15 percent and is limited by the details of the prototype circuit design of the resonators, and much larger tuning ranges are possible with straightforward design variations.

BACKGROUND

Regeneration was a common technique in early RF circuits, about 100 years ago, as a means to achieve higher gain given the vacuum tubes available at the time. It was also found that this regeneration could increase selectivity, enhancing the Q of tuned circuits.[1-2] Regeneration is no longer in wide use, thanks to the high gain available from modern devices, and due to the challenges of controlling circuits that operate at or

near instability. More recently, Q enhanced filters have been demonstrated on silicon, making use of regeneration.[3-4] This work made use of one active pole and one passive resonator, and stable Q enhancement was limited.

BASIC PRINCIPLES

The inherent frequency selectivity of a regenerative circuit can be understood by considering a simple positive feedback loop, as shown in **Figure 4**. This circuit will result in a periodic response in frequency, as shown in **Figure 5**, where the period is determined by the delay around the loop, and the throughput gain is determined by the gain in the loop. This response, with its periodic resonances and infinite set of poles, is not generally desired. A simple modification can be made to realize a single dominant resonance as shown in **Figure 6**. A resonator is inserted into the loop which suppresses higher harmonics, passing only the fundamental. The dominant pole of the feedback regenerative loop is adjustable by varying the delay around the loop and by tuning the resonator. The Q of this regenerative resonator can also be adjusted by changing the loop gain.

The delay and the gain can be anywhere in the loop, so this concept has considerable circuit flexibility, depending on system and circuit requirements. The circuit in **Figure 7** has a tunable resonator in the forward path, and adjustable gain in the feedback path. This gain is equivalent to negative resistance and can compensate for the loss of the resonator in the forward path. This allows a wide range of effective Qs to be realized. When there is no feedback, the resulting Q is that of the resonator on its own. As gain is increased, the loss of the resonator can be completely compensated, and any further increase in gain results in oscillation.

The response of the circuit in Figure 7 can be seen in **Figures 8** and

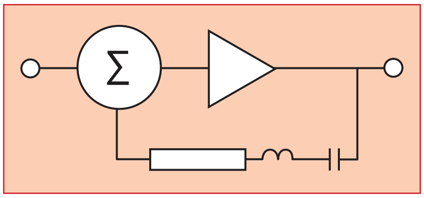

Fig. 6 Incorporating a resonator in a regenerative circuit.

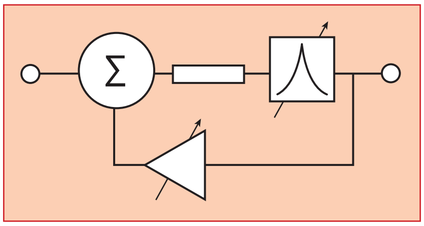

Fig. 7 A tunable regenerative circuit with variable Q.

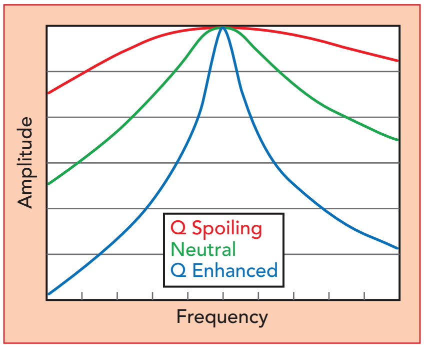

Fig. 8 The Q in a regenerative circuit can be adjusted by changing loop gain.

9. Figure 8 illustrates the effect of changing the gain around the loop, from positive for Q enhancement, to negative for Q spoiling. Figure 9 shows the response if the loop gain is held constant, and the resonator is tuned. The level of Q enhancement remains constant, and the resonant frequency is tuned. It should be noted that the throughput gain of the regenerative filter increases proportionally with Q enhancement, so the plotted responses have been normalized accordingly for better clarity.

LIMITATIONS WITH CONVENTIONAL REGENERATION

Regenerative circuits, such as the ones illustrated here so far are challenging to control. Maximum Q enhancement is achieved near the threshold of instability. To optimize Q enhancement, quenching circuitry has been devised, including circuitry known as Super-Regeneration.[2] Super-Regenerative circuits have limited application because of the periodic operation of the quenching circuit.[5] Oscillation frequency jumps, and hysteresis, are also problems with regenerative circuits, resulting in unpredictable control characteristics. This has given regeneration a reputation of being finicky and only useful in limited esoteric applications.

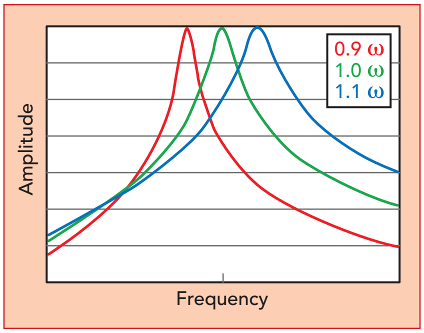

Fig. 9 The resonant frequency of a regenerative circuit can be changed by adjusting loop delay and tuning the resonator.

NEW APPROACH

A new circuit has been developed and demonstrates an innovative circuit approach that overcomes these aforementioned limitations. It incorporates multiple passive resonators in the regenerative loop. This approach results in a circuit that behaves as a single pole, and which overcomes issues with control and stability.[6] Three resonators in the loop are adequate to ensure controllable and predictable performance. The initial demonstration of this concept was implemented with off the shelf components on an FR4 board, shown in ***Figure 10***. The

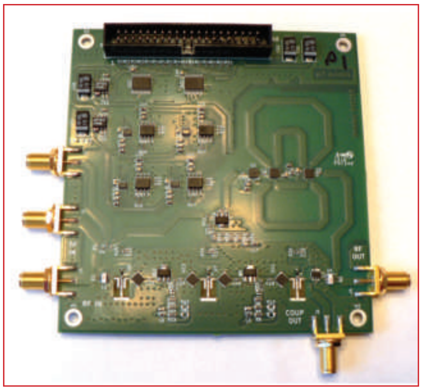

Fig. 10 Anlotek's ATL3 active resonator is the building block for tunable filters.

block diagram is shown in ***Figure 11***. The ATL3 circuit incorporates three resonators, which were implemented with coupled lines on the FR4 board, tunable with varactors. The Q of these internal resonators is 70, but they could be much lower. A Q of 10 is sufficient to realize an ATL3 active resonator with an enhanced Q of greater than 1000. This implies that the filters are attractive for semiconductor implementation. For the first time, compact high performance bandpass filters can be fully integrated on chip. They can operate at any frequency commensurate with the targeted semiconductor technology.

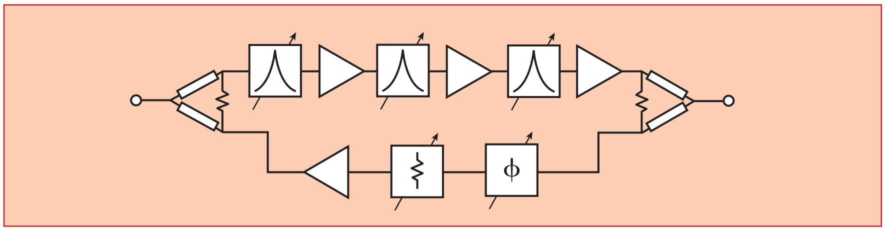

Fig. 11 The block diagram of ATL3 active resonator.

The performance of the ATL3 demonstration is illustrated in ***Figures 12*** and ***13***, showing how Q can be enhanced, as well as how the resonant frequency can be tuned. Repeatable and stable Qs of 2000 have been achieved with this demonstration board. The resonant frequency can be tuned over a relative band of 15 percent which is not a limitation of the ATL3 concept. Rather it is a limitation with this demonstration prototype due to the choice of resonator used. Larger tuning ranges could be achieved with a redesign of the passive resonators and the varactor tuning structure, similar to broad banding VCOs. Further, switches can be used to extend tuning with multiple matching circuits, varactors or resonators.

CONTROL AND CALIBRATION

Another attractive feature of this circuit is the capability for self-calibration. This is done by increasing loop gain until the onset of oscillation. This provides an accurate indication of the resonant frequency. It also provides the control point just beyond stable operation. This is possible because, with its three passive resonators, the ATL3 is innately well behaved.

The circuit has three adjustable elements, all digitally controlled via DACs. They are (1) amplifier gain, (2) resonant frequency and (3) phase shift. Amplifier gain adjusts the loop gain. ATL3 has three amplifiers in the forward path, and in the demonstration, they are all controlled together. Resonant frequency is controllable with varactors integrated in coupled-line resonators. The ATL3 has three such resonators in the forward path. They are also controlled together in the ATL3 prototype, but could be controlled individually. The phase shifter provides delays via

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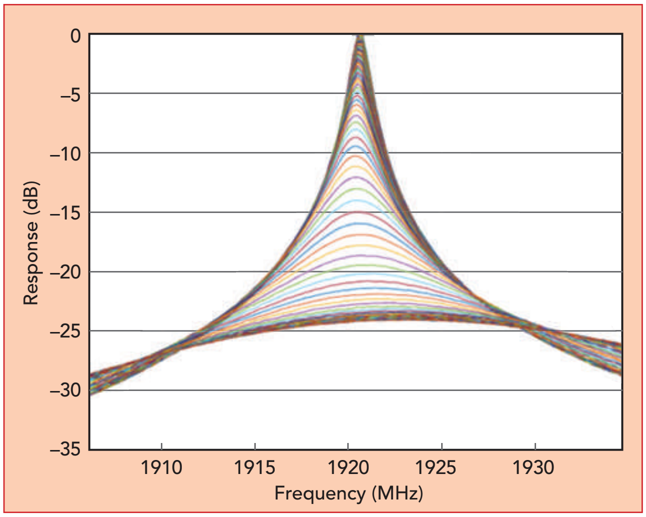


Fig. 12 Measured response of ATL3 showing variable Q as loop gain is adjusted.

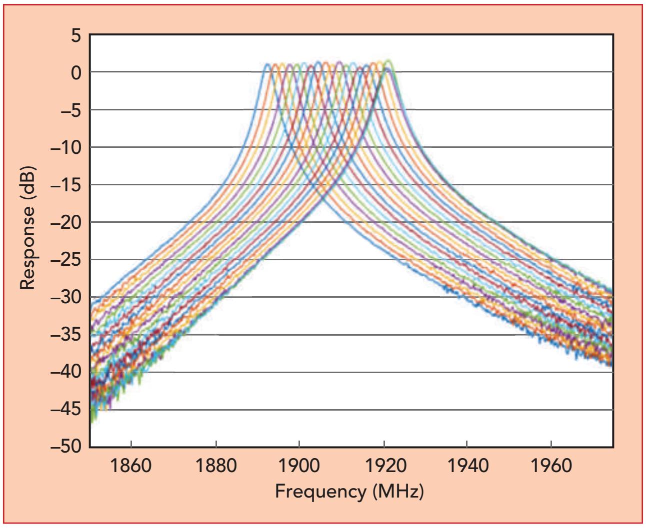


Fig. 13 Frequency tuning ATL3.

transmission line sections in nominal 90 degree steps. The phase shift is set to achieve optimum stable control, necessary because of the total electrical length of the loop. In a compact IC implementation, the phase shifter can be designed out.

The calibration and control of the circuit can be seen in ***Figure 14***. Figure 14a shows response contours for the ATL3 as gain control, denoted by a_{cont}, is varied. As a_{cont} is increased, loop gain is decreased. Figure 14b shows the same data, plotted in 3D. As loop gain is increased, by reducing a_{cont}, the ATL3 reaches the onset of oscillation at about 2 V. For lower values of a_{cont}, from 0 to 2 V, is the unstable region where the ATL3 self-oscillates, on the left side of the plot. For a_{cont} larger than 2 V the loop gain is less, and ATL3 is stable. A key point of this figure is the dashed red line which indicates the peak frequency response in the stable region and the oscillation frequency in the unstable region. Note that

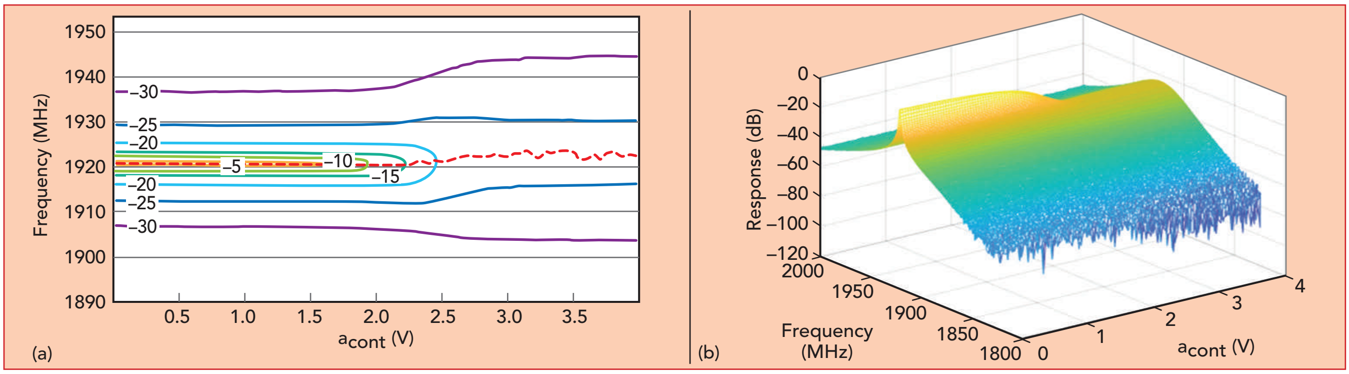


Fig. 14 Response of ATL3 as loop gain is varied with a_{cont}, where lower voltage result in higher loop gain: (a) contour plot, (b) 3D plot.

the self-oscillation frequency of the unstable region corresponds precisely with the peak filter response in the stable region. This is the key for self-calibration, so that the ATL3 circuit can self-calibrate autonomously without outside assistance. Further, the frequency variation as a deviation of the red dashed line as a function of a_{cont}, is much less than 1 percent. This demonstrates the orthogonality of the Q control and frequency control, which in addition to facilitating self-calibration, also simplifies overall filter control.

LINEARITY AND NOISE

Since ATL3s are active resonators, they provide gain and consume DC power. Noise and linearity need to be considered in system design. In a multipole filter, with multiple ATL3 active resonators in cascade, power consumption, linearity and noise must be budgeted across the resonators to optimize overall performance.

The linearity of the ATL3 demonstration board has been evaluated by measurement of AM-AM and AM-PM characteristics. Two tone measurements are impractical with resonators of such high Q and narrowband resonances. Since both forward gain and loop gain increase with Q enhancement, linearity is affected. ***Figure 15*** gives an indication of this mechanism. As the Q enhancement is increased, the sensitivity of the ATL3's overall gain compression to the gain compression of the loop gain block is also increased. Further, as Q is increased there is more energy storage in the ATL3's passive resonators, which results in larger voltage swings across the varactor diodes. Careful design is necessary to achieve acceptable

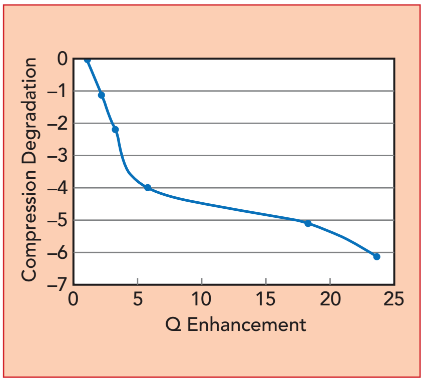
gain compression distortion while maintaining low power consumption. This includes budgeting power consumption across the gain blocks, location of gain blocks within the ATL3s and optimizing the system configuration accounting for the ATL3s' gain.

A theoretical minimum noise figure of the ATL3 is close to 3 dB, due to the fundamental feedback of the loop. This noise figure (NF) limitation can be mitigated with a low noise gain block in front of the ATL3. Hence, with application specific design, the effective NF can be minimized to the point that it is not relevant. The current ATL3 demonstration board described in this work was designed for objectives other than low noise. This is evident from the block diagram of Figure 11. Here the input signal feeds directly into a forward path of a lossy splitter and lossy resonators followed by buffer gain blocks. Further, the gain blocks do not provide sufficient gain to offset accumulated losses, leading to a high NF. If the loop was arranged differently, with the gain block in the forward path and the resonators in the feedback path, then the overall NF would approach that of the theoretical 3 dB. The next step is designing such a filter as an IC.

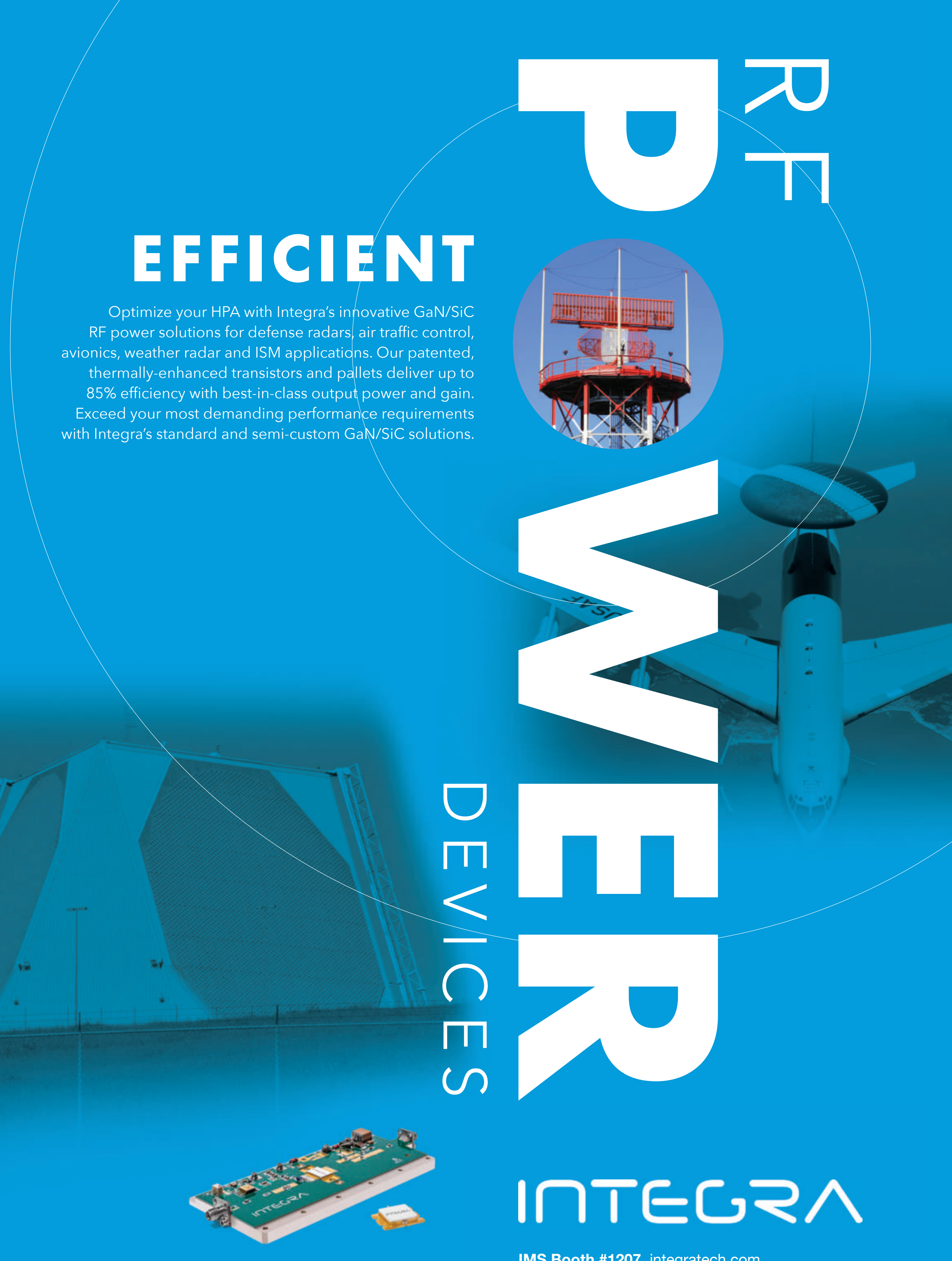
LOOKING FORWARD

The 3 pole MP3 filter described in this article was demonstrated by cascading three of our ATL3 active resonators. Higher order filters are readily realized by cascading more ATL3s, so that virtually any conceivable all-pole filter can be synthesized. Multi-band filters can be implemented by parallel combinations of groups of cascaded ATL3s.

Although the ATL3 active resonator demonstration boards are physically large, they need not be so. ATL3 can readily be designed as an integrated circuit, and the circuit elements would be appropriately small. The largest physical area will be needed for the passive resonators. But since it only needs passive resonator Qs on the order of 10, these too would be quite compact. ATL3 can be designed to operate at any frequency consistent with the semiconductor process being used. All that is needed is sufficient gain to overcome resonator loss. At mmWave frequencies the passive resonators will be very small, making ATL3 an attractive candidate for 5G applications, including in beam steered arrays. There is no other compact technology for highly selective filters at microwave frequen-



▲ Fig. 15 Substantial Q enhancement is measured for Anlotek's ATL3, with modest degradation in linearity.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cies over 6 GHz or for mmWave. This makes Anlotek's regenerative technology a good candidate for a wide range of applications above 6 GHz.

SUMMARY

The era of semiconductor electronics has seen a constant migration of traditional discrete circuit functions into alternate integrated circuit implementations. Transistor intensive designs have replaced traditional approaches, taking advantage of the small size, low cost and functionality of transistors. This new design technique offers a path for high performance analog filtering that is fully integratable on chip. Stable, agile and highly selective bandpass filters are realizable using only readily integratable low Q resonators, gain blocks and digital control. This circuit has demonstrated the first high performance analog filter technology that is naturally native to integrated circuit technology.

With proper system architecture and circuit design, Anlotek's filter technology is applicable to a wide range of applications and a wide range of frequencies, from RF through mmWave. With its frequency agility, self-calibration and ease of semiconductor integration, the technology offers system capabilities and flexibility not heretofore available.

As 5G systems and devices roll out, we will see the same crowding of frequency bands witnessed with the growth of 3G and 4G technologies. 5G is pushing to higher frequencies than have been used in earlier systems, beyond the capabilities of the SAW and BAW filter technologies used in those systems. The size and cost of cavity filters limits their utility. Feedback filters are notoriously difficult to stabilize and control at high Q, but this innovation of multiple resonators in the feedback path, provides stability, calibration and control.■

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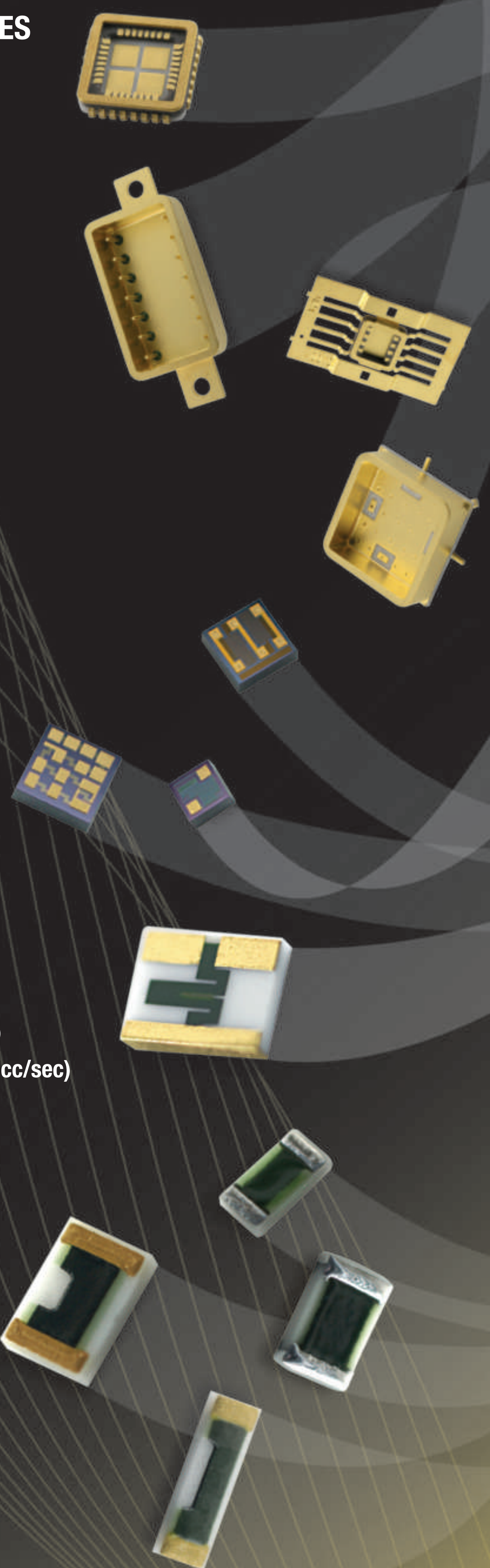

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INVITED PAPER

Tuning Electrically Short Antennas for Field Operation

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Ulrich L. Rohde
Informatics, Cybersecurity; Federal University of the Armed Forces of Germany, Munich, Germany

Even as the current sun spot cycles do not favor radio operation in the HF band (defined here as 1.5 to 30 MHz), there are military and amateur radio applications for 20 W battery-operated radios with whip antennas. In general, the whip antenna which makes the radio portable is not optimized for signal propagation: a whip antenna has no ground return or proper counterpoise. While some users drag a wire up to 8 m behind, this is not an ideal solution.[1-2]

This article explores optimizing antenna performance for HF and VHF (defined here as 30 to 108 MHz) manpacks using an antenna tuning unit (ATU). Two Rohde & Schwarz battery-operated manpacks with internal ATUs were used for testing, comparing their internal ATUs with the performance obtained using external tuners. The two R&S units are multiband, multirole and multimode software-defined radios (SDR), covering HF and VHF (R&S®MR3000H) and 25 to 512 MHz (R&S®MR3000U, shown in ***Figure 1***). They are similar to other HF, VHF and UHF transceivers popular with radio amateurs.

Fig. 1 **R&S®MR3000U manpack radio, covering 25 to 512 MHz.**

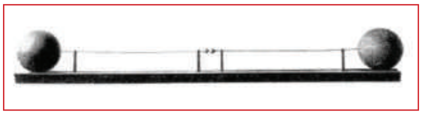

Fig. 2 **Original dipole made by Heinrich Hertz in 1887 used balls at each end to form a capacitive load (Source: Deutsches Museum in Munich).**

SHORT ANTENNAS

The first resonant dipole antenna, developed by Heinrich Hertz in 1887, was driven from a "noisy" spark gap transmitter (see ***Figure 2***). Both sides were equally long and used end-loading metal balls, acting as a capacitive device to reduce the length of the two λ/4 resonant segments.[3]

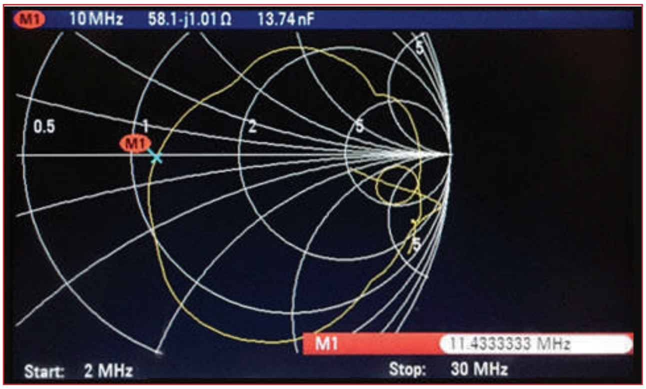

Fig. 3 **Measured impedance of a 2 x 5 m non-resonant dipole antenna from 2 to 30 MHz.**

Now consider a symmetrical, non-resonant dipole, each side 5 m long, with the center point connected to a battery-operated network analyzer

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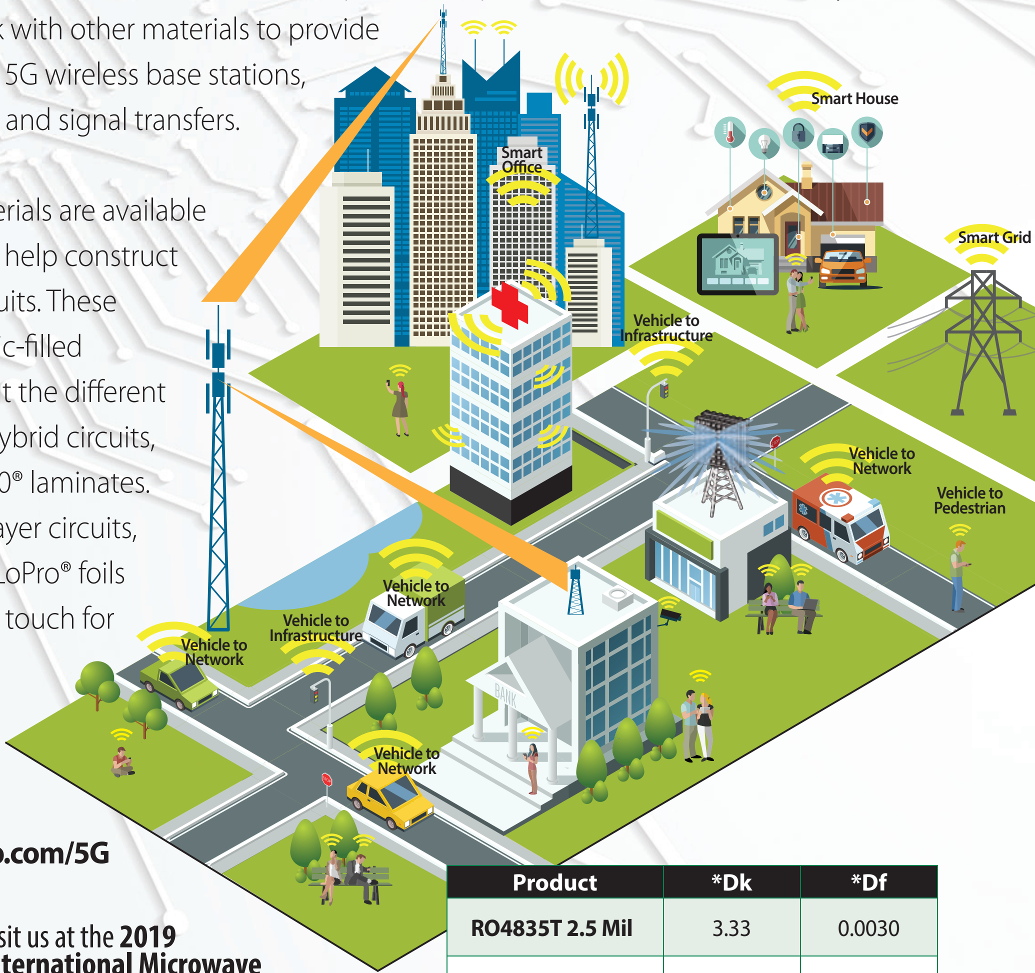

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approximately the same size and surface area as a manpack. The analyzer is connected to the symmetrical dipole with a mechanically small, 1:1 symmetrical-to-asymmetrical ferrite transformer covering 1 to 60 MHz. ***Figure 3*** shows the measured impedance of the antenna from 2 to 30 MHz, which covers both tactical military and some amateur radio bands. The typical mobile/portable application using a vertical antenna reflects the evolution of the dipole to a monopole: a symmetrical two-wire antenna made asymmetrical with a transformer and best performing with a set of resonant radials and a counterpoise or some kind of grounding.

The magnetic field of the antenna is generated by RF current in the antenna wire or rod, perpendicular to the antenna. The electric field of the antenna is needed for resonance. Many antennas are bent at the end to make them mechanically smaller. An extreme example is the capacitive hat; another is a "loading" coil located about two-thirds of the length—although this reduces the usable bandwidth.

The electrical equivalent of an electrically short antenna is given by

$$C_a = \frac{0.24 \times l}{\log \frac{1.15 \times l}{D}} \quad (1)$$

$$R_F = \frac{Z_a^2 + jR_S.Z_a \tan\left(2\pi \frac{l}{\lambda}\right)}{R_S + jZ_a \tan\left(2\pi \frac{l}{\lambda}\right)} \quad (2)$$

where C_a is the equivalent capacitance of the antenna in pF, D is the diameter of the wire, R_F the input-output impedance of the $\lambda/4$ antenna, R_S the radiation resistance, Z_a the characteristic impedance of the wire and l the length of the element.

Grounding is necessary to close the loop for the currents. ***Figure 4*** illustrates the behavior of the electric field lines for a vertical antenna over ground. The field lines penetrate the surface of the Earth and produce a current that flows back to the ground point, incurring heat losses. The antenna's efficiency, η, is defined as

$$\eta = \frac{R_S}{R_S + R_v} \quad (3)$$

where R_S is the radiation resistance and R_v the total effective loss resistance. For electrically short anten-

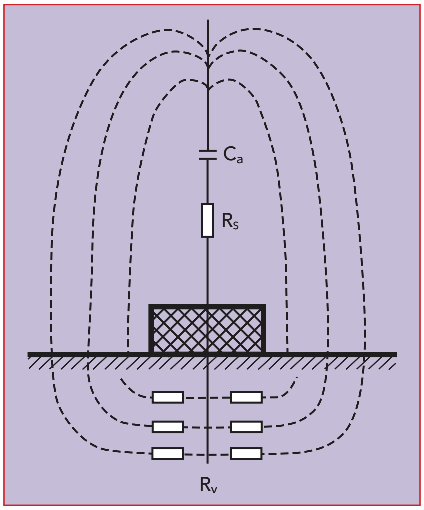


Fig. 4 Vertical antenna showing the current loop through the ground.

nas with radiation resistance values of only a few ohms, the resulting antenna efficiency can be very low, especially with long-wave and extremely long-wave communication systems. In such cases, R_V can be reduced with a ground network or a wire network extending over the ground as a counterpoise, especially with unfavorable ground conditions (see ***Figure 5***). All symmetrical antennas not excited with respect to ground, such as dipoles, benefit from the antenna's independence from the ground resistance—as long as the entire antenna is elevated above the ground.

Electrically short antennas, typically λ/10 or shorter, look like a capacitor with a typical capacitance of 25 pF/m of length, e.g., 75 pF for a 3 m rod. At 2 MHz, where the wavelength is 150 m, an inductor of 84 μH is required for resonance. The radiation comes from the current in the antenna, not from the voltage; the voltage is maximum at the end. To better understand the radiation, consider the case where the whip antenna's length, l, is λ/4. The vertical radiation pattern of the antenna over ground is[1,3]

$$F\left(\theta;\frac{l}{\lambda}=\frac{1}{4}\right)=\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} \qquad (4)$$

The radiated power, RF current and radiation resistance of the λ/4

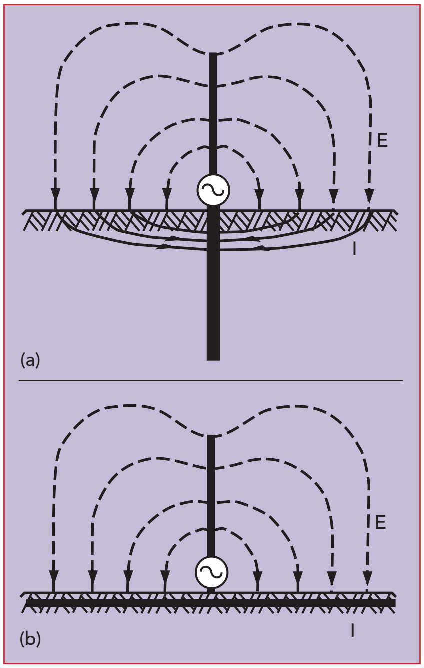


Fig. 5 A poor ground near the antenna's base results in losses from the return current (a), while a ground network or counterpoise reduces the losses (b).[4]

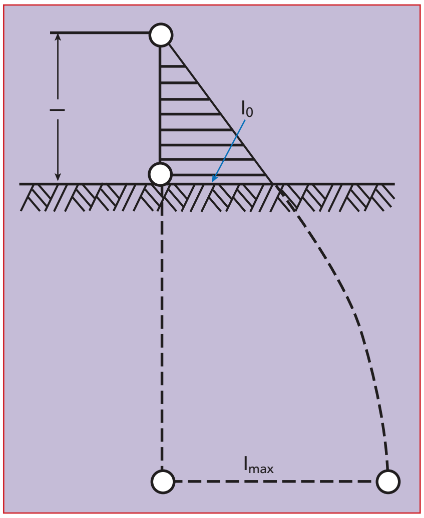
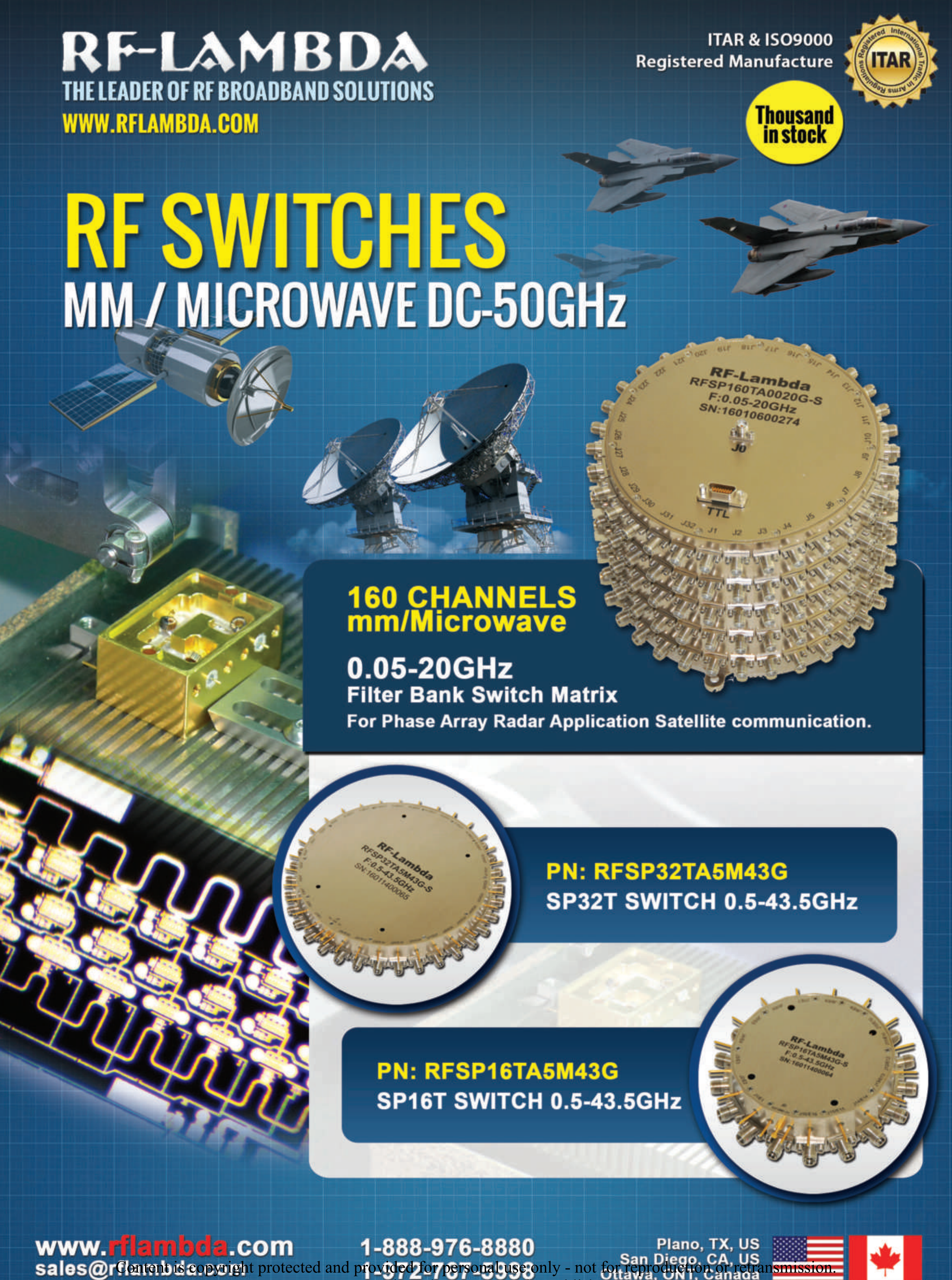


Fig. 6 Current distribution in a short antenna, including the ground current.[3]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antenna over ground is determined from the power radiated in the half sphere. Solving for R_S:

$$P_S = \tilde{I}_0^2 R_S = \int_{\theta=0}^{\theta=\pi/2} \frac{\tilde{E}_\theta^2}{Z_0} \cdot 2\pi r^2 \sin\theta d\theta$$
$$= \tilde{I}_0^2 \cdot 60 \int_0^{\pi/2} F^2\left(\theta, \frac{1}{\lambda}\right) \sin\theta d\theta$$
$$\left(\text{since } R_S = 60\,\Omega\right) \qquad (5)$$

$$P_S = \tilde{I}_0^2 \cdot 60 \int_0^{\pi/2} \frac{\cos^2\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta} \sin\theta d\theta$$
$$R_S = 60 \frac{C + \ln 2\pi - C_i(2\pi)}{4} =$$
$$60 \times 0.61 = 36.6\,\Omega \qquad (6)$$
$$C_i(x) = \int_\infty^x \frac{\cos u}{u} du, \text{z.B.}$$
$$C_i(2\pi) = -0.0225; C_i(4\pi) = -0.0061$$

where C is Euler's constant (0.5772) and $C_i(x)$ is the cosine integral. The radiation resistance of the electrically short antenna based on the electric field can be calculated from:

$$P_S = \int_0^{\pi/2} \frac{E_\theta^2}{Z_0} \cdot 2\pi r^2 \sin\theta d\theta$$
$$= Z_0 \left(\frac{I_0 l}{2\lambda}\right)^2 \cdot 2\pi \int_0^{\pi/2} \sin^3\theta d\theta \qquad (7)$$

$$R_S = 60\pi^2 \left(\frac{l}{\lambda}\right)^2 \int_0^{\pi/2} \sin^3\theta d\theta \qquad (8)$$

$$R_S = 40\pi^2 \left(\frac{l}{\lambda}\right)^2 = 395 \left(\frac{l}{\lambda}\right)^2 \Omega \qquad (9)$$

The radiation resistance of the short antenna is obviously very low.

EFFECTIVE HEIGHT

To calculate the effective height of an electrically short antenna, consider that the open circuit voltage, V_0, of the antenna is proportional to the antenna field strength, E, where the antenna is located:

$$V_0 = h_{eff} E \qquad (10)$$

The proportionality factor h_{eff} has the dimension of length and is known as the effective height. If the current in the antenna is independent of location (i.e., a Hertzian dipole), then h_{eff} corresponds to the antenna's geometrical length, l. Otherwise, the effective height will be less because of the non-uniform current distribution. In the general case, h_{eff} is determined by converting the current area into a rectangle with the same area and the maximum current, I_0, at its base (see ***Figure 6***). Its height is then equal to h_{eff}. Computationally,

$$I_0 h_{eff} = \int_0^h I_y dy, h_{eff} = \int_0^h \frac{I_y}{I_0} dy \qquad (11)$$

The effective height is related to the effective area, A, and characteristic impedance Z_0[3-4] as follows:

$$A = \frac{h_{eff}^2}{4} \frac{Z_0}{R_S}, h_{eff} = 2\sqrt{A \frac{R_S}{Z_0}} \qquad (12)$$

Figure 7 shows the differences in theoretical impedance of wire antennas with different wire diameters. ***Figure 8*** plots the measured impedance versus frequency of a 35 ft. long whip antenna, showing the

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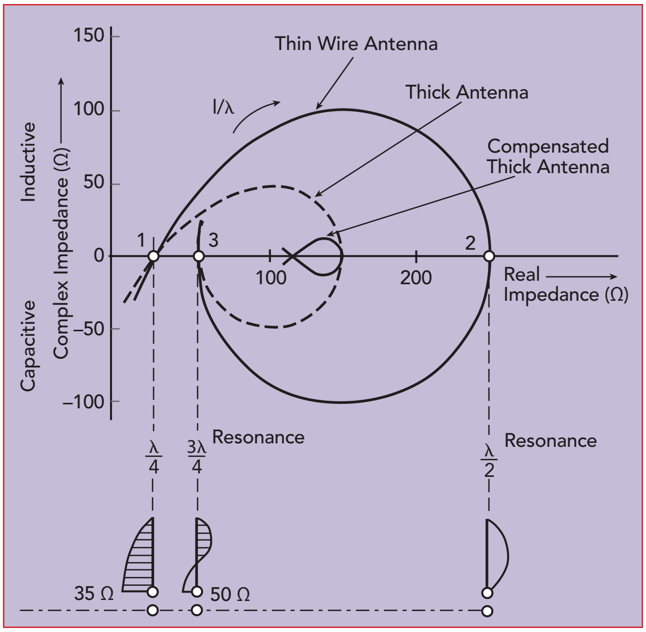


Fig. 7 Theoretical input impedance of three wire antennas with different diameters.[4]

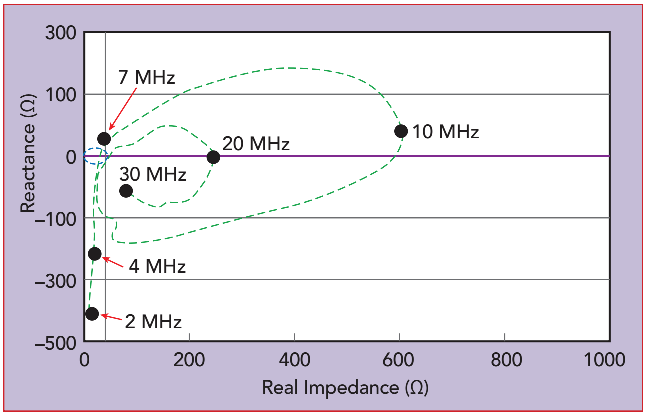


Fig. 8 Measured impedance of a 35 ft. whip antenna used on a ship.[5]

maximum real impedance is approximately 600 Ω at 10 MHz (λ/2), and the real loss resistor is never below 10 Ω. The imaginary part of the impedance is −400 Ω at 2 MHz and approximately 200 Ω at 9 MHz.

ANTENNA LOADING AND TUNING

Where a whip antenna is loaded affects the antenna's performance. ***Figure 9*** compares base and center loading. With center loading, both the radiation resistance and integrated surface are larger, which are better for radiation.

The typical lowpass configuration for antenna tuning is a series L, shunt C network, also called a Collins filter (see ***Figure 10***). For the 35 ft. whip antenna operating at 2 MHz (Figure 8), the network needs an

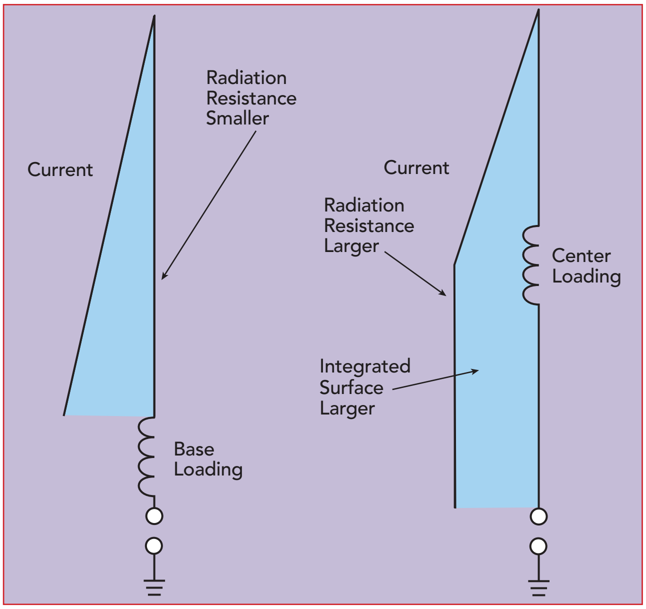
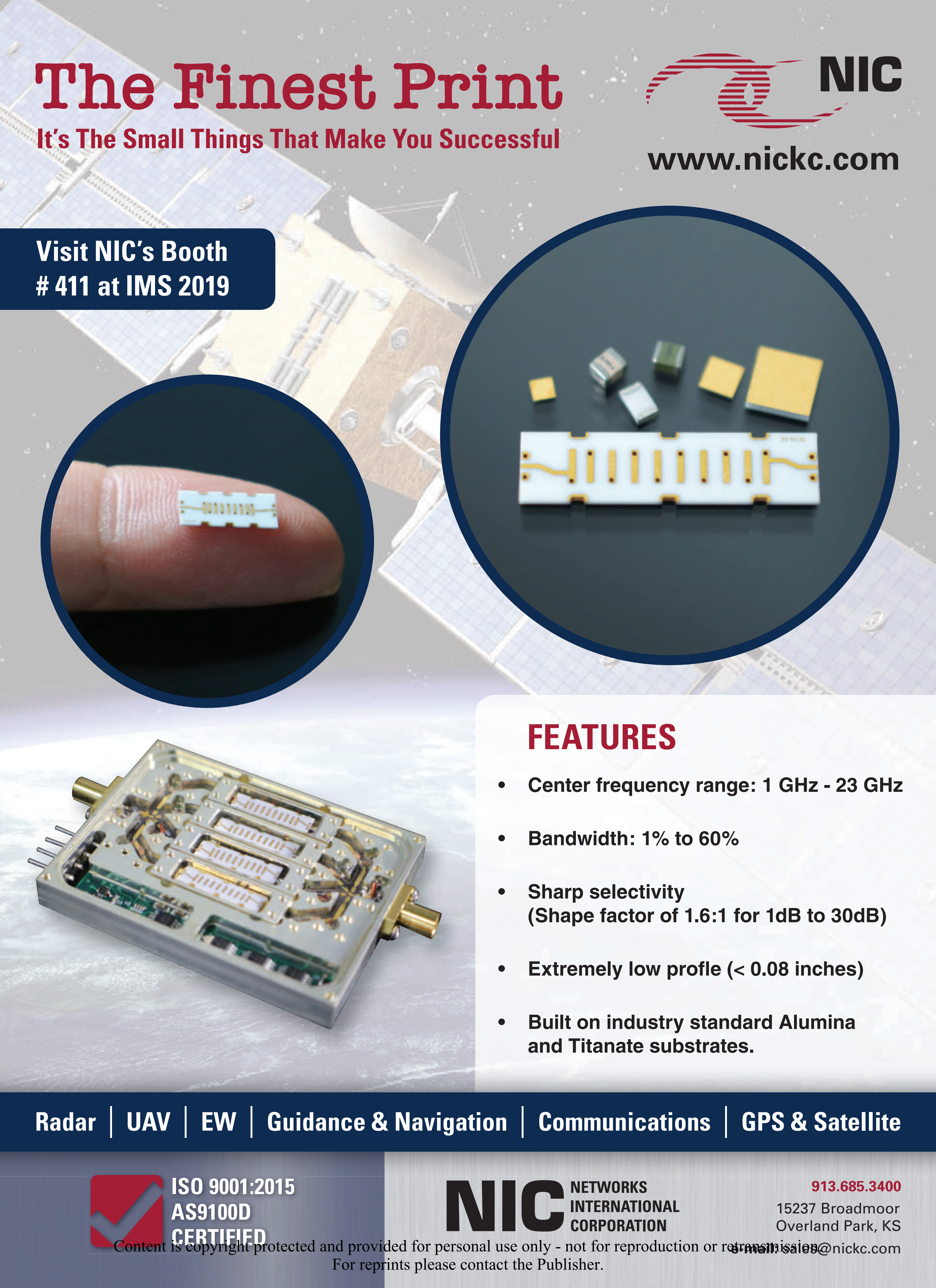


Fig. 9 Center loading a whip antenna creates a larger integrated surface for the current than base loading, which improves radiation.[6] The two figures are not to scale.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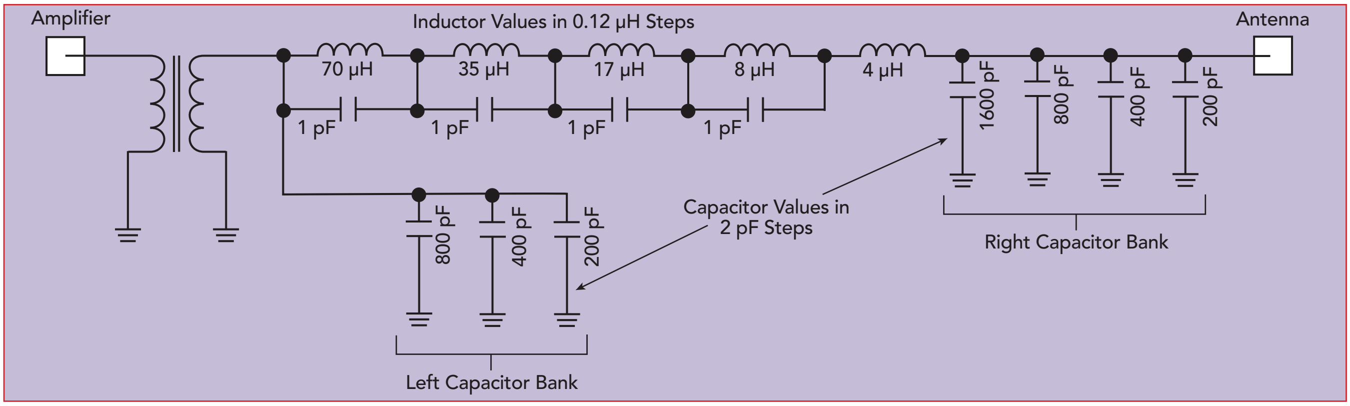


Fig. 10 Schematic of a Collins antenna tuner with an input transformer.

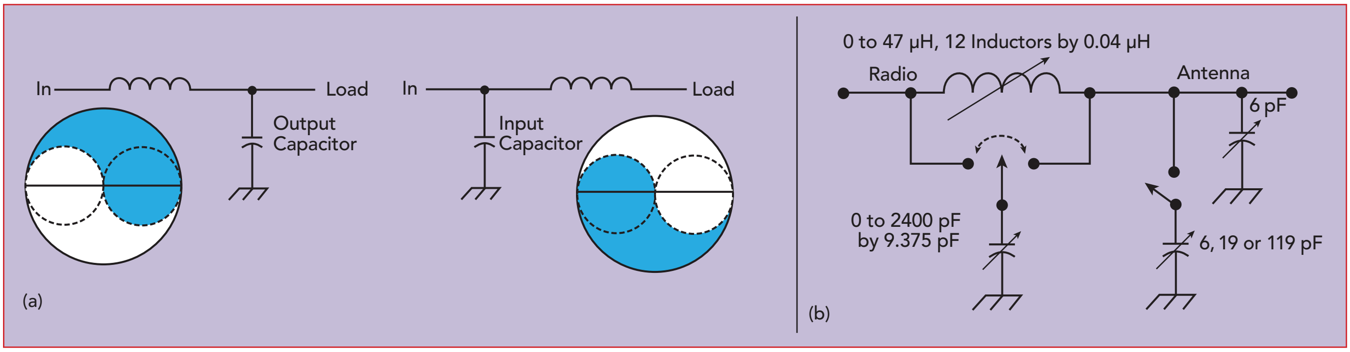


Fig. 11 Tuner matching options: the right capacitor bank is used when the load resistance is > 50 Ω, and the left capacitor bank is used when the load resistance is < 50 Ω (a). Tuning network similar to that of the ICOM AT130 (b).

inductor of 100 μH and a shunt capacitor of 262 pF. Assuming a 4:1 input transformer and the sum of the radiation and ground loss resistance to be larger than 12.5 Ω (50/4), the tuner only needs two variable elements, and either the left or right capacitor bank in the figure can be eliminated. The right capacitor bank is used when the load resistance is greater than 50 Ω (12.5 Ω using the 4:1 transformer), and the left capacitor bank is used when the load resistance is less than 50 Ω (12.5 Ω using the 4:1 transformer). In this case, at 2 MHz, R = 12 and X_c = −400 Ω, the required series inductor will be 33.42 μH and the left capacitor bank is used to set a value of 3.18 nF. The most inductive impedance is at 9 MHz, approximately 600 +j200 Ω, such that 25 μH and 370 pF are needed for tuning.

The inductances for tuning are found in commercial input/output switchable antenna tuners operating from 1.5 to 30 MHz. The tuning network looks like an "L," where the switched shunt capacitors can be connected to either side of the inductors.[7] ***Figure 11a*** shows the matching ranges of the tuner with the capacitors on each side of the inductors, and ***Figure 11b*** shows a simplified schematic of the main capacitor bank that is switched to either the input or output side of the inductors. The inductors are wound with 0.048 in. diameter, enameled copper wire and have approximately 0.04 μH step size. The capacitor step size is 9.375 pF. This tuner has nine switchable inductors, 10 switchable capacitors and two positions for one of the capacitor banks (i.e., on either side of the inductors), yielding 1,048,576 tuning combinations. The 6 pF capacitor at the output represents the ceramic antenna mount or connector. For best performance, antenna tuners use air core coils or very low permeability powdered iron cores. As such, some of the measured intermodulation distortion (IMD) products result from ferrite saturation, not from the power amplifier driving the antenna.[8-9]

Occasionally, a tuner design uses a highpass, T-configuration rather than a π (see ***Figure 12***). The LC_1 forms one resonant circuit, LC_2 forms the other circuit and the two are tuned to the resonant frequency. The left loop and the right loop are dependent. Generally, when the value of C_2 is too small, input resonance occurs yet there is no loading and no output power obtained. This is the flaw of the design: the highpass filter is mathematically over-determined. The left loop can be in resonance, and no output power (voltage) is available in the right loop. Other drawbacks of this frequently-used design are higher loss, the lack of harmonic suppression and LC combinations where the

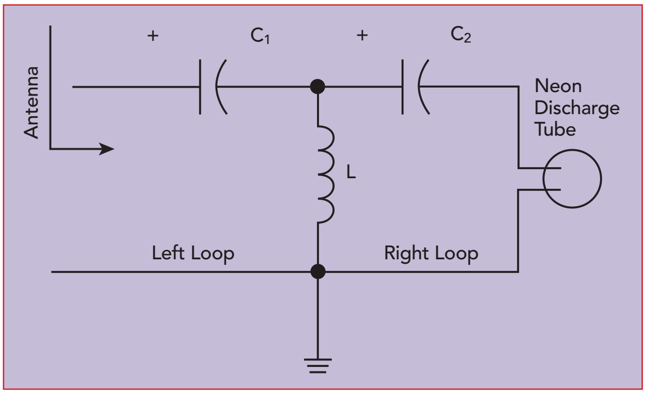


Fig. 12 T-configuration ATU.

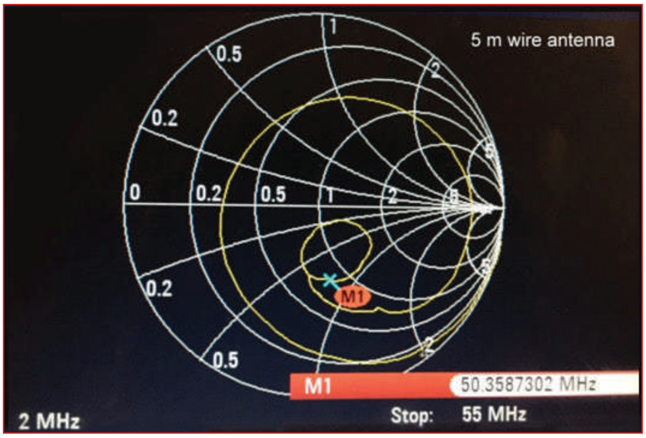


Fig. 13 Measured S_{11} of a 5 m wire antenna with 8 m ground wire, 2 to 55 MHz.

TABLE 1
ANTENNA IMPEDANCE AND L, C MATCHING VALUES (1:1 INPUT TRANSFORMER)

Frequency (MHz)	Z = a + jb (Ω)	L (µH)	C (pF)
Cshunt Lseries Antenna Matching			
2	20, -j540	45	2000
3	20, -j400	22	1300
4	22, -j294	13	975
5	23, -j230	8.1	609
6	26, -j186	5.5	500
7	26, -j150	4.0	440
8	27, -j118	2.8	370
9	33, -j95	2.1	326
10	29, -j70	1.5	270
12	37, -j14	0.47	157
14	145, j170	0.55	245
Lseries Cshunt Antenna Matching			
15	380, -j308	1.8	115
18	40, -j118	1.22	88
Cshunt Lseries Antenna Matching			
21	40, -j86	0.86	76
24	32, -j64	0.33	99
30	32, -j40	0.33	80
50	41, -j37	0.168	298

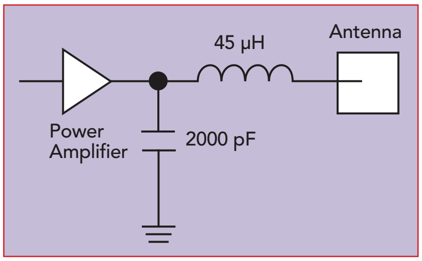


Fig. 14 Resonance tuning for the 5 m wire antenna with 8 m ground wire at 2 MHz.

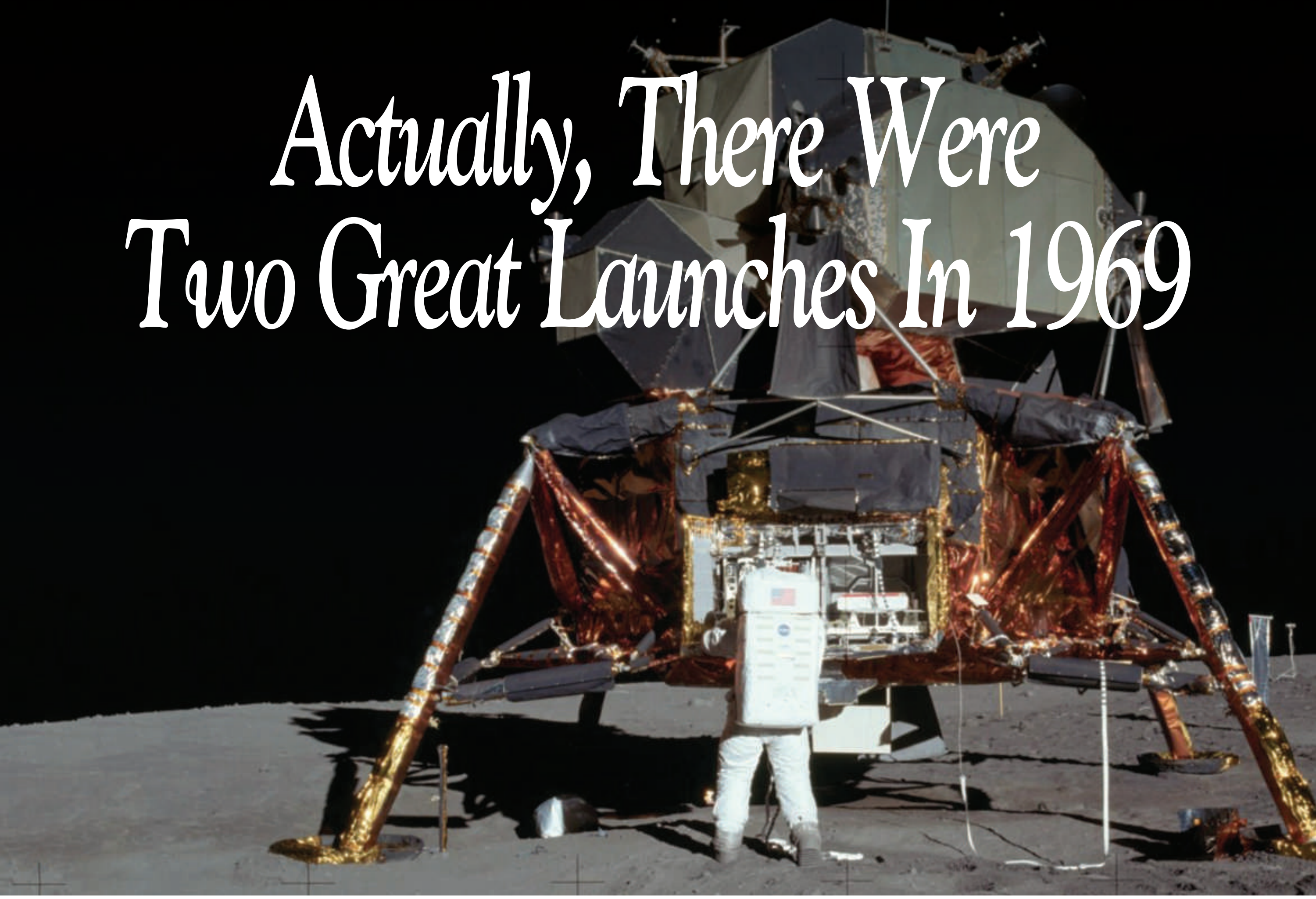
tuner absorbs most, if not all, the power without tuning the antenna perfectly.[6] For electrically short antennas, this can be overcome with a voltage probe at the output, such as a pre-ignited neon bulb. The neon discharge tube glows when there is maximum voltage at the output of capacitor C_2. If the frequency is below 30 MHz, a blue color is emitted; if the frequency is above 30 MHz, a pinkish color is emitted.

2 MHz TUNING

For a 5 m wire antenna with an 8 m ground wire and π tuner, ***Figure 13*** shows the measured antenna impedance, and ***Table 1*** summarizes the antenna impedance and the L and C values needed for matching, assuming a 1:1 (50 Ω) input transformer.[10-11] The LC combination minus the capacitance value of the antenna rod or wire must resonate at the test frequency. ***Figure 14*** shows the antenna resonance tuning at 2 MHz, and ***Figure 15*** shows the simulated Z_{11} vs. frequency, with Re{Z_{11}} plotted in Figure 15a and Im{Z_{11}} in Figure 15b. The lower curve in Figure 15a closely matches the desired 20 Ω at 2 MHz; however, it assumes no losses in the tuner. The upper curve, assuming a realistic Q of 200, shows 22 Ω at 2 MHz. As power is I^2R, a 10 percent increase in Re{Z_{11}} causes a power loss of approximately 10 percent, from 20 to 18 W available for radiation. These losses are frequently overlooked. While the two-element tuning network produces the desired real and imaginary values, the 8 m ground wire is too short at this frequency, so there is no useful grounding.

GROUNDING

An antenna tuner can improve the matching but not the radiation.

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At a single frequency, the asymmetric dipole shows a resonance close to 12 MHz, the antenna to case impedance is 37 Ω—almost purely resistive—and the system works. A symmetrical, non-resonant antenna like an inverted V with an elevated tuner and an asymmetrical antenna cable isolating the radio and RF, by actually grounding it, will give superior results. If this is not possible, to obtain a symmetrical antenna system a ground connection to some electrical wire, fence or similar structure is recommended. If the built-in antenna tuner can tune end-fed, high impedance, low current, long wires, this may be a good solution, although the radio is no longer a manpack, more of a portable solution for a stationary setup. Some counterpoise is needed for good results.

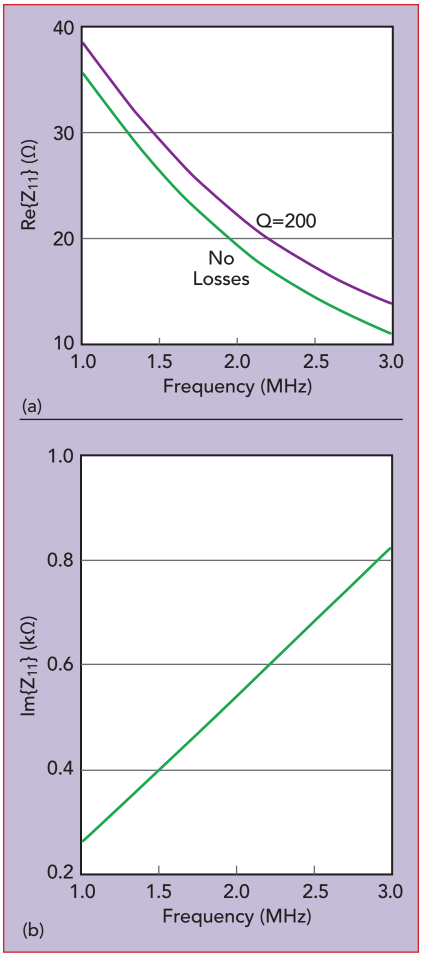
Table 2 shows field strength measurements with a 2 × 5 m non-resonant, wire dipole in a V configuration, tuned using an ATU; the measurement is made at 10 m distance using a test receiver with antenna. For comparison, the table includes the frequency dependent field strength for the 3 m rod antenna.

Radio amateurs often use ICOM tuners. Generally, they are reliable in all weather conditions and, with a huge tuning range, find a good match and fit all the 100 W radios, even non-ICOM radios with a simple adaptor. The tuner layout shifts the coils by 90 degrees to minimize magnetic coupling (see ***Figure 16***). Any number of inductors will not mutually couple if they are placed with their axes forming a 54.74 degree angle to a common plane,[12] although such placement is not always physically ideal. The ICOM AH-4 tuner has nine inductors, 10 capacitors and two positions, equating to 1,048,576 tuning combinations. The tuning range is shown in ***Figure 17***. Part of the magic of the tuner's effectiveness is the search algorithm.

Figure 18 shows the measured S_{11} from 2 to 30 MHz of a 2.5 m whip antenna with two ground configurations, floating and next to the body. Floating is the worst case. For a VHF/UHF manpack, ***Figure 19*** shows the antenna S_{11} measured from 20 to 200 MHz.

HF PROPAGATION

Recently, HF communication has fallen out of grace and HF manpacks have become less interesting. The 11-year sunspot cycle causes poor propagation, making the band unattractive. Appliances such as long-life LEDs produce high conducted and radiated interference, and noise blanker implementations in SDRs are not very effective. The difference between summer and winter propagation is also a factor. In the summer months, beginning in May, the D layer of the ionosphere makes day propagation up to 15 MHz difficult; low frequency night propagation works better up to 10 MHz. While propagation forecasts are available on the internet, particularly for long distance connections, 10 to 60 mile connections are more complex: too far apart for VHF/UHF



▲ Fig. 15 Simulated $Re\{Z_{11}\}$ (a) and $Im\{Z_{11}\}$ (b) at 2 MHz.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960.0 MHz
-135.9 dBm
COMMUNICATION

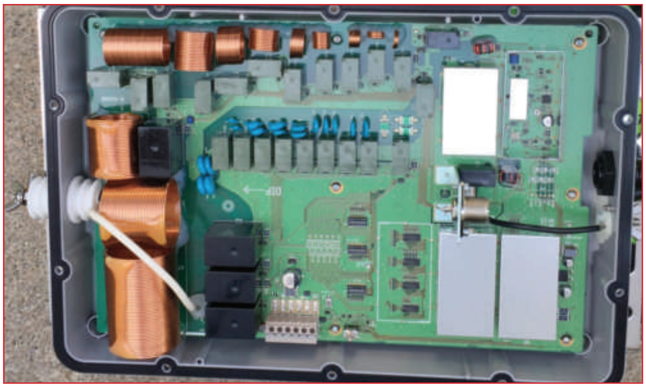

Fig. 16 ICOM antenna tuner with 90 degree offset coils.

TABLE 2

FIELD STRENGTH AT 10 M WITH 5 W CARRIER MEASURED WITH R&S PR100 TEST RECEIVER

	Field Strength (dB µV)	
Frequency (MHz)	2 x 5 m Wire Dipole	3 m Rod Antenna
28.4	68.7	76 (Near Field)
18.145	60	45
14.347	51	35
7.185	58	31
3.85	46	33

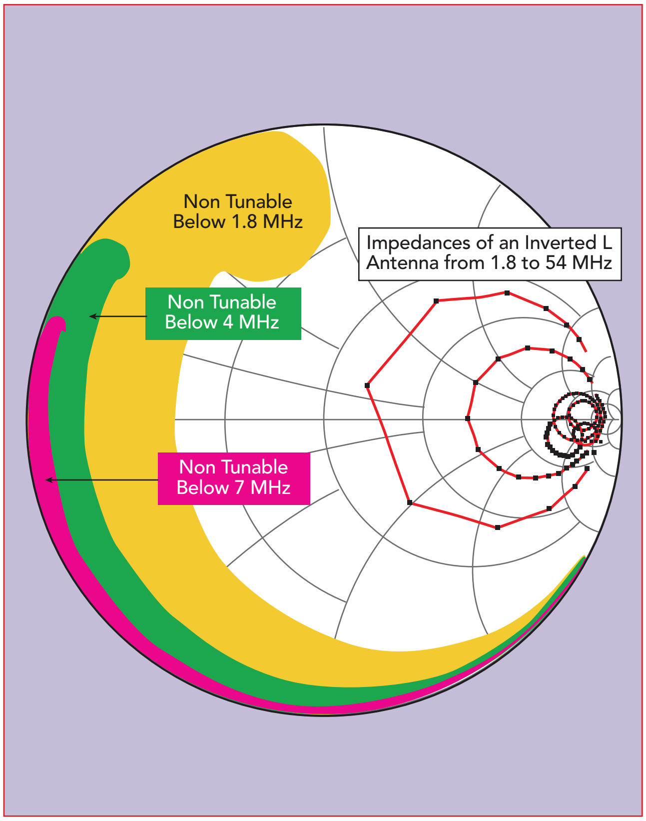

Fig. 17 Tuning range of ICOM AH4 antenna tuner.[13]

and too close for HF. Frequencies from 1.5 to 8 MHz would work well, but effective use of those frequencies requires better antennas than manpacks have, and local RF noise does not help. The D layer further complicates use of the band. During the day, 5 to 8 MHz provides 300 to 500 mile coverage, which increases to at least 2000 miles shortly before sunset. Two MHz is better for close communication. The old ship SOS frequency (2.182 MHz) has been replaced by satellite telephones.[6,12-16] The 20 m radio amateur band for voice operation covers 14.15 to 14.35 MHz. Even for this small difference, propagation may vary significantly, as the coherence bandwidth is small.[17]

However, the amateur radio communities hang on to low-power operation (QRP) and remain true believers. During hurricane season and other natural disasters, using these portable stations saves lives.

SUMMARY

For radio communications, the antenna is probably the most critical part of the link, so grounding and antenna tuner losses should be

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Fig. 18 Measured S_{11} of a 2.5 m whip antenna with floating ground (a) and ground next to the body (b).

avoided as much as possible. The inductor is always the lossy part of the ATU, while the capacitors, typically mica, are infinitely better.

For best operation, antenna radials should be λ/4. One is sufficient for tuning; up to four will produce a symmetrical azimuth pattern. When λ/4 is not possible, radials several wavelengths long will do. Connecting the HF radio ground to a large metallic object is a good choice. For the tests supporting this article, a grounding spear of about 10 in., similar to a tent support, was used.

These requirements for optimum antenna performance make HF manpack radios somewhat complicated and unattractive. Nonetheless, the well matched and radiating antenna provides the most success, and some of these highly portable radios (see ***Figure 20***) provide vital communications in disaster areas—recently in Puerto Rico and South Florida.■

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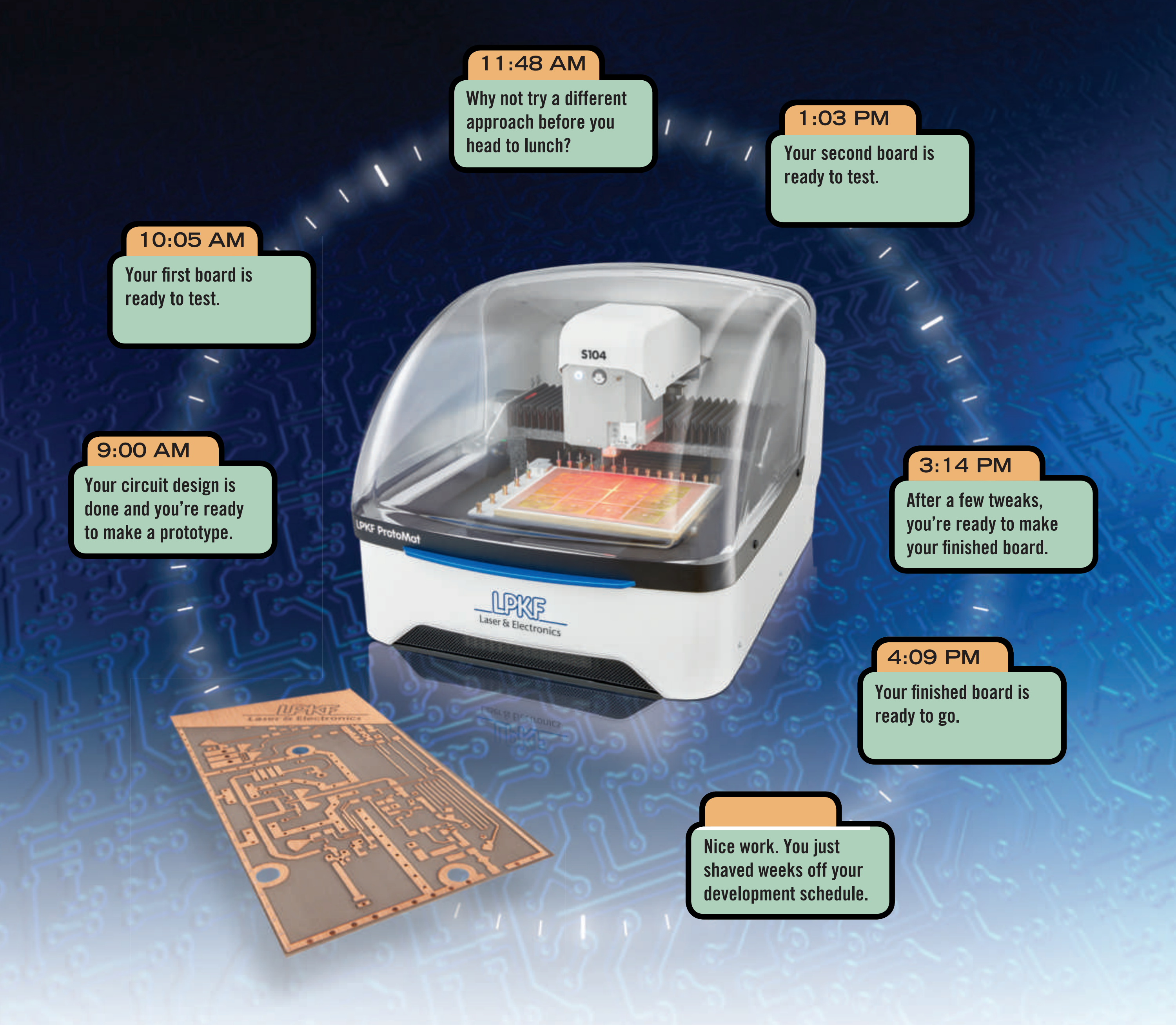

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Fig. 19 Measured S_{11} of an antenna for a VHF/UHF radio, from 20 to 200 MHz.

Fig. 20 VHF/UHF (left) and HF/VHF (right) manpacks. The UHF/VHF manpack shown uses a thick vertical pole antenna, and the HF manpack uses a 5 m dipole (the yellow wire).

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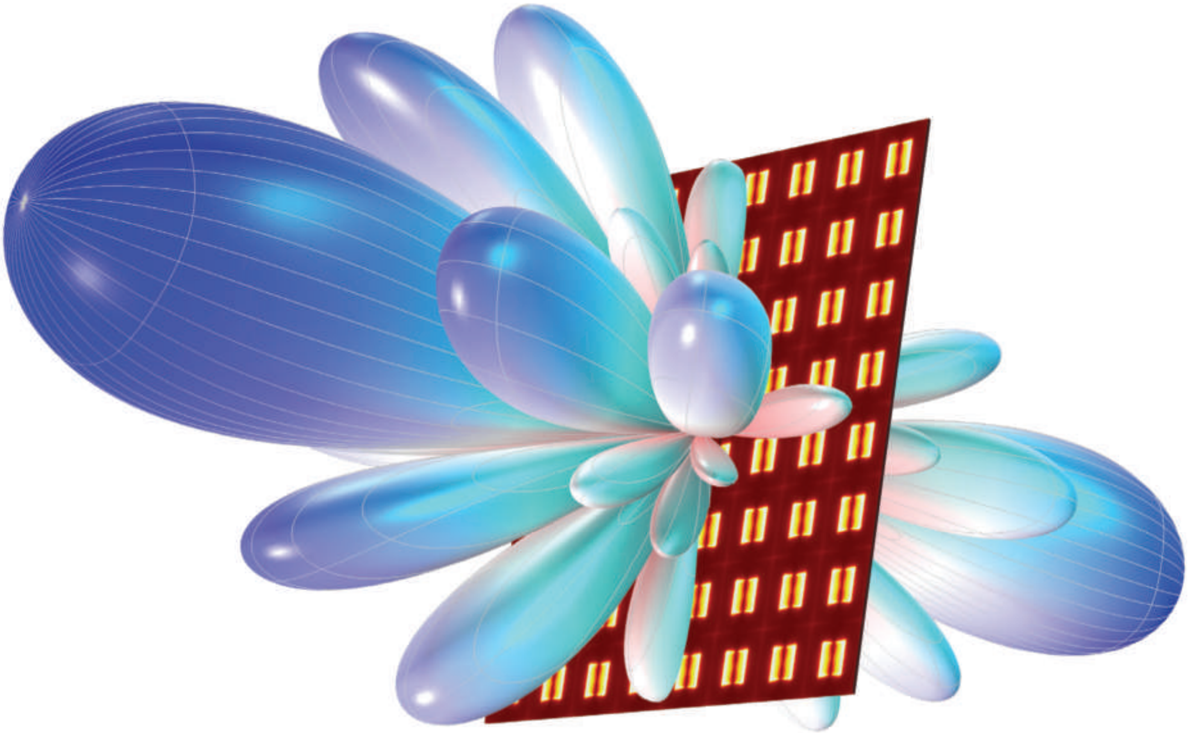

INVITED PAPER

Design and Production Challenges of Wire-Wrapped Ferrite RF Passives for Broadband Applications

Richard Bay-Ramyon
MiniRF, Fremont, Calif.

The latest cable and sub-6 GHz 5G wireless networks present design and manufacturing challenges not only for the active semiconductors but also for widely used wire-wrapped ferrite RF components, such as transformers, splitters, couplers and baluns. As frequency and bandwidth requirements extend from hundreds of MHz to multiple GHz, the performance of these passive components must improve. Innovative designs, materials and manufacturing methods shrink their sizes while reaching higher operating frequencies and achieving broader bandwidths, by reducing parasitics that degrade performance and pose quality control challenges.

The increased demand of the information market has led to a massive growth in the amount of data that is acquired, transported and processed. Some forecasts suggest that data traffic in general will more than triple in the next five years, and mobile data traffic will grow by nearly 8× by 2023.[1-2] Much of this traffic is expected to be carried by upcoming 5G networks.[2] This explosion of data traffic is driving enhancements in the CATV networking infrastructure and mobile networks to accommodate higher data rates and, thus, higher frequency and bandwidth technologies for both active and passive components.

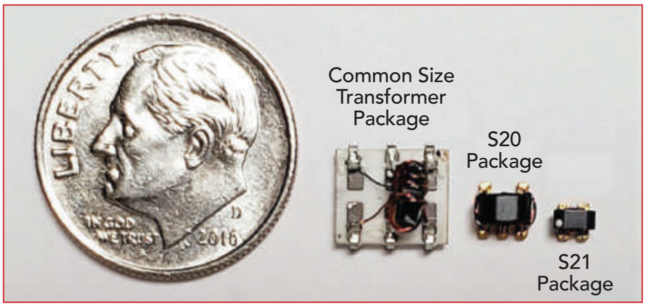

Fig. 1 Common surface-mount transformer with soldered leads compared to S20 and S21 packages with welded leads.[5]

Hence, it is no surprise that there is a growing demand for higher performance and higher frequency wire-wrapped ferrite RF passives (wire-wound ferrites), specifically transformers, baluns, splitters and couplers.[3-4] These components are used for impedance matching, balancing and signal power flow; they are crucial to the operation of virtually all digital and RF communication devices in the networking infrastructure. They are also found in many of the "last mile" broadband appliances. As with other digital and RF communication components, there are substantial considerations and design challenges to accommodate higher frequencies and higher bandwidths.

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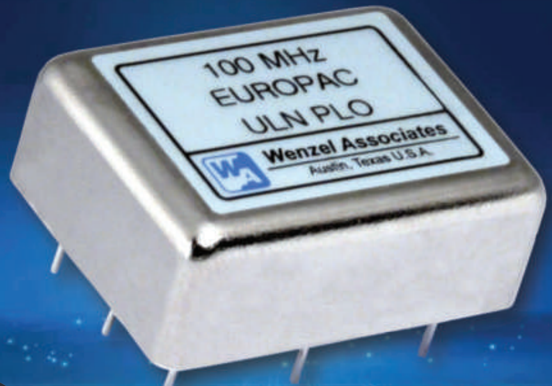

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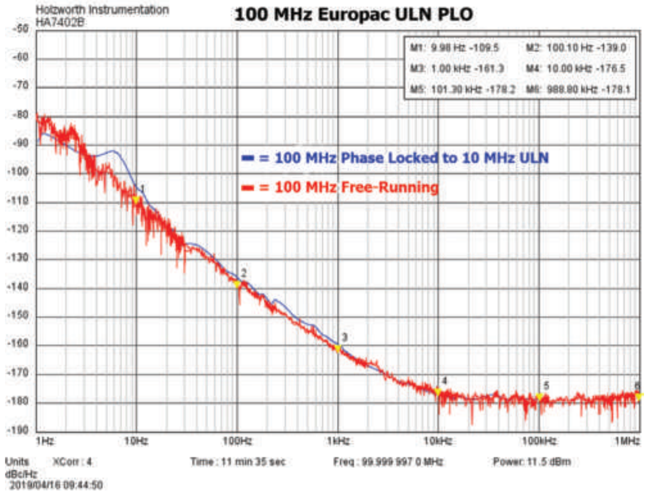

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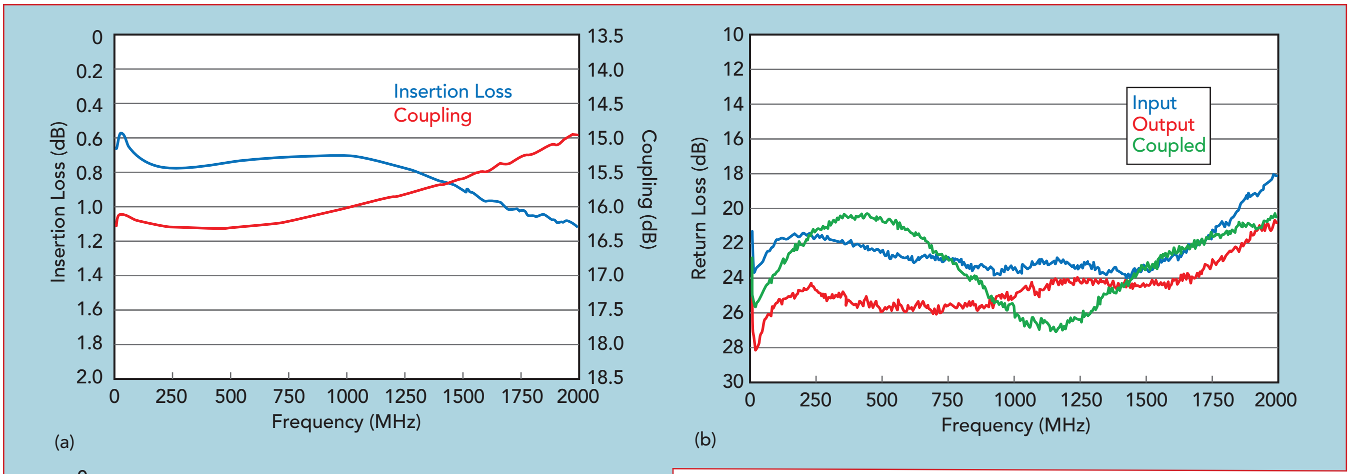

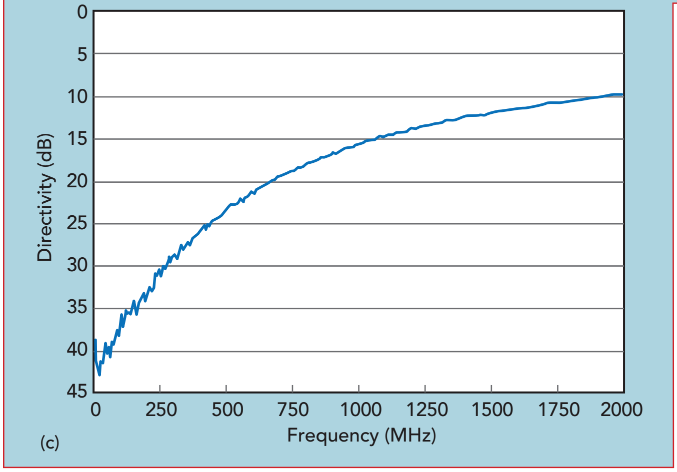

Fig. 2 Measured insertion loss and coupling (a), return loss (b) and directivity (c) performance of a MiniRF 1.8 GHz wire-wound directional coupler.

CHALLENGES AND DESIGN CONSIDERATIONS

In prior years, bandwidth requirements for wire-wound ferrite-based RF passives were limited to MHz frequencies. Recently, the trend has been to GHz bandwidths with an emerging demand for beyond 2 to 3 GHz. At higher frequencies, many factors can reduce wire-wound ferrite performance. For instance, the skin effect, which increases resistive loss proportional to frequency, begins to play a bigger role beyond a few hundred MHz. The proximity effect and fringe-field effects also contribute to greater losses at higher frequencies. Moreover, there is parasitic capacitance between the wires, known as inter-winding capacitance and parasitic series inductance. These factors tend to be less significant at low frequencies, where insufficient parallel inductance and core losses are the most significant contributors to insertion loss.

Hence, a significant challenge in the design and manufacturing of high bandwidth and high frequency wire-wound ferrite components is to achieve a balance between low and high frequency inductance for wideband operation. Other factors to consider are phase and amplitude balance across the bandwidth of operation. Generally, low frequency phase and amplitude balance are good, but challenges with respect to high frequency parasitics, manufacturing tolerances and wire quality become significant at higher frequencies.

Wire geometries and winding techniques also play a role in wire-wound ferrite impedance properties, as well as core size and dimensions. Hence, when designing components that are physically smaller, scaling factors associated with impedance must be carefully considered. Moreover, core material permeability is a function of temperature; with board-level densification and component proximity to high-power density devices, such as high-power GaN amplifiers, ensuring consistent impedance, balance and minimum loss during operation is a challenge.

In high performance semiconductors, many manufacturing considerations have been addressed through the use of highly automated manufacturing and quality control systems. This is yet to be viable with wire-wound ferrite components, as their unique physical construction has traditionally been beyond the capability of automated technologies. Greater manufacturing automation could dramatically improve tolerances, which directly impacts virtually all aspects of wire-wound ferrite performance.

New challenges are also arising, as emerging applications with unique needs demand custom designed components. Expertise with wire-wound ferrites has been, and continues to be, a niche area where few companies have the knowledge to design and manufacture innovative high frequency/high bandwidth wire-wound ferrites.

TECHNIQUES, METHODS AND APPROACHES

One method to reduce the losses associated with higher frequencies is to reduce the overall size. Reducing the core geometry, while allowing for a much more compact and cost-effective component, also decreases the series inductance that degrades high frequency performance. ***Figure 1*** compares a common size surface-mount transformer with reduced geometry packages. A MiniRF S21 package, for example, covers a seventh the area and enables much higher frequency and bandwidth operation. Minimizing the ferrite size provides manufacturing benefits, as well, while limiting the impact of parasitics, losses and board-level interference. Smaller wire-wound ferrite packages better accommodate the reduced lead pitches of the ICs used in the latest 5G wireless and high throughput data interconnect standards, such as DOCSIS 3.1.

Another package-level solution to enhance performance at higher frequencies is to eliminate solder—instead weld bond leads directly to the contacts. Welding eliminates the need for solder material, provides a mechanically stronger bond, enhances reliability and improves electrical performance over wide temperature ranges. Wire bonds are commonly used in IC packaging and high performance and high power RF/microwave devices for the very same reasons, allowing for tighter tolerances to be maintained for dimensionally sensitive wire-wound ferrites. Lead length tolerances are also improved, which impacts phase and amplitude balance.

Ferrite core material selection is key to achieving the desired inductance versus frequency. The frequency and temperature dependant permeability of the core is a major contributing factor to inductance over much of the operating bandwidth. For high bandwidth and high frequency wire-wound ferrites, a core material with high permeability at low frequencies and consistently decreasing permeability toward high frequencies is desirable. Moreover, a core material with permeability less sensitive to temperature and with a high Curie temperature greater than 150°C is necessary.

Wire selection is another design and manufacturing consideration. Wire size, length, geometric stability, braiding (if applicable) and wire laminate all impact impedance, parasitics and losses. Matching wire and core geometries is important, especially at higher frequencies where even small geometric imperfections can significantly influence performance.

Although manufacturing automation for wire-wound ferrites is evolving, there has been some innovation in wire-wound ferrite test automation. Automated post production testing captures full S-parameters over a wideband small signal sweep of each component. ***Figure 2*** shows the performance of a directional coupler. The data generated includes return loss, insertion loss, coupling and directivity, plus calculated amplitude and phase balance. From there, standardized tuning procedures are used to address each component individually to ensure quality.

CONCLUSION

In an industry where the trends in frequency and bandwidth are increasing, there is growing demand for high frequency and wideband wire-wrapped ferrite RF passive components meeting stringent performance criteria. Overcoming the design and manufacturing challenges requires smaller, higher performance components with tighter tolerances produced using more streamlined tuning and quality assurance methods.■

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INVITED PAPER

The Challenges of 5G Network Densification

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Network densification will be an integral part of deploying 5G architecture that promises vastly increased data rates, from megabits per second (Mbps) to gigabits per second (Gbps), and ultra-reliable lower latency, from tens of milliseconds to milliseconds. The 4G radio access network (RAN) is roughly 10× denser than the 3G network, and that densification is predicted to continue through 2022 before new 5G equipment takes over the growth trend. Macro cell towers carried the bulk of 4G mobile traffic, with small cells deployed where the capacity is needed most—close to the consumer. It is predicted that 5G networks will need to be 10× denser than 4G networks, a 100× increase over 3G. 5G densification will be accomplished in space, time and frequency.

Mobile network operators (MNO) have invested billions of dollars to buy different frequency bands within the same geographical areas, and they want to maximize their investments by using carrier aggregation to increase capacity. This necessitates using three, four or five different licensed bands at the same time, and they may use MIMO technology for additional capacity. All these requirements multiply the amount of RF hardware at a site. Excellent RF performance, with low loss, low passive intermodulation (PIM) and high inter-band isolation must be maintained, as the demands of 4G LTE-Advanced already require it. There is a cost associated with meeting all of these requirements. These sometimes conflicting factors are difficult to design into the components; nonetheless, new products have been able to solve the challenges and constraints of today's deployments. Solutions for tomorrow's rollouts will take advantage of these new techniques to satisfy the demands of more bands and configurations.

Outdoor small cells come in many different shapes, sizes and configurations. In this article, a small cell is defined as a single geographic site and can be made up of radios, antennas and other equipment. They can differ from city to city, even street corner to street corner, depending on the requirements of the site, municipal jurisdiction, MNO or subscriber population and mobility in the area. They can support multiple frequency bands, multiple sectors and multiple operators within a common structure. Each of these requirements brings unique challenges to the design and deployment of small cells at the scale required for 4G expansion and future 5G networks.

The challenge of location means that small cells must be put in the available space, both horizontally and vertically, which may not be ideal. Small cells can be located on dedicated poles, roof tops, inside street furniture and on existing utility poles (see ***Figure 1***). In New York City, for example, two of the poles at an intersection are reserved for public safety and traffic control, which limits the physical space available for small cells. What is possible really depends on the restrictions within each municipality. Additionally, neighborhood residents will not accept an eyesore to get better service, so pleasing

Fig. 1 Lamp post small cell (Source: Crown Castle).


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concealment is vital. Compact and adaptable components are critical to successfully deploying outdoor small cells.

In a neutral host small cell, a third party finances the small cell and rents access to the MNOs. A neutral host small cell can have two or more different network operators, each using multiple frequency bands. With each MNO using multi-band carrier aggregation, it is not uncommon to see 12 or more frequency bands within a single small cell. In this crowded RF environment, signal performance is critical, typically requiring the use of a multi-band combiner with minimal insertion loss and maximum inter-band isolation.

The small cell components must be physically small and offer the necessary RF performance. If the small cell equipment is too large, mounting the cell at the required location may not be possible. Every cubic inch of space within the enclosure is a premium, making component size and dimensions a critical design factor. If the small cell's physical size is small, more options will be available for locating the cell. This presents more options for network engineers, as they design the network architecture; however, it presents a larger challenge to the equipment vendors. Network equipment vendors must continually innovate and optimize designs to fit within the physical constraints and achieve the desired RF performance for the small cell marketplace.

Yet another consideration for small cell equipment is hardiness against the elements. The products must work across a large temperature range, from subzero temperatures away from the equator to scorching summers closer to it. They must be designed with dust ingress protection (IP) for desert climates and prevent corrosion in humid, salty coastal areas. The temperature specifications, IP or National Electrical Manufacturers Association ratings and salt/fog compliance are important factors to select the right equipment.

▲ Fig. 2 **Components designed for small cells must be small and withstand outdoor environments with varying temperature and moisture.**

For in-building coverage, distributed RAN (D-RAN) is a cost-effective way to meet wireless coverage and capacity needs in venues like stadiums, hospitals, office buildings and hotels. If small cells were deployed everywhere coverage is required, the cost would be very high and the system would be well over the capacity needed. D-RAN uses a small network of passive components with low power radios as the signal source. D-RAN is generally both a neutral host and multi-band. In the D-RAN architecture, a point of interface (POI) has several ports for combining, with multiple outputs for distribution. The POI allows for efficient combining and is a cost-effective solution for in-building designs, as the coverage and capacity can be optimized simultaneously.

D-RAN has some of the same design constraints as outdoor small cells. Small size of the components is critical to the ability to deploy the equipment where it needs to be placed, not just in a convenient location. But RF performance is still critical—if the network does not have the necessary RF performance, it is not able to do its fundamental job of wireless connectivity.

As the industry begins its foray into the 5G era, small cells need to be future proof. In only the last three years, just for 4G, the large U.S. MNOs have each increased spectrum usage by 100 MHz or more. Typical commercial bands now extend from 600 to 3800 MHz. Additionally, the RAN has begun to include unlicensed spectrum features for LTE-LAA, up to 5925 MHz.

Over the next decade, the increase in spectrum usage will be in the thousands of MHz. Ultra-wideband RF components that span several GHz of bandwidth, to cover the licensed and unlicensed sub-6 GHz range, provide the flexibility to adapt to existing and potential spectrum for future use. 5G will require even more spectrum below 6 GHz.

Flexibility to adapt to these changing spectrum requirements helps reduce the total cost for the MNOs to continuously upgrade their networks. Small cells are expensive to deploy and upgrade, especially if upgrades must be approved by the municipality. Deploying future proof technology can dramatically reduce the cost and time to deploy. D-RAN solutions must also be flexible to adapt for various use cases in stadiums, offices, warehouses and other locations. The more flexible the solution, the more likely it is to actually get deployed. Flexibility also extends to configuration, i.e., two sector, multiple bands, etc. Small cells and D-RAN will not just be single sector, single band deployments; the limited locations are too valuable for that. Compact, high quality, flexible products that do not sacrifice RF performance are indispensable.

Microlab has been focusing its R&D on small cell components, developing rugged, ultra-wideband and compact components. Each of the product categories offers frequency coverage options from 350 to 5925 MHz for TETRA, commercial wireless, CBRS, LTE-LAA and future 5G bands. These products have multiple mounting configurations that allow system integrators the flexibility to adapt to each site's unique requirements. Many of Microlab's products are designed to cover −40°C to +75°C, and the salt/fog series (see ***Figure 2***) complies with Telcordia GR-3108-CORE paragraph 6.2, Salt Fog Exposure, as Class 4 products for 30 days, defined by ASTM-B117. These products are hard anodized, resulting in an even harder and more durable coating. They come with an IP68 rating, which means they are protected against the effects of immersion in water under pressure for prolonged periods.

Fig. 3 **Neutral host small cell and D-RAN systems support several operators and must handle multiple carriers operating on different frequency bands.**

For small cell and D-RAN deployments, Microlab's MCC Series™ is a modular POI solution (see ***Figure 3***). Designed to fit any operator or neutral host provider, the series offers a modular solution that can accommodate any wireless communications band up to 6 GHz and can be adapted for any site with any band or carrier configuration. This one-size-fits-all platform was designed as a future proof solution, enabling easy upgrades and reconfigurations as capacity and bandwidth requirements evolve. The custom, bolt-on design supports fast and easy installation, with guaranteed end-to-end performance of the passive components.

For 5G networks, RF performance is even more critical, since 5G essentially maximizes the spectral efficiency (bps/Hz) of the LTE waveform to deliver ultra-reliable and low-latency communication and greater mobile broadband bandwidth. To provide these capabilities, the RAN ecosystem must perform.

5G will not be able to meet its performance goals without cell densification. Actually, hyper-densification is required to deliver the promise of 5G. So the industry must be able to deploy high quality small cells, for use indoors and outdoors, in a cost-effective and adaptable manner.■

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INVITED PAPER

From Waveforms to MIMO: 5 Things for 5G New Radio

Alejandro Buritica
National Instruments, Austin, Texas

5G New Radio (NR) is comparable to the mobile communications industry using LTE to describe 4G technology or Universal Mobile Telecommunications Service (UMTS) to describe 3G. As a start, the release 15 specifications for 5G NR were approved in June 2018. These will continue to evolve to cover the detailed technical functionality of Standalone (SA) access for 5G NR devices.

Here are five key technical aspects of the 5G physical layer that enable this global communications standard to deliver an abundance of reliable, data rich and highly connected applications.

1 5G NR WAVEFORMS

CP-OFDM: Downlink and Uplink

Researchers have been investigating different multicarrier waveforms in recent years, proposing many for 5G radio access. Waveforms that use orthogonal frequency division multiplexing (OFDM) work well for time division duplex operation. They support delay-sensitive applications and have demonstrated successful commercial implementation with efficient processing of ever-larger bandwidth signals. Also, the high spectral efficiency and MIMO compatibility of OFDM signals help meet the extreme data rate and density coverage needs of this new global cellular communications standard.

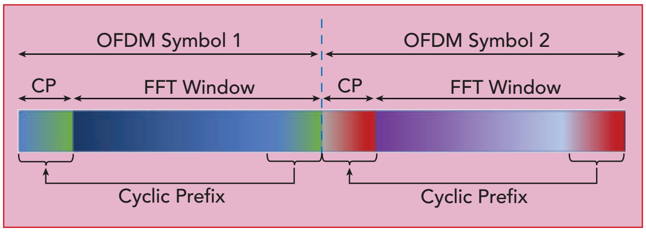
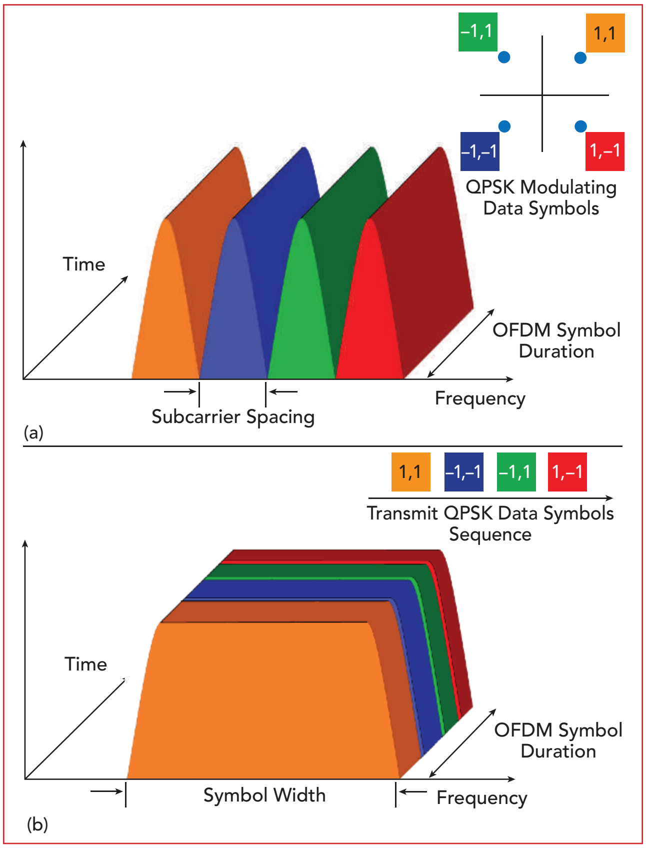


Fig. 1 A CP-OFDM symbol contains a cyclic prefix on each side of the data.

Thanks to channel estimation and equalization techniques, OFDM waveforms demonstrate great resiliency in frequency-selective channels. By attaching a copy of the end of the OFDM symbol to the beginning of the symbol (a cyclic prefix), a receiver can better tolerate synchronization errors and prevent intersymbol interference (see ***Figure 1***). So the 3GPP settled on using the cyclic prefix OFDM (CP-OFDM) as the waveform for 5G downlink and uplink for modulation schemes up to 256-QAM.

DFT-S-OFDM: Higher Efficiency Uplink

OFDM waveforms suffer from high peak-to-average power ratios (PAPR). Because the RF power amplifier consumes the most power in a mobile device, system designers wanted a waveform supporting high efficiency amplifier operation while meeting the spectral demands of 5G. For uplink (i.e., user to base station), NR offers user equipment (UE) the option of using CP-OFDM or a hybrid format waveform called discrete Fourier transform spread OFDM (DFT-S-OFDM). Using DFT-S-OFDM, the transmitter modulates all subcarriers with the same data (see ***Figure 2***). It lowers the peak-to-average ratio while retaining the multipath interference resilience and flexible subcarrier frequency allocation OFDM provides. Where the PAPR with CP-OFDM may be 11 to 13 dB, with DFT-S-OFDM it is only 6 to 9 dB.



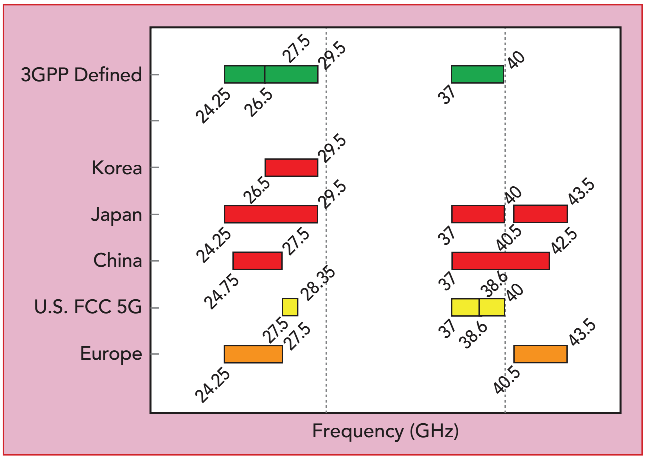
▲ Fig. 2 Time and frequency comparison of OFDM (a) and DFT-S-OFDM (b).

FLEXIBLE SUBCARRIER SPACING, FRAME STRUCTURE

2

Operation in multiple frequency bands is a new aspect of 5G NR, from the existing cellular bands below 3 GHz, to wider bands between 3 and 5 GHz, to the mmWave spectrum. ***Figure 3*** shows the current bands defined for NR operation above 6 GHz.

As the carrier frequency increases, so does system phase noise. For example, the difference in phase noise between carriers at 1 and 28 GHz is about 20 dB. This increase makes it difficult for a mmWave receiver to demodulate an OFDM waveform with the narrow, fixed subcarrier spacing (SCS) and symbol duration of LTE. Also, with



▲ Fig. 3 NR bands above 6 GHz.

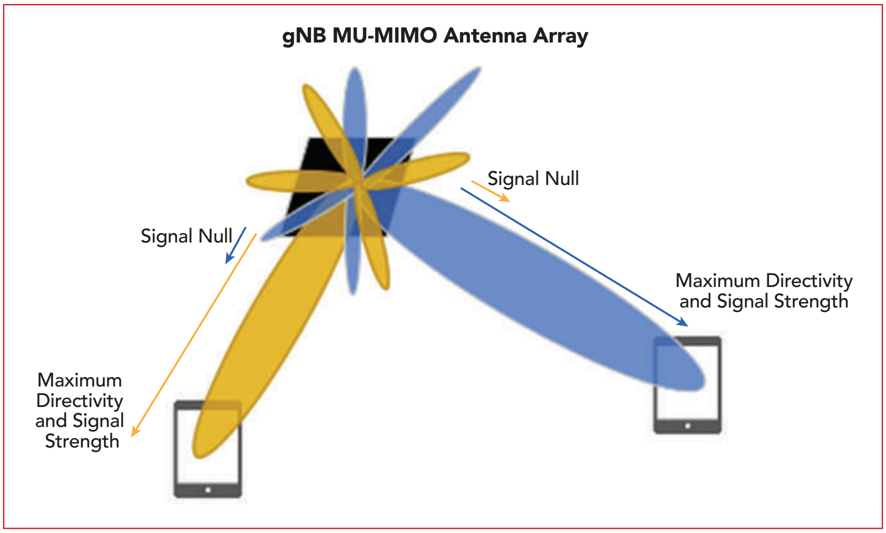


Fig. 4 Spatial multiplexing using MU-MIMO.

moving users, the channel coherence time decreases as the carrier frequency increases because of the Doppler shift, meaning the system has less time to measure the channel and finish a single slot transmission at higher carrier frequencies. Using a narrow subcarrier spacing at mmWave results in unacceptably high error vector magnitude, with considerable performance degradation.

To address these challenges, the 3GPP standardized on a flexible subcarrier spacing that scales the space between orthogonal subcarriers, starting with the 15 kHz subcarrier spacing used for LTE and going to 30, 60 or 120 kHz spacing at mmWave. Leveraging the LTE numerology ensures NR deployments will coexist and be time-aligned with LTE networks.

3 MIMO

To increase capacity and spectrum efficiency, 5G NR uses the distributed and uncorrelated spatial locations of multiple users. Using multiuser MIMO (MU-MIMO) technology, the base station (gNB) simultaneously sends data streams to different users, maximizing the signal strength at each user's location while reducing the signal strength (creating nulls) in the directions of the other receivers. This enables the gNB to talk with multiple UEs independently and simultaneously (see ***Figure 4***).

mMIMO for 5G

Massive MIMO (mMIMO) refers to a communications scenario with many more gNB antennas than users. A large difference between gNB antennas and UEs can yield huge gains in spectral efficiency, enabling the communications system to simultaneously serve many more

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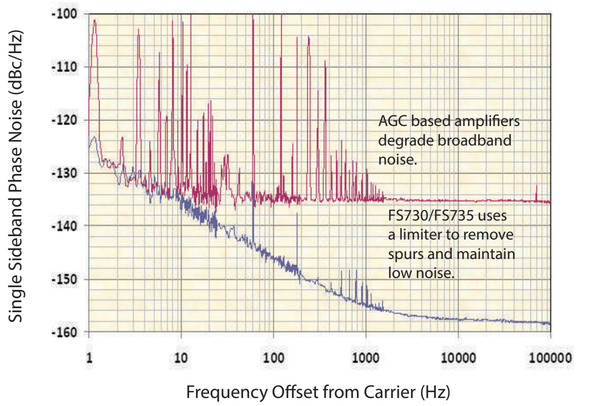

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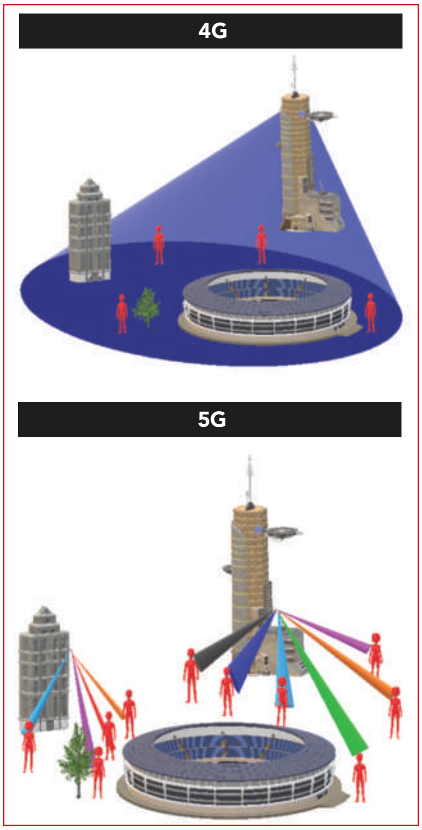

▲ Fig. 5 Spatial multiplexing with mMIMO increases gNB capacity.

devices within the same frequency band than today's 4G systems (see ***Figure 5***). Industry leaders have demonstrated the viability of mMIMO systems for 5G using software defined radio and flexible software, which enable rapid wireless system prototyping.[1]

4 mmWAVE FOR 5G

5G systems operating at 28 GHz or other mmWave bands have the advantage of more available spectrum, enabling larger channels. While the mmWave bands have less spectral crowding than the bands below 6 GHz, communications systems using at these frequencies must contend with very different propagation effects: higher free-space path loss and atmospheric attenuation, weak indoor penetration and poor diffraction around objects. To overcome these undesired effects, mmWave antenna arrays focus their beams and take advantage of antenna array gain. Fortunately, the size of these arrays decreases as the frequency increases, enabling a mmWave antenna array with many elements to be roughly the same size as a single, sub-6 GHz element (see ***Figure 6***).

As noted, the channel coherence time decreases significantly at mmWave frequencies, placing tough restrictions on UE mobility applications. As researchers continue to investigate new ways to improve mobility at mmWave, the first 5G mmWave deployments will likely serve fixed wireless access applications such as home broadband, backhaul and sidelink.

5 BANDWIDTH PARTS

As 5G applications grow, the diversity of devices and equipment will have to operate successfully across many different bands with varying spectrum availability. One example is the situation where a UE with limited RF bandwidth operates beside a more powerful device that can fill a whole channel using carrier aggregation and a third device that can cover the whole channel with a single RF chain.[2]

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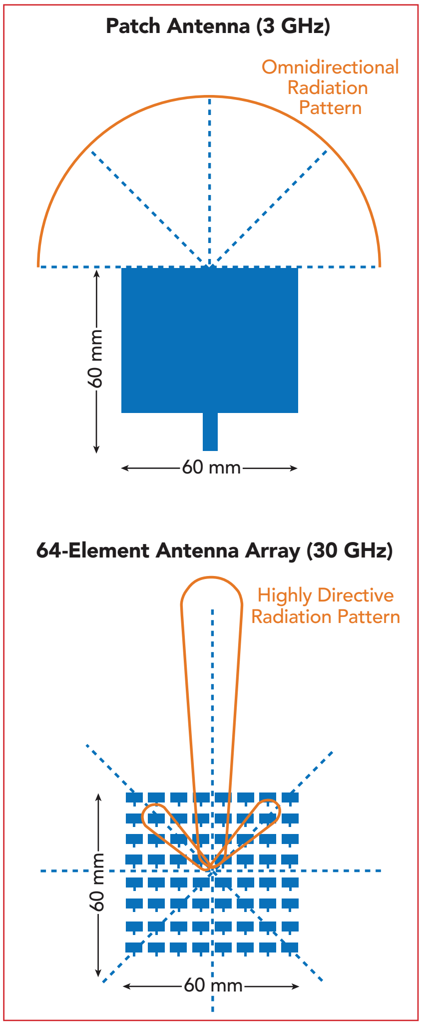
While wide bandwidth enables higher data rates for users, it comes with a cost. If UEs do not need high data rates, using wider bandwidth than required is an inefficient use of the RF and baseband processing resources. 5G NR introduces the concept of bandwidth parts (BWP), where the network negotiates for a certain UE to occupy one wideband carrier, separately configuring other UEs with a subset of contiguous resource blocks. This allows a greater diversity of devices with varying capabilities to share the same wideband carrier. This flexible network operation adjusting to the differing RF capabilities of UEs does not exist with LTE.

SUMMARY

Thanks to higher bandwidth channels and multiple numerology options, NR systems will operate in both sub-6 GHz and mmWave bands, appropriately handling multipath delay spread, channel coherence time and phase noise. NR leverages the latest developments in mMIMO and beamforming to maximize spectral efficiency and provide better quality of service for a larger number of users. Although creating the next generation of 5G devices presents significant design and test challenges, a platform-based approach to design, prototype and test these new wireless technologies is key to 5G becoming a reality within the next decade.■



▲ Fig. 6 64-element array at 30 GHz has the same size aperture as a single 3 GHz patch antenna.

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Characterizing Circuit Materials at mmWave Frequencies

John Coonrod
Rogers Corp., Chandler, Ariz.

Different dielectric constant measurement methods provide different results.

The dielectric constant (Dk) or relative permittivity of a circuit material is not a constant—despite what its name might imply. The Dk of a printed circuit board (PCB) material, for example, will change as a function of frequency. Also, using different Dk test methods on the same piece of material, they are likely to measure different Dk values, which are correct for those test methods. As circuit materials are increasingly employed at mmWave frequencies, with the growth of 5G and advanced driver assistance systems, it is important to understand how Dk changes with frequency and which Dk test methods are "best" applied.

No industry-standard best test method exists for measuring circuit material Dk at mmWave frequencies, although organizations such as the IEEE and IPC have committees devoted to this topic. It is not the lack of measurement methods; in fact, more than 80 are described in just one reference by Chen et al.[1] No method is ideal, with each having challenges and shortcomings, especially at frequencies from 30 to 300 GHz.

CIRCUIT vs. RAW MATERIAL TESTS

Tests for determining circuit material Dk or Df (the loss tangent or tanδ) are generally performed in one of two ways: either on the raw material or a circuit fabricated from the material. Raw material tests depend on high quality test fixtures and test equipment to extract Dk and Df values directly from the material. Circuit tests use a common circuit and extract the material parameters from the circuit's performance, such as measuring the center frequency or frequency response of a resonator. Raw material tests introduce uncertainties typically associated with the text fixture or test setup, while circuit tests contain uncertainties from the test circuit design and fabrication techniques. Because the two methods differ, measurement results and accuracy levels typically do not agree.

For example, an X-Band clamped stripline test defined by IPC,[2] a raw material test, may not provide Dk results agreeing with a circuit test of the same material. The raw material test creates a stripline resonator by clamping two pieces of the material under test (MUT) in a special test fixture. Air can become entrapped between the MUT and the thin resonator circuit which is part of the fixture. The air becomes part of the measurement and lowers the measured Dk. If a circuit test is performed on the same circuit material, without the entrapped air, the measured Dk will be different. For a high fre-


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quency circuit material with a Dk tolerance of ±0.050 determined from a raw material test, a tolerance of ±0.075 may result from a circuit test.

Circuit materials are anisotropic, often with different Dk values in the three material axes. Dk values typically differ little between the x- and y-axis, so for most high frequency materials, Dk anisotropy comparisons are usually made between the z-axis and the x-y plane. For the same MUT, test methods that measure Dk for the z-axis can provide different results than test methods used to evaluate Dk in the x-y plane, although the values of Dk may be "correct" for the given method.

The type of circuit used for a circuit test also influences the value of the measured Dk. In general, two types of test circuits are used: resonant structures and transmission/reflection structures. Resonant structures typically provide narrowband results, while transmission/reflection tests are usually wideband. Methods using resonant structures are typically more accurate.

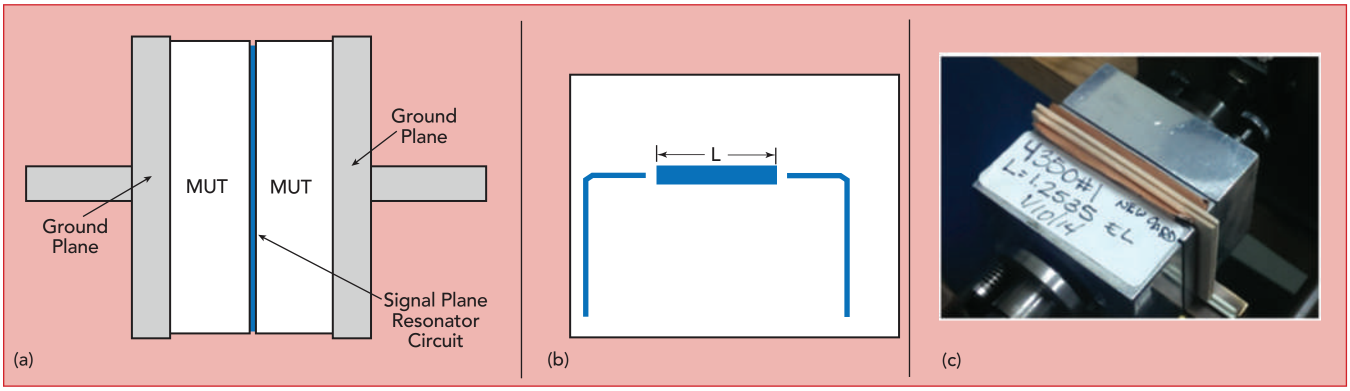
TEST METHOD EXAMPLES

An example of a raw material test is the X-Band clamped stripline method. It has been used by manufacturers of high frequency circuit laminates for years and is a dependable means of determining the Dk and Df (tanδ) in the z-axis of a circuit material. It uses a clamping fixture to form a loosely coupled stripline resonator from MUT samples. The measured quality factor (Q) of the resonator is the unloaded Q, so it can be measured with minimal impact from cables, connectors and fixture calibration. The MUT is a copper-clad circuit laminate with all the copper etched from the substrate prior to testing. The raw circuit material is environmentally conditioned, cut to size and placed into the fixture on both sides of the resonator circuit at the signal plane (see ***Figure 1***).

The resonators are designed with half-wavelength resonances starting at about 2.5 GHz, so node 4 is around 10 GHz; this is the node commonly used for Dk and Df measurements. Lower nodes and frequencies can be used—even the higher node 5 can be used, although higher nodes are usually avoided due to wave propagation or measurement issues from harmonics and spurious content. The extraction of the Dk or relative permittivity (ε_r) is straightforward:

$$\varepsilon_r = \left[\frac{nc}{2f_r\left(L+\Delta L\right)}\right]^2 \qquad (1)$$

where n is the node, c is the speed of light in free space and f_r is the



▲ Fig. 1 X-Band clamped stripline test fixture side view (a), stripline resonator (b) and photograph (c).

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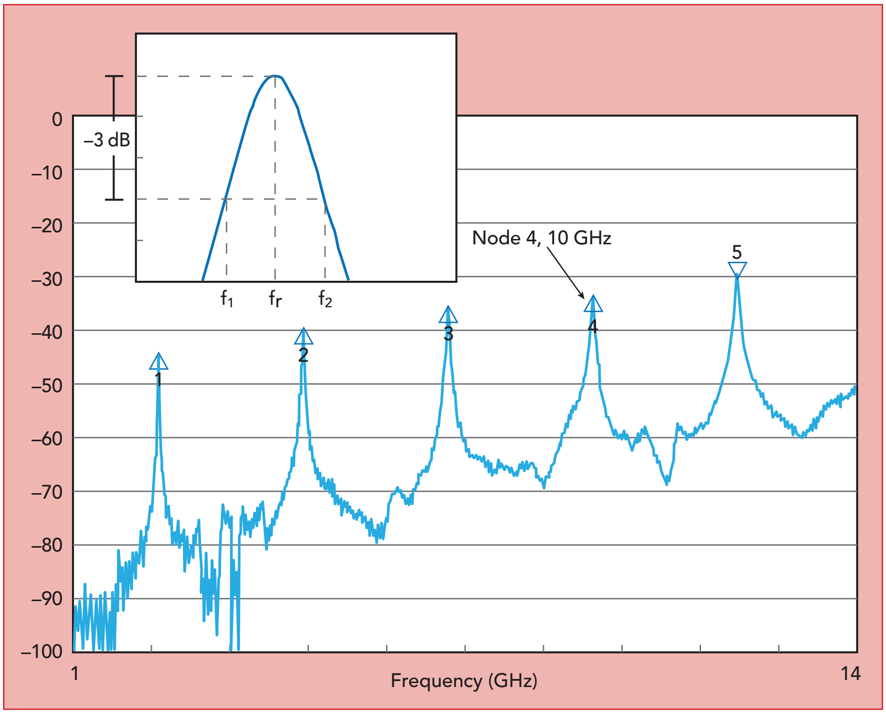

Fig. 2 Wideband clamped stripline measurement of a MUT 60 mils thick, with a Dk = 3.48.

center frequency of the resonant peak. ΔL compensates for the electrical length extension due to electric fields in the gap-coupled area. Extraction of tanδ (Df) from the measurements is also straightforward. It is a fraction related to the 3 dB bandwidth of the resonant peak after subtracting the conductor losses ($1/Q_c$) associated with the resonator circuit.

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} \qquad (2)$$

$$\tan\delta \propto \frac{1}{Q_d} \qquad (3)$$

$$\tan\delta = \left[\frac{f_2 - f_1}{f_r}\right] - \frac{1}{Q_c} \qquad (4)$$

Figure 2 shows a measurement using the clamped stripline test method with a 60-mil thick MUT with Dk = 3.48.

Ring resonators are often used as test circuits.[3] They are simple microstrip structures having resonances at integer multiples of the mean circumference of the microstrip ring (see ***Figure 3a***). They are typically loosely coupled, as loose coupling between the feed lines and the ring minimizes the capacitance of the gaps between the feed lines and the ring. This capacitance changes with frequency, causing the resonant frequency to shift and resulting in errors when extracting the material Dk. The conductor width of the resonator ring should be much smaller than the radius of the ring —as a rule of thumb, one-quarter the dimension of the ring radius or smaller.

The $|S_{21}|$ response of a microstrip ring resonator on a 10-mil thick circuit material with Dk = 3.48 is shown in ***Figure 3b***. An approximate calculation of the Dk is given by

$$2\pi r = n\lambda_g \qquad (5)$$

$$\lambda_g = \frac{c}{f\sqrt{Dk_{eff}}} \qquad (6)$$

$$Dk_{eff} = \left[\frac{cn}{2\pi rf}\right]^2 \qquad (7)$$

Although approximate, these formulas are useful for determining an initial Dk value. A more accurate Dk can be found using an electromagnetic (EM) field solver and precise resonator circuit dimensions.

Loosely coupled resonators are often used for Dk and Df measurements to minimize resonator loading effects. Coupling should be loose enough so the insertion loss is

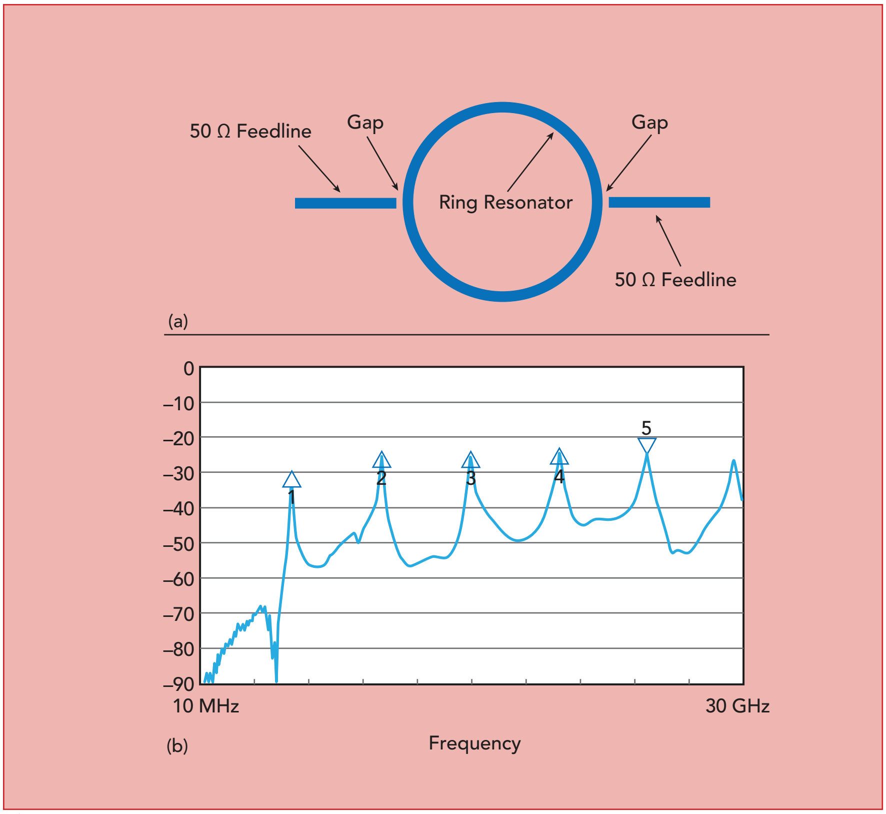

Fig. 3 Microstrip ring resonator (a) and wideband measurement (b).

20 dB or less at the resonant peak. In some cases, with extremely weak coupling, the resonant peak may be so weak that it cannot be measured. This typically occurs for resonant circuits with thinner substrates, the types of materials commonly used in mmWave applications, since the high frequencies have small wavelengths and circuit dimensions.

mmWAVE TEST METHODS

While there are many Dk test methods, only some are suitable for mmWave frequencies, yet none are accepted as industry standards. However, the following methods are accurate and repeatable at mmWave.

Differential Phase Length Method

The microstrip differential phase length method has been used for many years.[4] It is a transmission test method in which phase measurements are made on two circuits that only differ by physical length (see ***Figure 4***). To avoid any variations in circuit material properties, the circuits are fabricated side-by-side and as close together as possible on the MUT. The circuits are 50 Ω microstrip transmission lines of different lengths with a grounded coplanar waveguide (GCPW) signal launch. At mmWave frequencies, the GCPW signal launch is important, since the launch area can have a major impact on return loss. End-launch connectors should also be used, to make good pressure contacts between the coaxial connectors and the test circuit without soldering, allowing the same two connectors to be used for the shorter and longer circuits. This minimizes the effect of the connectors on measurement results. For consistency, the same connectors should be oriented to the same ports of the vector network analyzer (VNA). If connector A is oriented to port 1 of the VNA and connector B to port 2 for testing the shorter circuit, the same should be true when testing the longer circuit.

Subtracting the phase angles of the short and long circuits will also subtract the effects of the connectors and the signal launch areas. If the return loss is good for both

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220 - 330 GHz

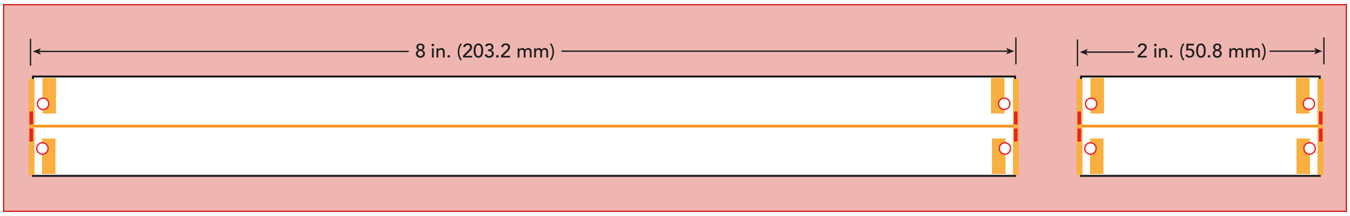

Fig. 4 Top view of the long and short microstrip circuits used in the differential phase-length method.

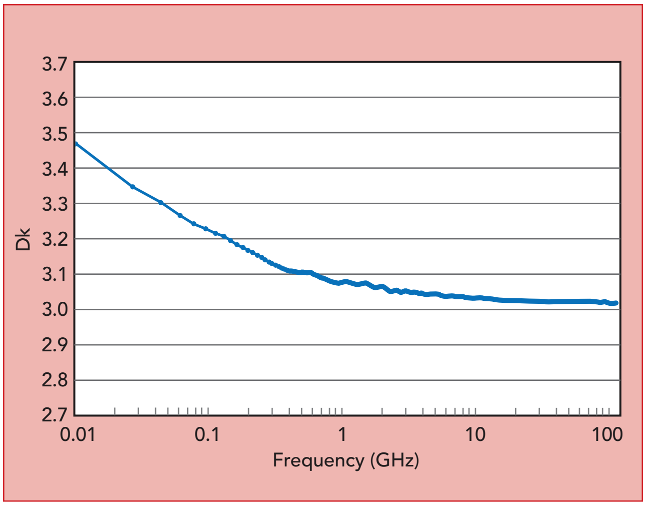

Fig. 5 Dk vs. frequency measured with the microstrip differential phase length method.

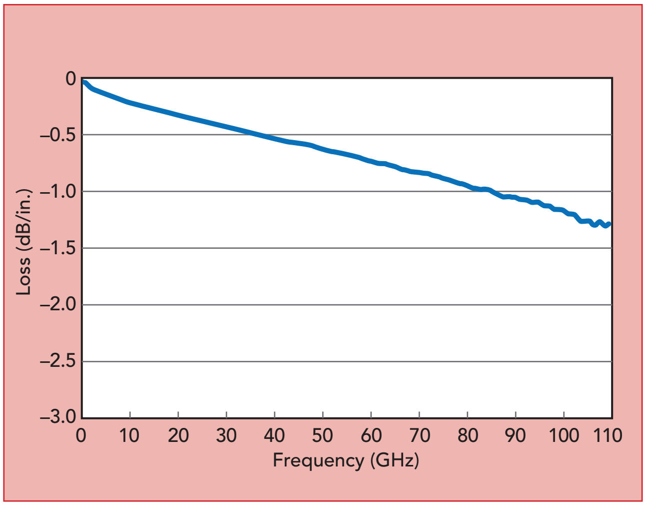

Fig. 6 Insertion loss vs. frequency determined from the microstrip differential length measurements.

circuits and the connectors have consistent orientation, most of the effects of the connectors will be minimized. When using this method at mmWave frequencies, return loss at these transitions of better than 15 dB through 60 GHz and 12 dB from 60 to 110 GHz is considered acceptable.

The extraction equations for the microstrip differential phase length method are based on a manipulation of the microstrip phase response formula for circuits with different physical lengths:

$$\Phi = 2\pi f \frac{\sqrt{Eff\_\varepsilon_r}}{c} L \quad (8)$$

$$\Delta\Phi = 2\pi f \frac{\sqrt{Eff\_\varepsilon_r}}{c} \Delta L \quad (9)$$

$$Eff\_\varepsilon_r = \left[\frac{\Delta\Phi c}{2\pi f \Delta L}\right]^2 \quad (10)$$

where c is the speed of light in free space, f is the frequency of the S_{21} phase angle, ΔL is the difference in physical lengths of the two circuits and $\Delta\Phi$ is the difference in phase angle between the shorter and longer circuits.

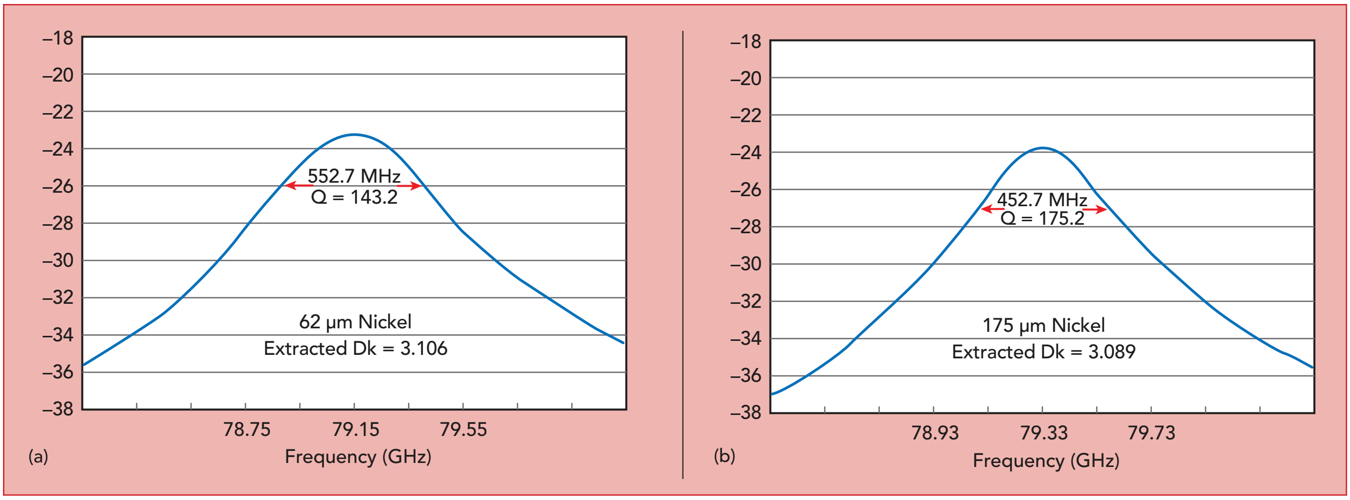

Fig. 7 mmWave ring resonator measurements of a MUT with 62 µm thick (a) and 175 µm thick (b) nickel plating.

The test method comprises a few simple steps:

- Measure the S_{21} phase angle as a function of frequency for the shorter and longer circuits.
- Use the formulas to determine the measured effective Dk.
- Obtain precise and accurate circuit dimensions that can be entered into an EM field solver using the initial Dk value for the material.
- Use the software to generate a simulated effective Dk value. Change the Dk in the solver until the measured and simulated effective Dk values for the material match at the same frequency.
- By incrementing the frequency into the mmWave region and repeating this process, the Dk value can be determined across a range of frequencies through mmWave.

Figure 5 shows a measurement using the microstrip differential phase length method with 5-mil thick RO3003G2^{TM} circuit material. The curve was generated using a Microsoft Windows PC program developed by Rogers Corp.[5] The data reflects the usual trend of decreasing Dk with increasing frequency. At lower frequencies, larger changes in Dk occur versus frequency; however, from 10 to 110 GHz, the Dk shows little change. This curve reflects a material with low loss and rolled copper with a smooth surface. A material with high loss and/or higher copper surface roughness will exhibit an increased negative slope in the Dk-frequency relationship. Using this test method, the insertion loss for circuits using the MUT can be obtained by subtracting the S_{21} values of the shorter and longer circuits at each frequency (see ***Figure 6***).

Ring Resonator Method

The ring resonator method is another approach for mmWave characterization. While ring resonators are often used below 10 GHz, with proper fabrication precision they can be used effectively at mmWave frequencies. Fabrication is important because the effects of circuit dimensions and dimensional tolerances are greater at mmWave, with any variation reducing accuracy. The thickness of the copper plating on the circuit material also varies, as does the gap dimension. Most mmWave ring resonators are thin (usually 5 mils), and the gap between the feed line and resonator

ring is also small. Thickness and gap variations for a gap-coupled ring resonator will impact both coupling and the resonant frequency.

When comparing two circuits built on the same circuit material and with different copper plating thicknesses, the circuit with the thicker copper will exhibit a lower Dk. The resonant frequencies of the two circuits will also differ, even though they should be the same for the same circuit material and test method. ***Figure 7*** shows an example where the thickness variation in a circuit's final plated finish causes differences in the extracted Dk for the same material. Whether the finish is electroless nickel immersion gold (ENIG) or other plated finishes, the issue remains.

Besides these fabrication issues, conductor width variation, etched-space variation, trapezoidal effects and substrate thickness variation cause similar effects. If all these variations are accounted for, one individual ring resonator measurement can yield the correct Dk value; however, many test routines will assume nominal circuit dimensions and extract an incorrect Dk. At lower frequencies these effects do not impact Dk accuracy as much as at mmWave frequencies.

Another significant variable using ring resonators at mmWave is the gap coupling changing with frequency. It is typical for ring resonators to be evaluated using multiple nodes, with the nodes usually spaced by significant differences in frequency. As a result, gap coupling variation can be a significant source of error. To overcome this, a differential circumference method is used. This approach uses two ring resonators, essentially identical except the ring circumferences differ in size and are integer multiples of each other (see ***Figure 8***). With two ring resonators, the higher order resonant nodes used in the Dk extraction have some frequencies in common. Since the feed lines and gaps are the same, the effects of gap coupling are decreased—theoretically eliminated—which leads to better accuracy in the extracted Dk. The Dk is calculated from the equations:

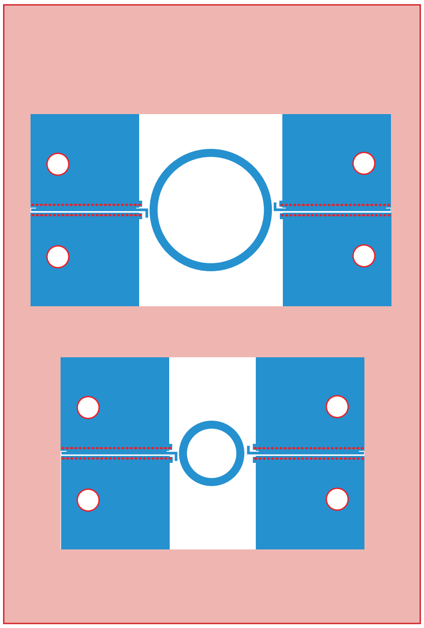

Fig. 8 Test rings used with the microstrip differential circumference ring resonator method.

$$L_1 + \Delta L = \frac{n_1 c}{2 f_{r1} \sqrt{Eff\_\varepsilon_r}} \quad (11)$$

$$L_2 + \Delta L = \frac{n_2 c}{2 f_{r2} \sqrt{Eff\_\varepsilon_r}} \quad (12)$$

$$Eff\_\varepsilon_r = \left[\frac{c\left(n_1 f_{r2} - n_2 f_{r1}\right)}{2 f_{r1} f_{r2} \left(L_2 - L_1\right)} \right]^2 \quad (13)$$

The ring resonators in Figure 8 are microstrip structures, with the feed lines tightly-coupled GCPW to avoid open-end feed line resonances, which could interfere with the ring resonant peaks. If the feed lines were open-ended microstrip, they would have their own resonances. The only way to avoid this is to make the feed lines much shorter or use tightly-coupled GCPW feed lines. Since the differential circumference ring resonator method yields the circuit's effective Dk, it is still necessary to make accurate circuit dimension measurements and use a field solver to extract the material Dk.

CONCLUSION

The mmWave test methods discussed here are circuit-based. Several other methods may be considered, such as raw material tests, but most yield a material Dk for the x-y plane rather than the z-axis (thickness). Circuit designers are more interested in the z-axis Dk, but for those willing to work with x-y material Dk values, free-space measurements, split-cylinder resonator measurements and waveguide perturbation testing are additional test methods.

The clamped broadside coupled stripline resonator test method has also been evaluated for determining circuit material Dk at mmWave frequencies. Unfortunately, this approach is most effective with small pieces of MUT and is not practical for volume testing. The quest continues to find a good raw material test to characterize materials at mmWave frequencies.■

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INVITED PAPER

Designing Wide Instantaneous Bandwidth Doherty PAs for Cellular

Tim Das
NXP, Chandler, Ariz.

The 3.5 GHz band is emerging as prime 4G and 5G spectral real estate around the globe. Radio interfaces are evolving through LTE-Advanced and LTE-Advanced Pro, raising the bar on base station power amplifier (PA) capability and performance. Instantaneous signal bandwidth is the key to a suitable solution. This article outlines the fundamentals of PA design for a symmetrical, wideband Doherty using load-pull and introduces concepts such as "Doherty friendliness" and "digital predistortion (DPD) compatibility." The design example of a wideband Doherty PA (DPA) demonstrates a solution suitable for 3.5 GHz LTE-Advanced: a two-stage LDMOS DPA delivering 6.61 W average (35 W peak) at 37 percent efficiency, with 24.5 dB gain and over 300 MHz instantaneous signal bandwidth.

The RF carrier is the virtual packhorse of the cellular network. Today's 4G LTE-Advanced network operates with the concept that a team of packhorses, in aggregate, carry a heavier burden. With LTE-Advanced Pro, the next evolutionary step in cellular network technology, multiple packhorses are tied together: some we own, some we borrow when needed. The beasts we borrow come from a shared pool, such as the Citizen's Broadband Radio Service (CBRS) spectrum.

The U.S. CBRS spectrum—3550 to 3700 MHz—is open to the public and administered via a central server for "dynamic shared use," either within a building or outdoors via small cells. Mobile network operators in the U.S. are thrilled about this new cost-effective option for LTE-Advanced network capacity expansion. In China and other leading 5G nations, the 3.5 GHz band—3400 to 3800 MHz—will become primary licensed spectral real estate for 5G.

LTE-Advanced Pro was introduced with 3GPP Release 13 and builds on LTE-Advanced from 3GPP Release 10. LTE-Advanced accommodates five simultaneous carriers, aggregating 100 MHz bandwidth. With LTE-Advance Pro, the capacity jumps to 32 simultaneous carriers, mixing licensed and shared spectrum with higher-order modulation and higher-order MIMO, using up to 640 MHz aggregate bandwidth. These capabilities push the requirement for instantaneous signal bandwidth (ISBW), the maximum modulated signal bandwidth, ever higher in the radio interface, which is particularly challenging for the RF PA (RFPA) design.

RFPA technology, on its own, is unable to address the linearity requirements of LTE-Advanced over wide bandwidths. Using adaptive numerical methods, DPD provides the necessary bridge to the performance required of higher-order modulation and wider signal bandwidth. The RFPA is engineered to dovetail with the DPD system, a task that would be quite difficult if the RFPA and DPD were not designed for compatibility—a quality RFPA designers call "DPD compatibility." More on this in a bit.

The following discussion will demonstrate the fundamentals of DPA design based on

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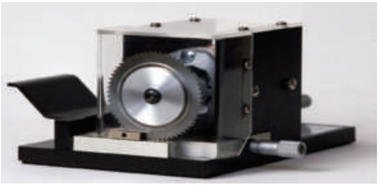

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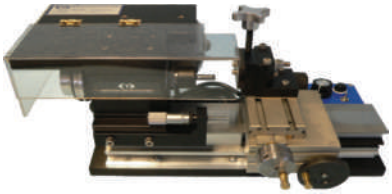

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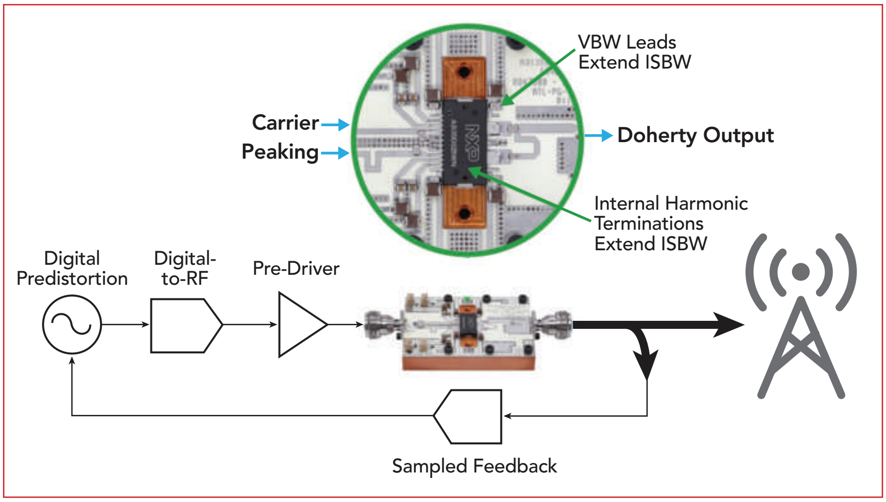

Fig. 1 Wideband Doherty PA with DPD.

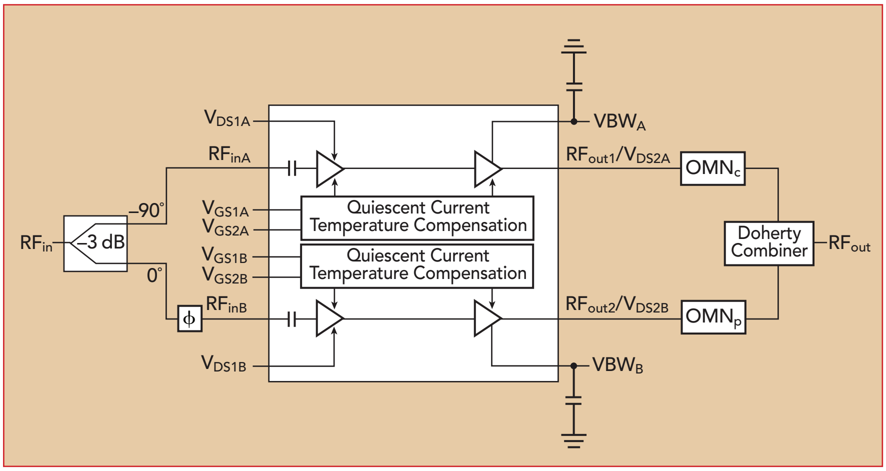

Fig. 2 Functional block diagram of the NXP A3I35D025WN Doherty PA.

a device uniquely suited for LTE-Advanced applications, a solution using NXP's A3I35D025WN, a two-stage LDMOS DPA that delivers 3.4 W average (45.2 W peak) with 34 percent efficiency, 24.5 dB gain and greater than 300 MHz instantaneous signal bandwidth (see ***Figure 1***).

DPA DESIGN

The DPA is the current topology of choice for efficient, high power RF amplifiers (see ***Figure 2***). The "trick" of the Doherty configuration is: At lower signal power, the peaking drain is in an off state and the carrier path is providing the full power gain, as efficiently as possible based on the bias. As the signal level increases, the peaking transistor turns on, changing the impedance it presents to the Doherty combining node. At full power, the carrier's performance is pulled from optimal efficiency to maximum power. However, the magic is that none of the energy used to pull the carrier drain is wasted.

The designer selects the load impedance targets for the carrier and peaking amplifiers for the two modes of Doherty operation: full power and the peaking path off. Z_{opt} reflects the full power mode, corresponding to the maximum output power, and Z_{mod} reflects the peaking off mode, corresponding to optimal efficiency. Z_{opt} is the target drain impedance at the carrier and peaking drains in full power mode. In this mode, the carrier and peaking paths combine constructively at the Doherty combining node, and the peaking output is actively load-pulling the carrier output toward maximal output power. Z_{mod} is the target drain impedance at the carrier drain in the peaking off mode. In this mode, the peaking path is in its off state and should not be loading the Doherty combination node significantly.

These impedances are selected from the load-pull contours at the predefined bias settings at the band-center and band-edge frequencies (see ***Figure 3*** and ***Table 1***). Note the gamma spacing between the Z_{opt} and Z_{mod} points: |gamma| = 0.3333 or 2:1 VSWR. This spacing corresponds nicely with the 2:1 VSWR load modulation of the carrier drain with a symmetrical Doherty—the first characteristic which indicates the Doherty friendliness of the device. Also note any significant gradient in output power, efficiency, gain and AM-to-PM vs. load impedance in and around the Z_{opt} and Z_{mod} points, i.e., within 2:1 VSWR. There should be no significant gradient in load-pull contours across frequency; the lack of any significant pitch also reflects Doherty friendliness for wideband applications.

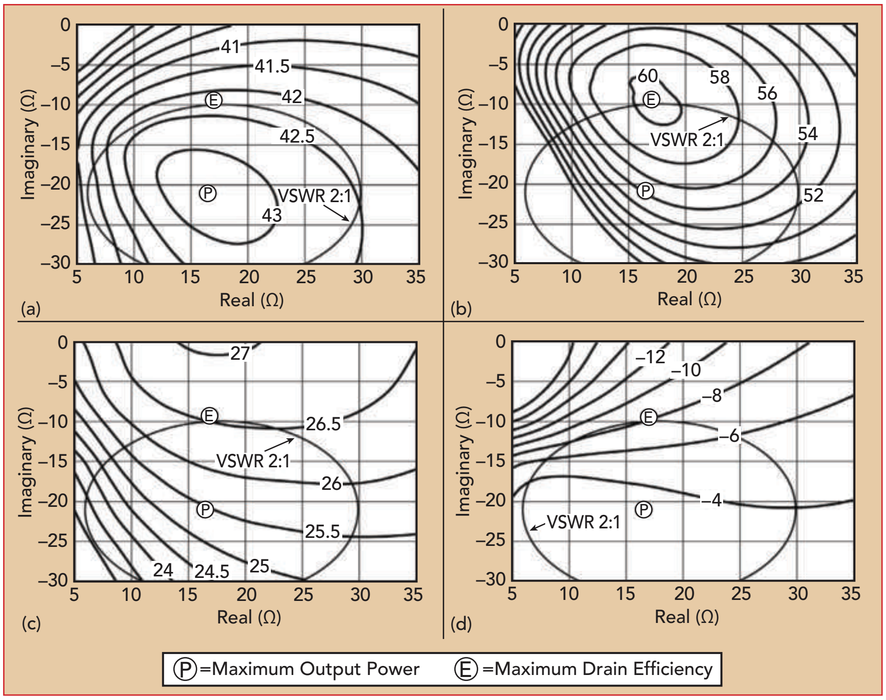

Fig. 3 **3600 MHz load-pull contours: output power (a), drain efficiency (b), gain (c) and AM/PM at 3 dB compression (d).**

TABLE 1

CARRIER AND PEAKING LOAD IMPEDANCE TUNING TARGETS (GAMMA = 0.3333 < 67.7° BETWEEN Z_{opt} AND Z_{mod})

f (MHz)	Z_{opt} (Ω)	Z_{mod} (Ω)
3500	17.1 - j22.3	20.7 - j9.3
3600	15.0 - j21.3	15.7 - j11.0
3700	13.8 - j20.6	12.7 - j11.6

The best starting point for the optimal device bias is at or near class AB, as defined in the product datasheet (see ***Table 2***). As noted, in the Doherty configuration, the carrier amplifier will be operated in class AB and the peaking path in or near class C. Thermal tracking circuits on the A3I35D025WN DPA regulate the quiescent current over wide temperature variation, and the datasheet specifies the quiescent current accuracy over temperature, gain variation over temperature and output power variation over temperature. Consider using an off-chip temperature monitor if the datasheet specification for variation over temperature is not sufficiently precise for the target application.

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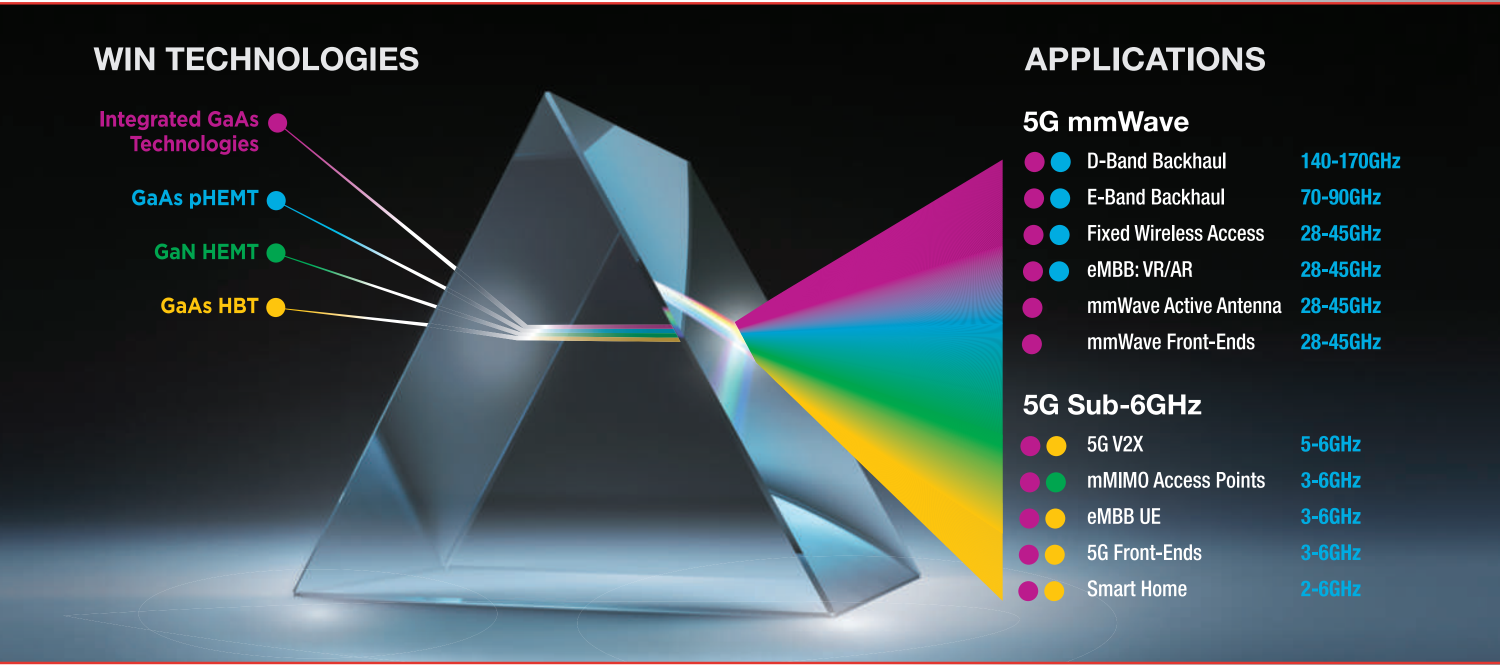

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ICs specifically configured to bias LDMOS Doherty circuits are available, such as TI's AMC7834 or ADI's AD7294. In addition to setting the bias, they monitor temperature, current and voltage. The key parameters to monitor and control are the carrier amplifier quiescent current, maximum channel or junction temperature and accommodating part-to-part variation in the transistor pinch-off voltage.

DPA Tuning

To optimize the performance of the DPA, the design needs to be tuned, paying attention to the following:

- The peaking leg in the off state may load the carrier output through the Doherty combiner, shifting it from the Z_{mod} target impedance. The designer needs to adjust the line length of the peaking output to present a high impedance at the combining node.
- It is much easier to tune the Doherty if the test fixture design includes provisions for separately tuning the carrier and peaking outputs to each of the target impedances.
- On combination of the carrier and peaking paths, adjust the phasing between the two paths to align constructive combination.
- Tuning requires at least a couple of iterations of fine adjustments of the output matching network, input matching network, phase alignment and the bias for optimal performance.
- If the solution falls short of expectations after several iterations of fine tuning, revisit the Doherty combiner design to see if that is limiting the performance.

ISBW

The large-ISBW of a PA is usually limited by either the video bandwidth (VBW) or the RF bandwidth of the DPA circuit. VBW is usually dominated by the drain capacitance (C_{ds}), bond wires, leadframe inductance and package parasitics, which the designer should minimize. To extend ISBW, the A3I35D025WN has special purpose pins labelled "VBW" that provide access to an internal RF "cold node" on the drain of each final stage transistor. A high-quality chip capacitor on each VBW pin provides an alternate path to RF ground for the baseband currents, avoiding inductance in the prematch network or on the drain bias feed lines and pushing the drain impedance resonances beyond the baseband frequencies. For multi-stage PAs, such as the A3I35D025WN, the interstage matching networks should not limit RF bandwidth, efficiency or gain.

A topic beyond the scope of this article, but worth mentioning, is another difficulty with wideband PA design: higher-order intermodulation distortion (IMD) can produce products which fall in-band. Designs such as the A3I35D025WN mitigate IMD products with on-chip harmonic terminations.

Thermal Design

The integrity of the Doherty design should be confirmed by checking the thermal integrity and stability. The maximum operating channel or junction temperature must be comfortably below the datasheet maximum rating of 225°C, as operation at or beyond the maximum rating will degrade the mean-time-to-failure. A stack-up of thermal resistances, beginning with the DPA thermal resistance from junction to case, provides a quick check of thermal design integrity (see ***Figure 4***). The most effective means of heat conduction

TABLE 2
RECOMMENDED A3I35D025WN DPA BIAS

Single Path	V_{dd} (V)	Stage 1		Stage 2	
		Gate Voltage (V)	Drain Quiescent Current (mA)	Gate Voltage (V)	Drain Quiescent Current (mA)
Carrier: Class AB	28	3.41	32	3.30	111
Peaking: Class C	28	2.79	0	2.52	0

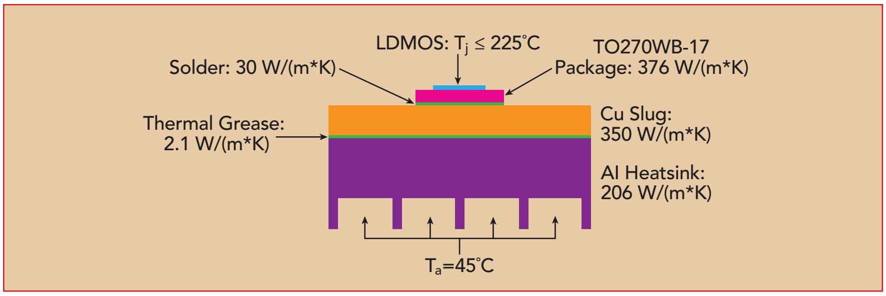

Fig. 4 Assembly stack for thermal modeling.

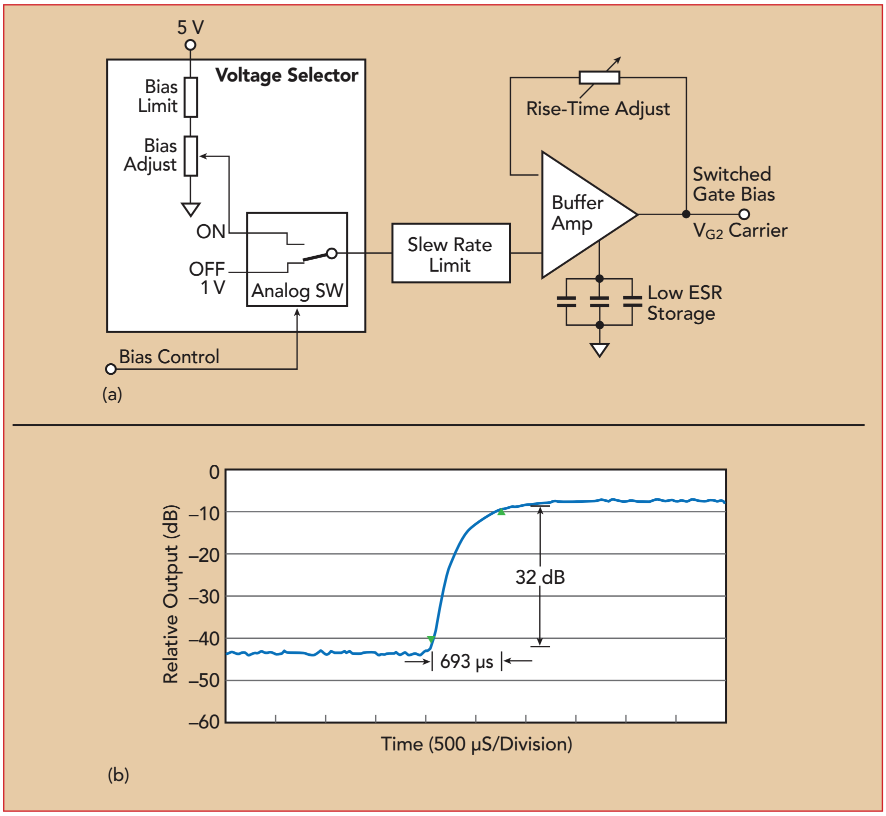

Fig. 5 Gate switching circuit (a) and output power response (b) for TDD operation.

from the device is soldering the package bottom directly to a copper slug through a cutout in the PCB, which is at RF ground potential.

Accommodating TDD

For fastest time-division duplex (TDD) switching, the gate capacitance should be minimized to below 1 nF, adding a series resistance (~50 Ω) on the gate bias feed to dampen any overshoot on the transitions (see ***Figure 5***). On RF envelope peaks nearing transistor saturation, Schottky diode current on the gate can momentarily surge to 100 mA, so some charge storage is needed on the gate.

DESIGN VALIDATION: CBRS PA

Using the dual-stage A3I35D025WB in a symmetrical Doherty configuration, a PA was designed for TDD operation in the CBRS band (see ***Figure 6***). DPA performance with a CW input signal and without DPD is shown in ***Figure 7*** and summarized in ***Table 3***. Figure 7a shows the gain compression at 3400, 3600 and 3800 MHz, and Figure 7b shows the drain efficiency vs.

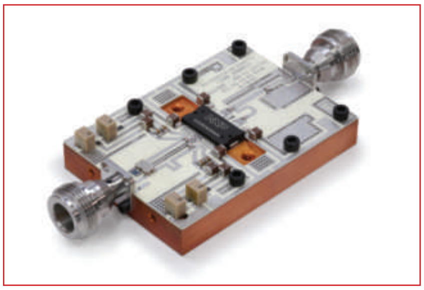

Fig. 6 A3I35D025WN PA test fixture.


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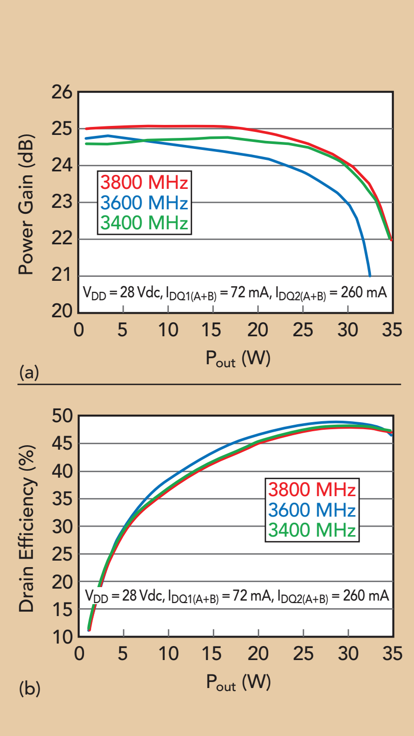


▲ **Fig. 7** **Output power vs. power gain (a) and drain efficiency (b) at 3400, 3600 and 3800 MHz.**

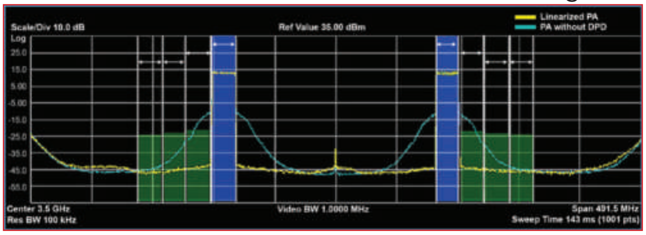
output power at the same three frequencies.

Driven by two carriers, the linearity performance of the DPA at 3600 MHz, with and without DPD, is shown in ***Figure 8***. At 3600 MHz, with two, 20 MHz LTE carriers separated by 200 MHz and 7 dB peak-to-average ratio, the DPA achieves 6.61 W average power with 37.1 percent efficiency and 24.5 dB power gain. The adjacent channel leakage power is –56.8 dBc at ±20 MHz offset from the carrier, –58.6 dBc at ±40 MHz offset and –59.3 dBc at ±60 MHz offset.

The ISBW of this DPA is greater than 300 MHz, which enables it to use DPD linearization over the full CBRS band. Depending on the DPD friendliness of the DPA, the DPD may require the output ISBW to be as much as 3 to 5× the baseband frequency to adequately sense the amplifier's dominant intermodulation products. The ISBW requirement for DPD can be relaxed somewhat if the DPA has other favorable aspects of DPD compatibility. The DPD system may be sensitive to the symmetry of the IMD products, variation in gain compression characteristics (AM-to-AM and AM-to-PM) across the tuned band and memory effects.

SUMMARY

This article discussed the design of a symmetrical, wideband DPA for the CBRS band, reviewing the fundamental theory of DPAs and covering the design approach to optimize the performance of the carrier and peaking amplifiers and the overall DPA. The importance of ISBW for wideband operation with DPD was discussed, including design approaches to maximize the ISBW and the compatibility of the device technology to DPD. Using a commercial, two-stage LDMOS MMIC from NXP, the DPA delivered 6.61 W average output power with 37 percent efficiency, 24.5 dB gain, adjacent channel leakage of –56.8 dBc at ±20 MHz offset and greater than 300 MHz instantaneous signal bandwidth—suitable for covering the full 3550 to 3700 CBRS band.■



▲ **Fig. 8** **PA linearity with and without DPD.**

TABLE 3

WIDEBAND DPA PERFORMANCE W/O DPD

Frequency (MHz)	Linear Gain (dB)	Output Power at 3 dB Gain Compression (W)	Efficiency at 6 W Pout (%)	ISBW (MHz)	Supply Voltage (V)
3400	25.1	35.5	33.9	> 300	28
3600	25.4	35.5	33.5		
3800	24.7	35.5	31.8		

New Vector Network Analyzer Masters Complex Measurements

Rohde & Schwarz
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The new Rohde & Schwarz ZNA vector network analyzer (VNA) was designed to master the most challenging measurement tasks—such as component and module characterization in the aerospace & defense sector—which put strict requirements on the performance, stability, reproducibility and versatility of the VNA test platform.

For both active and passive devices, the R&S ZNA provides the flexibility required to handle the testing challenges of today and tomorrow. As shown in ***Figure 1***, the VNA has a unique hardware architecture, offering up to four internal coherent signal sources, eight truly parallel measurement receivers and two internal local oscillators (LO). The ZNA is currently available with either 26.5 or 43.5 GHz upper frequency limit, with two or four test ports. The excellent trace noise of > 0.001 dB at 1 kHz IF bandwidth ensures accurate and highly reproducible measurements of active and passive devices.

Beyond the hardware, an intuitive and innovative operation concept, with full touch support and measurement wizards for various components, shortens test setup times.

MIXER AND AMPLIFIER CHARACTERIZATION

A full mixer characterization requires time to set up traces and channels with the various parameters to measure conversion loss, isolation and matching—both amplitude and phase. The new device under test (DUT) centric concept of the R&S ZNA takes this burden away from the user. After defining basic parameters like frequency range and power levels, the user selects the parameters to be measured, and the network analyzer configures the setup (see ***Figure 2***). This capability enables the measurement to be set up quickly without in-depth knowledge of the instrument's optimum settings, saving time and increasing reproducibility.

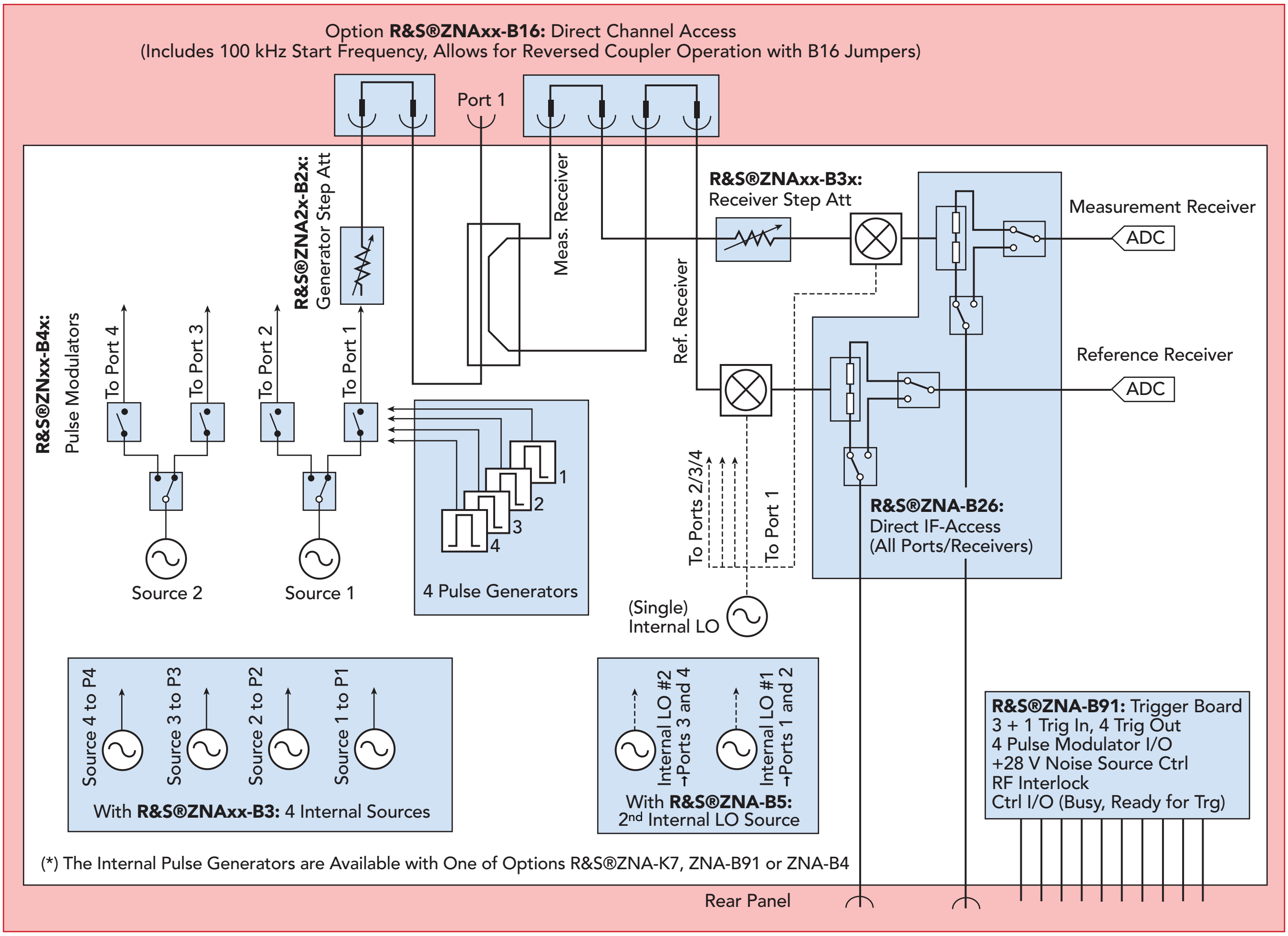

Fig. 1 Functional block diagram of the R&S ZNA.

Fig. 2 Full touch capability and measurement wizards ease test setups.

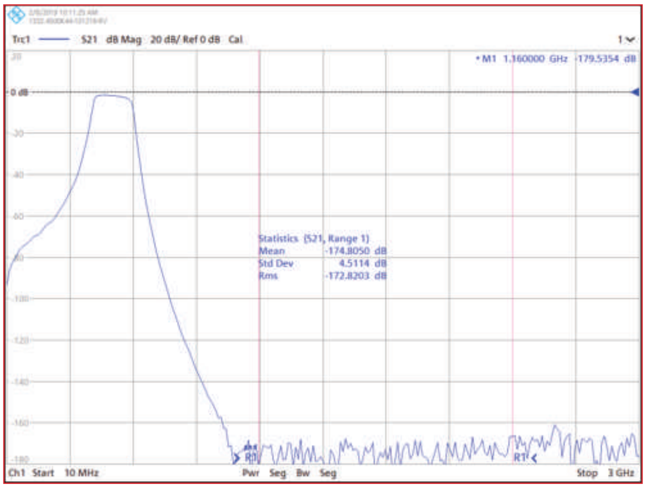

Fig. 3 The ZNA's 170 dB dynamic range enables challenging filter measurements.

With phase-coherent synthesizers, phase and group delay measurements can be performed without additional reference mixers. The second internal LO enables the RF and IF signals to be measured simultaneously, yielding twice the measurement speed with highly accurate results.

The 100 dB electronic power sweep range makes amplifier compression point measurement an easy task, without suffering from the switching effects of step attenuators, and spectrum analysis functionality enables searching for spurious signals. The internal pulse modulators support point-in-pulse testing with up to 50× faster pulse profile testing of the DUT than before, testing often required in aerospace & defense and wireless applications.

Frequency converters without LO access, like ones used in the satellite industry, are difficult to measure due to their frequency drift. Rohde & Schwarz's unique

and patented two-tone approach enables the ZNA to measure the group delay and relative phase, even on frequency drifting converters. The measurement of both tones is performed simultaneously, thanks to the instrument's hardware architecture, so possible drift effects of the DUT apply to both tones and are cancelled out in the measurement results. To handle drifts exceeding the instrument's IF bandwidth, the R&S ZNA can perform an LO search sweep, and using the second internal LO doubles the measurement speed.

HIGH DYNAMIC RANGE, EXTENDED FREQUENCY RANGE

High blocking filters used in aerospace and defense systems or base stations require the measuring equipment to have high dynamic range, both to measure very low signal levels and to use a wider IF bandwidth for the required dynamic range. Consequently, the measurement is faster and filter tuning easier. The reverse coupler mode in the R&S ZNA typically achieves a dynamic range of 170 dB (see ***Figure 3***). To avoid saturating the measurement receivers in the filter passband, the ZNA employs a segmented sweep with different parameters for the stopband and passband.

Many applications, such as on-wafer component testing, 5G mobile communications, point-to-point radio, imaging and fundamental research, use frequencies in the mmWave and THz range. Automotive radar uses 77/79 and 120 GHz has been demonstrated for short-range sensors, for example. Choosing from a range of Rohde & Schwarz frequency converters, the upper frequency coverage of the R&S ZNA can be extended. High output power and dynamic range are the key parameters of Rohde & Schwarz frequency converters, essential for on-wafer device or antenna characterization. Bypassing the input mixer stage of the VNA and using the direct IF inputs of the R&S ZNA for these measurements increases the dynamic range by some 7 dB. Up to four converters can be used with the R&S ZNA to characterize differential, multiport and frequency converting devices.

The basis for a future proof, high-end VNA is powerful hardware with excellent RF performance and functionality. Four sources, eight receivers, two LOs and other hardware components add the flexibility needed for complex measurement tasks, and the easy-to-use, DUT-centric measurement wizards simplify setup, enabling the optimal use of the instrument's capabilities. The most challenging measurement tasks can be mastered with the R&S ZNA.

VENDORVIEW

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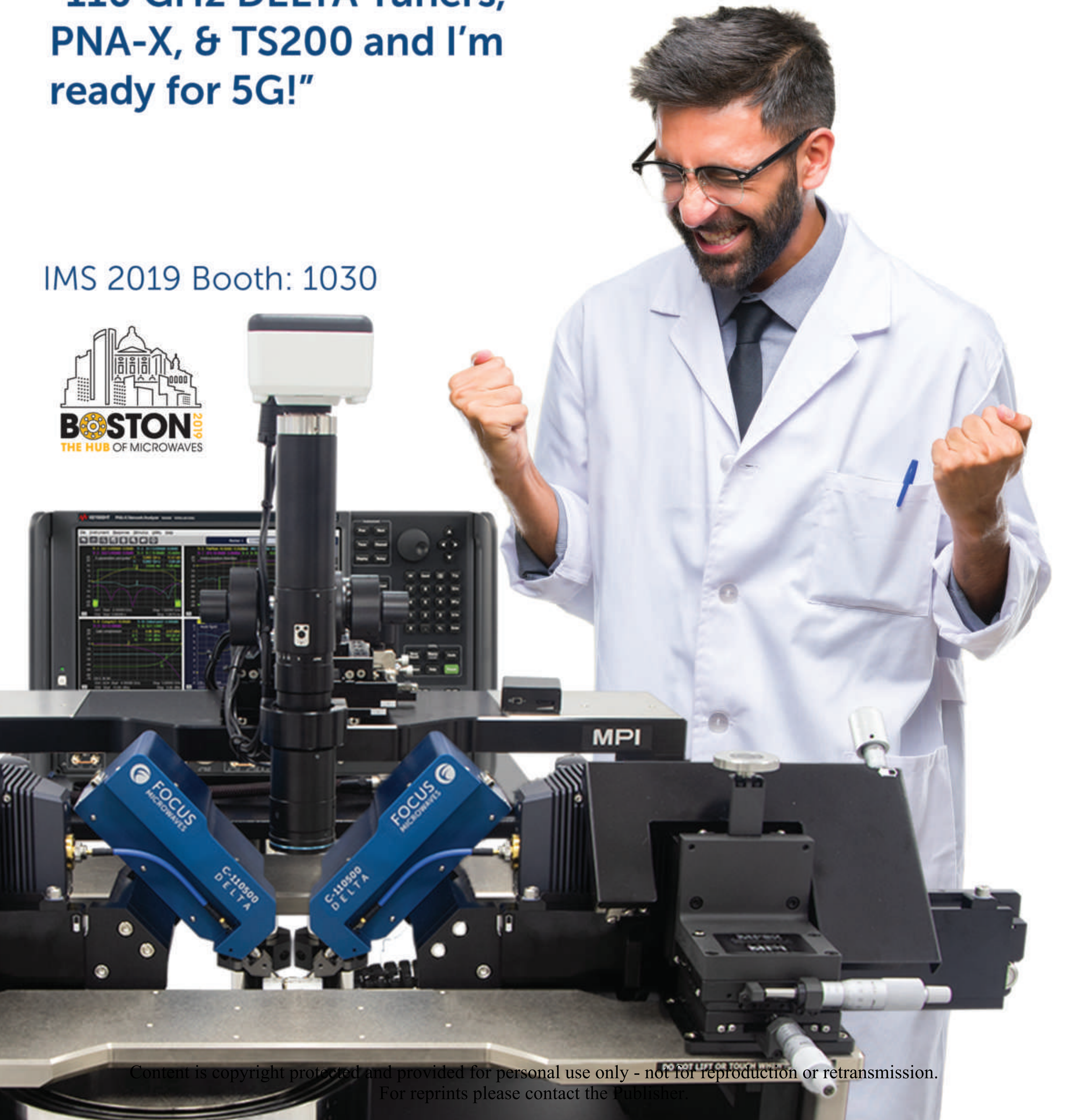

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Modular, Open Architecture Transceivers Enable Next-Generation EW Systems

Mercury Systems
Andover, Mass.

As the defense industry continues to push for cost savings and improved delivery schedules, electronic warfare (EW) system designers are faced with new challenges. Where the previous development model relied on custom subassemblies that proved to be high cost, the emerging model leverages common designs and open standards to reduce cost and expedite delivery. This is especially critical for high performance microwave front-ends. Their technical complexity and specific performance requirements have traditionally led to custom designs and unique form factors.

To address this need, companies like Mercury Systems are introducing common standards and a modular design philosophy. This new approach is demonstrated in Mercury's RFM3101 wideband microwave transceiver. Offering low spurious RF performance from 6 to 18 GHz in a convenient 3U OpenVPX™ form factor, the RFM3101 integrates up- and down-conversion modules, image rejection filtering and built-in LO generation (see ***Figure 1***). This compact and rugged module achieves low phase noise and a 1 GHz IF bandwidth.

The key to Mercury's modular design is the OpenRFM™ architecture. This approach defines the internal RF interfaces, maximizing the product's flexibility and enabling rapid design modification. The RFM3101 leverages this architecture by including two OpenRFM module sites (see ***Figure 2***). The standard configuration consists of one transmit module and one receive module. However, with the standard interface, the transceiver can easily be customized for specific applications by swapping out the microwave modules. For example, a variant can easily be created with two receive and no transmit channels. The same modules can be inserted into a 6U OpenVPX product for a combined total of five transmit and receive channels.

As new technology becomes available, RF performance can be improved through modifications in the individual modules. This reduces both the cost and timeline for product updates. Additionally, this approach supports customization to specific program needs by limiting the scope of the design modifications. Parameters such as instantaneous bandwidth, frequency range and output power can be adjusted at the module level instead of requiring a full product redesign. By offering a standard product with the option to customize, Mercury Systems supports customers looking for an off-the-shelf solution and those requiring custom design.

The OpenRFM architecture simplifies the manufacturing process by separating the build of the sensitive microwave modules from the build of the control and digital blocks. Prior to final integration, the microwave modules are assembled and tested by Mercury's experienced RF and microwave technology group. This team combines expertise with automated assembly at the die

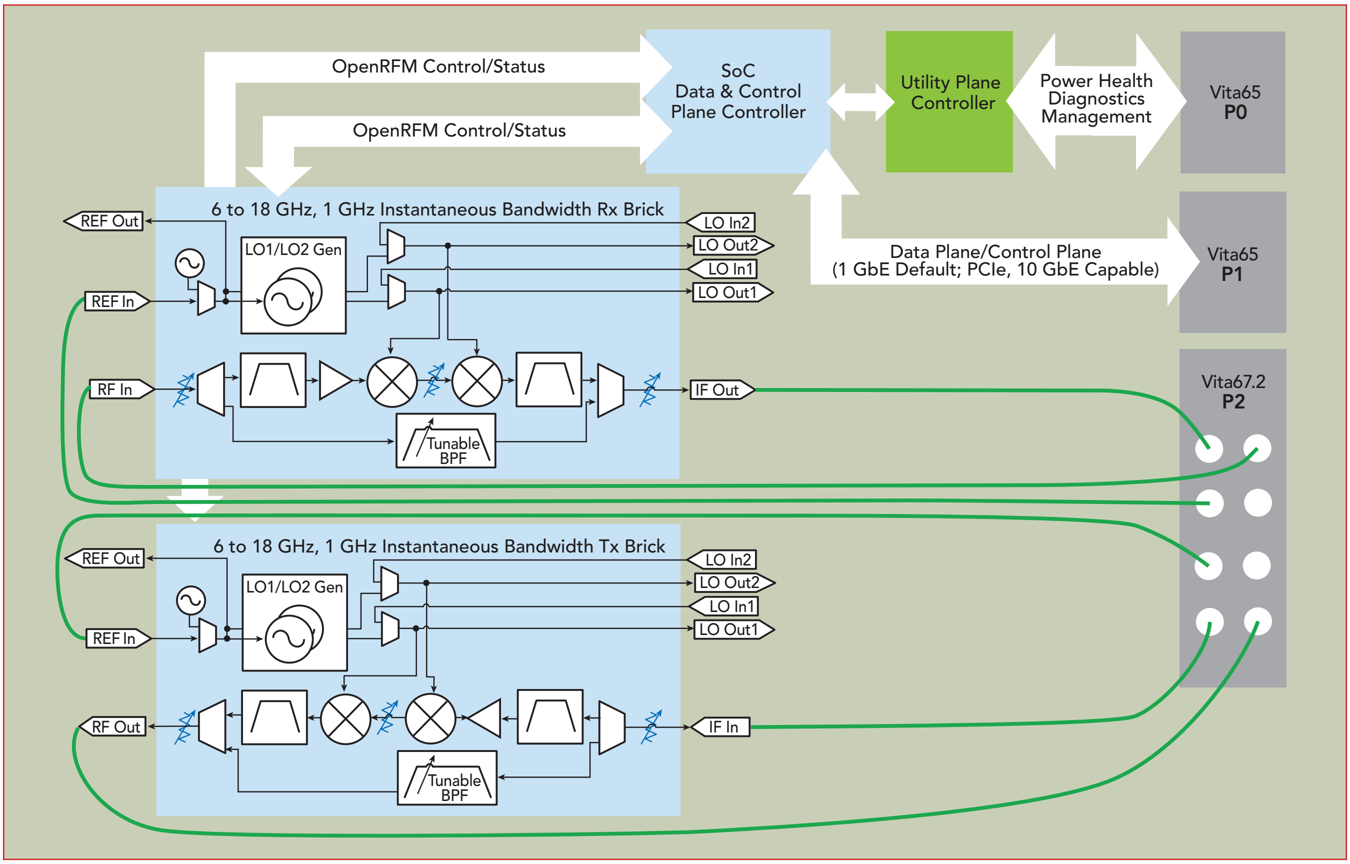

Fig. 1 Block diagram of the RFM3101 6 to 18 GHz transceiver.

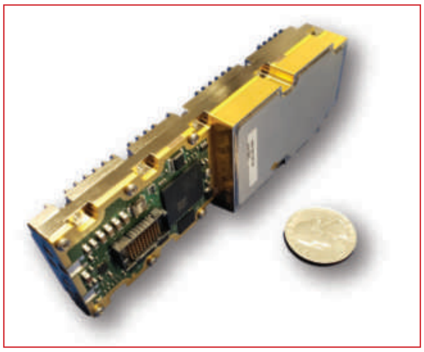

Fig. 2 The RFM3101 transceiver was designed to the OpenRFM form factor.

Fig. 3 RFM3101 microwave transceiver integrated with an IF digital processing module, clock generation module and an Intel® Xeon®-based processing module, all supplied by Mercury Systems.

level with testing and troubleshooting highly integrated microwave subassemblies to rapidly produce high quality hardware. To ensure compatibility with Mercury's IF processing technology and the OpenVPX standard, the final integration is performed by Mercury's mixed-signal technology group. Through the defined OpenRFM interface, each team applies its technical expertise with the confidence that all the pieces can be combined efficiently.

An additional benefit of the RFM3101 transceiver is its compliance to the OpenVPX (VITA 65) standard, which simplifies the process of integrating the module into a system with other OpenVPX products. Instead of spending significant resources developing custom interfaces, OpenVPX enables easy integration of the RFM3101 microwave front-end with a direct digitization IF processing module. For more complex applications, the concept is easily scaled to support multiple, coherent channels by adding additional modules, including Mercury's CLK3001 clock generation and distribution card (see ***Figure 3***).

This modular approach enables rapid system design through the use of commercial off-the-shelf (COTS) technology, and it also supports easy upgrades. This benefit is critical for the EW systems depending on broadband microwave transceivers. As advanced technology becomes available on the global stage, EW systems face new threats. To respond, next-generation EW systems must offer high performance while enabling modular upgrades with the latest technology. Through the adoption of an open architecture such as OpenVPX, EW systems can be updated quickly and at minimal cost. As the demands faced by next-generation EW systems continue to evolve, more system designers are turning to transceivers compliant with open architecture, like the RFM3101, which offer the flexibility and upgradability to support current system needs while preparing for the future.

Mercury Systems
Andover, Mass.
www.mrcy.com

6 to 18 GHz, 100 W TWT PA

Quarterwave's TWT amplifiers (TWTA) were developed to meet the demanding requirements for measuring radar cross-section and simulating target signatures, essential to the development of advanced radar and stealth technology. They have become the industry standard for reliable, stable and low noise TWTAs for determining radar parameters and generating signals for EW and training.

The model CCU50CW, part of the Compact Commercial Series, provides a minimum of 100 W CW peak power from 6 to 18 GHz, with no more than 0.1 dB power ripple. The spurious output is −55 dBc or better up to 250 Hz from the carrier and −60 dBc outside 250 Hz. The amplifier's gain range for achieving the rated output power is 39 to 63 dB, i.e., the input level can be as low as −13 dBm. For pulsed applications, the amplifier supports pulse widths down to 0.1 μs with the standard pulse repetition frequency (PRF) range up to 500 kHz, which can be optionally extended to 3 MHz. The high PRF and pulse fidelity of the CCU50CW differentiates it from competing power amplifiers, both TWT and solid-state.

An internal microprocessor monitors TWT operation and controls the power supply and modulator and protects from fault conditions. The microprocessor monitors TWTA voltages, currents and VSWR and handles faults caused by excessive temperature, pulse width, PRF and the access lid interlock. An RS-232 interface (Ethernet is an option) enables remote monitoring and control via PC, with Windows-compatible software provided. The TWTA can also be supplied with a touch screen interface.

The amplifier is cooled by forced air with an internal fan and can be bench or, optionally, rack mounted. The operating temperature range is 1°C to +50°C, derated to 10°C with increasing altitude, up to 10,000 ft.

VENDORVIEW

Quarterwave
Rohnert Park, Calif.
www.quarterwave.com

27 to 67 GHz Interconnect Solutions

MCV Microwave has developed a full line of high performance connectors, adapters and custom cable assemblies covering 27 to 67 GHz, with special interconnect solutions to 110 GHz. MCV's standard 50 and 75 Ω connectors and adapters include SMA, SMB, mini SMB, MCX, MMCX SMZ/BT43, 1.0/2.3, 1.6/5.6, 7.0/16.0, BNC, TNC and Types N, F and G. For precision and high frequency applications, the range of 50 Ω connectors and adapters comprise 1.0, 1.85, 2.4, 2.92 and 3.5 mm, as well as SSMA, SMA, AMPM, SMP TNC and Type N, covering the typical RF/microwave frequencies, including all the 4G and 5G bands. FAKRA automotive RF connectors and cable assemblies are available. Tight dimensional control and gold, nickel, silver or tri-metal plating assure the highest performance.

Using proprietary cable assembly techniques with selected cable types and high-quality connectors—most made in-house with some from suppliers—MCV offers both standard and custom RF cable assemblies to satisfy most all customer requirements. Standard RF cables include RG and LMR with shielding options, semi-rigid, conformable, corrugated low loss dielectric, low passive intermodulation (PIM), high-power and multi-port solutions including D38999. These test cable assemblies perform to 110 GHz and offer a flexible and hand-formable alternative to semi-rigid and semi-rigid cable with complex hand forming, achieving performance to support test and system jumpers with precision network analyzers and general lab use.

MCV's custom cables are built to precise electrical lengths for phase matching or delay line applications, such as missile seeker and phased array antennas. The delay between two cables is typically less than 2 ps, and a group of 20 cables will have phase matching within ±5 degrees. MCV's superior fabrication achieves typical VSWR less than 1.2:1 (return loss better than 20.8 dB) for cable assemblies with right-angle connectors and 1.15:1 (return loss better than 23.1 dB) for cable assemblies with straight connectors.

VENDORVIEW
MCV Microwave
San Diego, Calif.
www.mcv-microwave.com

IMS2019 Conference/ Special Sessions Overview

IMS2019 General Chairs' Welcome

Mark Gouker, MIT Lincoln Lab and Lawrence Kushner, Raytheon

Boston and the local Steering Committee welcome the microwave world to the 2019 International Microwave Week. This year's event takes place from Sunday, June 2 through Friday, June 7, and features the Radio Frequency Integrated Circuit (RFIC) Symposium, the International Microwave Symposium (IMS), the 5G Summit and the ARFTG Microwave Measurements Conference. The technical presentations and industry exhibits will be held at the Boston Convention and Exhibition Center (BCEC). The social and networking events and opportunities will take place throughout the revitalized Seaport District. This neighborhood, adjacent to the BCEC, has undergone a remarkable transformation since the 2009 IMS, and is now home to many museums, shops, restaurants and nightlife. The 2019 International Microwave Week will be memorable for years to come.

Boston Convention and Exhibition Center (Source: MCAA).

Boston has a rich microwave heritage that continues through today. The Radiation Laboratory, run by the Massachusetts Institute of Technology (MIT) during the 1940s, made seminal contributions to the emerging microwave engineering field. Much of this knowledge was transferred to surrounding industry and universities in the 1950s. More recently, the local IMS Steering Committees have taken particular pride in balancing the traditions of IMS with innovative twists and a focus on creating the best experience for the technical and industry exhibition attendees. This year's symposium continues this philosophy with new features that include:

- A significantly enhanced mobile app has been developed to accelerate the momentum to make this the primary interface to the International Microwave Week.

Planar Monolithics Industries, Inc.

Industry Leader in IF Log Video Amplifiers/SDLVAs

PMI offers a variety of IF Log Video Amplifiers/SDLVAs covering the DC to 4 GHz frequency range. PMI's IF Log Video Amplifiers/SDLVAs offer high dynamic range along with excellent temperature stability. Most IF Log Video Amplifiers/SDLVAs provide a limited IF output. PMI offers many standard models with various options that are available at: https://www.pmi-rf.com/categories/dlvas-erdlvas-sdlvas


DLVA-7M-80-SFF


DLVA-70M-80-12V


SDLVA-315M362M-65-CD-1


SDLVA-100M3G-70-MAH


SDLVA-0120-70-0225

PMI Model No.	Frequency Range (MHz)	TSS	Log Slope (mV/dB)	Dynamic Range Log (dBm)	Size (Inches) Connectors
DLVA-7M-80-SFF https://www.pmi-rf.com/product-details/dlva-7m-80-sff	5.5 - 8.5	-80 dBm	25	-70 to 0	2.2" x 1.5" x 0.55" SMA (F)
DLVA-70M-80-12V https://www.pmi-rf.com/product-details/dlva-70m-80-12v	50 - 90	-80 dBm	25	-80 to 0	3.51" x 1.5" x 0.47" SMA (F)
SDLVA-315M362M-65-CD-1 https://www.pmi-rf.com/product-details/sdlva-315m362m-65-cd-1	315 - 362	-80 dBm	50	-65 to 0	3.75" x 1.5" x 0.5" SMA (F)
SDLVA-100M3G-70-MAH https://www.pmi-rf.com/product-details/sdlva-100m3g-70-mah	100 - 3000	-70 dBm	10	-60 to +5	2.3" x 2.2" x 0.36" SMA (F)
SDLVA-0120-70-0225 https://www.pmi-rf.com/product-details/sdlva-0120-70-0225	200 - 2500	-65 dBm	25	-65 to +5	3.75" x 1.5" x 0.5" SMA (F)
GMDA-D1007 https://www.pmi-rf.com/product-details/gmda-d1007	500 - 2000	-65 dBm	25	-60 to +7	3.5" x 3.2" x 0.5" SMA (F)
HADA-D2001 https://www.pmi-rf.com/product-details/hada-d2001	500 - 2000	-44 dBm	50	-40 to 0	2.5" x 1.5" x 0.44" SMA (F)
SDLVA-0R5G4G-70dB-100R https://www.pmi-rf.com/product-details/sdlva-0r5g4g-70db-100r	500 - 4000	-73 dBm	25	-70 to 0	3.2" x 1.8" x 0.4" SMA (F)
SDLVA-0R71R3-75-CD-1 https://www.pmi-rf.com/product-details/sdlva-0r71r3-75-cd-1	700 - 1300	-70 dBm	40	-70 to +5	3.75" x 1.5" x 0.5" SMA (F)


GMDA-D1007


HADA-D2001


SDLVA-0R5G4G-70dB-100R


SDLVA-0R71R3-75-CD-1

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El Dorado Hills, CA 95762 USA
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- Filters & Switched Filter Banks
- Form, Fit, Functional Products & Services
- Frequency Discriminators & IFMs
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- Millimeter Wave Components (Up to 50 GHz)
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- Rack & Chassis Mount Products
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- SDLVAs, ERDLVAs & DLVAs
- Single Side Band Modulators
- SMT & QFN Products
- Switch Matrices
- Switched Filter Banks
- Switches – Solid State
- Systems - Radar Sense & Avoid
- Systems – Fly Eye Radars
- Threshold Detectors
- USB Products

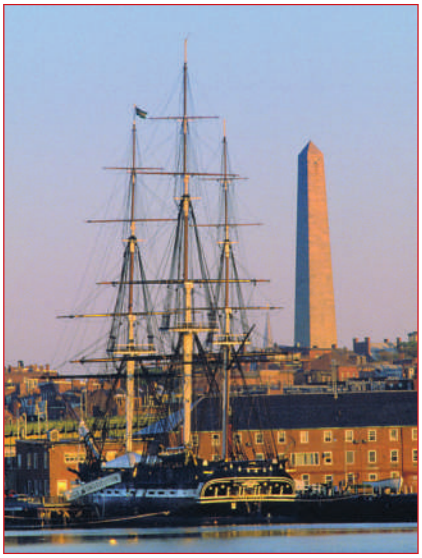
- Increased focus on startups and young professionals through the introduction of a Startup Pavilion in the Industry Exhibition along with an IP 101 information session, startup panel session and the Next Top Startup contest. Young professionals will have a lounge specifically to meet and exchange ideas and experiences.
- Introducing Sixty Second Presentations where interactive forum authors can prerecord an overview of their papers, allowing attendees to get a preview of the paper's content and target the papers of most interest to their work.
- Interactive panel sessions with real-time audience participation via the Slido App.
- Reduced cost for student attendees: by volunteering one day of service to the Symposium, they qualify for a $250 Superpass that allows attendance to all the conferences. The student rates for workshops are also reduced: $50 for half-day and $100 for full-day workshops.
- Sweet Treats Tuesday to welcome the attendees to the industry exhibit. Dessert items will be provided during the lunch break, encouraging everyone to come to the Exhibition Floor for a treat and begin interactions with the industry exhibitors.

The overall format of the International Microwave Week remains the same. The RFIC Symposium begins on Sunday with workshops and concludes Tuesday morning. The 5G Summit, once again co-sponsored by MTT-S and ComSoc, picks up on Tuesday afternoon and concludes that evening with a panel session. The IMS will run Sunday through Friday with the Industry Exhibition taking place Tuesday through Thursday. The ARFTG Microwave Measurements Conference will also begin on Sunday with jointly sponsored workshops on Sunday and Monday, and the technical sessions on Thursday and Friday. In all, there will be over 9,000 attendees from around the world participating in the technical sessions, workshops and the Industry Exhibition. There will be more than 600 exhibitors showcasing the latest developments in microwave hardware, software, components and systems.

IMS2019 will begin with workshops and short courses on Sunday and Monday. The opening plenary session will be held Monday evening featuring a presentation on "The Mind-Body Problem for Intelligent RF," by Dr. William Chappell, director of the Microsystems Technology Office at DARPA. This will be followed by the Welcome Reception at the Seaport World Trade Center. The IMS2019 technical sessions will run Tuesday through Thursday, with the closing session on Thursday afternoon featuring Dr. Dina Katabi from MIT describing her work at the intersection of wireless microwave systems and machine learning focused on biological applications. The closing celebration reception will be held immediately after. The Symposium will conclude with additional workshops held on Friday.

The Industry Exhibition is another center piece of the International Microwave Week and will take place on Tuesday through Thursday. In addition to Sweet Treats Tuesday, the Industry-hosted reception will be held Wednesday late afternoon. The Exhibition Floor will be home to the MicroApps Theater, the Societies' Pavilion and the new Startup Pavilion. The IMS schedule again will include exhibition-only time on Wednesday afternoon to ensure all attendees have an opportunity to interact with and learn about the latest products from the microwave industry exhibitors.

The evenings throughout the week will be filled with social and networking opportunities, both organized and informal, so that attendees can catch-up with colleagues from across the globe. The RFIC and IMS Plenary Sessions and Welcome Receptions will be held on their respective Sunday and Monday evenings. Tuesday evening will have the Young Professionals' social event and the Amateur Radio Social. Wednesday evening will have the Women in Microwaves (WiM) Reception and the Awards Banquet featuring Ryan Chin, CEO of Optimus Ride, as the guest speaker. Thursday evening will have the post-closing session celebration. In addition, there are dozens of restaurants and night spots within walking distance of the BCEC and the IMS hotels for informal and more private gatherings.



USS Constitution (Old Iron Sides) and Bunker Hill Monument (Source: MCAA).

Finally, no overview of IMS would be complete without an invitation to spend a few days in the host city before or after Microwave Week. Whether you stay in your hotel in the Seaport District or move into a hotel in Boston's Back Bay neighborhood to be more central to the sights, there is an amazing variety of things to see and do. Boston has a number of world-class museums, including the Museum of Fine Arts, the Isabella Stewart Gardner Museum, the Institute of Contemporary Art and the Museum of Science. There are many attractions centered on the American Revolutionary period, such as the Boston Tea Party Ships and Museum, Paul Revere House, the Old State House and the Freedom Trail. Boston is well known for its universities, and visiting the many campuses, each with its unique personality, is a great experience. If you visit MIT be sure to include a trip to the MIT Museum, known as the best research and innovation museum in Boston. No trip to Boston would be complete without a visit to Harvard and its Museum of Natu-

ral History. Here, the world-famous glass flowers—the Ware Collection of Blaschka Glass Models of Plants—will delight and amaze you. For the sports fans, visit the Boston Sports Museums in TD Garden, take a tour of Fenway Park or watch the Red Sox vs. Tampa Bay Rays. Mostly, take time to get to know some of Boston's neighborhoods. From Harvard Square, the North End, to the Seaport District, the city's varied personalities and charm will leave a lasting impression.

IMS2019 Focus Sessions

Anton Geiler, Metamagnetics

The IEEE MTT-S IMS2019 will offer a number of Focus Sessions in addition to the regular technical sessions. Focus Sessions highlight emerging new technical topics that are gaining importance and are of high interest to the RF and microwave community. These sessions encompass a wide range of topics and may either involve a specific emerging technology or cover several technologies that are relevant to a common application. The following Focus Sessions are being developed for IMS2019:

- **Emerging mmWave Transistor Technologies with Extreme Linearity and Efficiency for 5G and DoD Applications:** This focus session will cover some of the emerging mmWave transistor technologies that have shown promise to match or surpass state-of-the-art power-added efficiency (PAE) and linearity beyond "10 dB" rule of thumb in linearity/Pdc ratio. These technologies hold significant potential for 5G wireless communications and DoD RF systems in the mmWave regime.
- **Microwaves in Quantum Computing:** This focus session will address various aspects of microwave qubits for quantum computing and associated challenges including 3D RF signaling, parametric amplification and cryogenic microwave circuits. It will highlight the links between the rapidly growing field of quantum computing and microwave field theory and techniques and how those can be leveraged to achieve the vision of "quantum supremacy."
- **Next-Generation Acoustic Technologies for 5G:** This focus session examines the challenges our community faces in addressing the requirements of wider bandwidths and higher carrier frequencies for 5G wireless communications, in particular in power amplifiers and filters. Despite the rapid advances in surface acoustic wave (SAW) and bulk acoustic wave (BAW) technologies, keeping up with the changes in wireless standards is proving challenging. In addition to high frequencies of operation and wideband filters, other 5G enabler technologies such as carrier aggregation and MIMO will be addressed in this focus session.
- **Thermoacoustic Imaging—Listening to the Sound of RF and Microwave:** This focus session delves into the interactions of RF/microwave waves and ultrasound to achieve deep spectroscopic contrast with high resolution in deep biological tissues. Important advances in thermoacoustic imaging, including magnetically mediated imaging using magnetic coils,


Lawn on D (Source: MCAA).

spectroscopic imaging and communication in water, ultra-high resolution imaging with impulse microwave excitation, as well as X-ray and electric field induced imaging will be reviewed. By bridging the two different worlds of ultrasonic detection and thermoelastic wave induction and propagation, thermoacoustic imaging is pushing the limits in the boundary of interdisciplinary domains.

2019 RFIC Symposium

Stefano Pellerano, Intel; Waleed Khalil, The Ohio State University; and Brian Floyd, North Carolina State University

The 2019 IEEE Radio Frequency Integrated Circuits Symposium (RFIC) will be held in Boston from Sunday, June 2 to Tuesday, June 4. The RFIC Symposium is the premier integrated circuit (IC) design conference focused exclusively on the latest advances in RF, microwave and mmWave IC technologies and designs, as well as innovations in high frequency analog/mixed-signal ICs. For 2019, the conference will also extend its focus to emerging circuit technologies related to RFIC, such as RF circuits and systems incorporating MEMS sensors and actuators, heterogeneous and 3D ICs, silicon photonics, quantum computing ICs, hardware security and machine learning applications, wearable and implantable systems, biomedical applications and autonomous systems like automotive and drones. We cordially invite you to participate in this international symposium.

For 2019, RFIC is promoting a new educational experience for the attendees: a "Technical Lecture" comprising a one and a half hour interactive short course delivered by a distinguished speaker during lunchtime on Sunday, between the AM and PM workshop sessions. For 2019, Prof. Ali Niknejad from University of California, Berkeley, will teach "Fundamentals of mmWave IC Design in CMOS." Do not forget to register in advance since we expect a very high attendance and seats will be limited to the first 250 participants.

To encourage student attendance, IMS2019 is offering deep registration discounts and numerous benefits for student volunteers who are IEEE members and willing to help with conference activities. For more details, visit https://ims-ieee.org/students-main/student-volunteers.

The 2019 RFIC Symposium will begin on Sunday with 12 RFIC-focused workshops (11 full-day and one half-day) and one technical lecture. In addition, there will be several joint RFIC/IMS workshops on Sunday and Monday. These workshops cover a wide range of advanced topics in RFIC technology and IC design, including power amplifiers, 5G systems, silicon photonics, quantum computing and hardware security.

Following the full day of Sunday workshops, the RFIC Plenary Session will be held in the evening beginning with conference highlights, the presentation of the Student Paper Awards and the Industry Best Paper Award.

The 2019 RFIC Plenary Session will conclude with two visionary plenary talks:

- Dr. Greg Henderson, senior vice president, Automotive, Communications and Aerospace/Defense at Analog Devices, will outline "The Digital Future of RFICs," describing how digitally-assisted-and-enabled RFICs are enabling the future of wireless sensing and communications with real world examples for applications like 5G and automotive radar.
- Dr. Ir. Michael Peeters, program director, Connectivity and Humanized Technology at imec, will address the question "Do the networks of the future care about the materials of the past?" and take a look at how the latest requirements for RFIC circuit design, new network capacity, reliability and latency can drive technology choices for the next 10 years.

Immediately after the plenary session, the RFIC reception will follow, with highlights from our in-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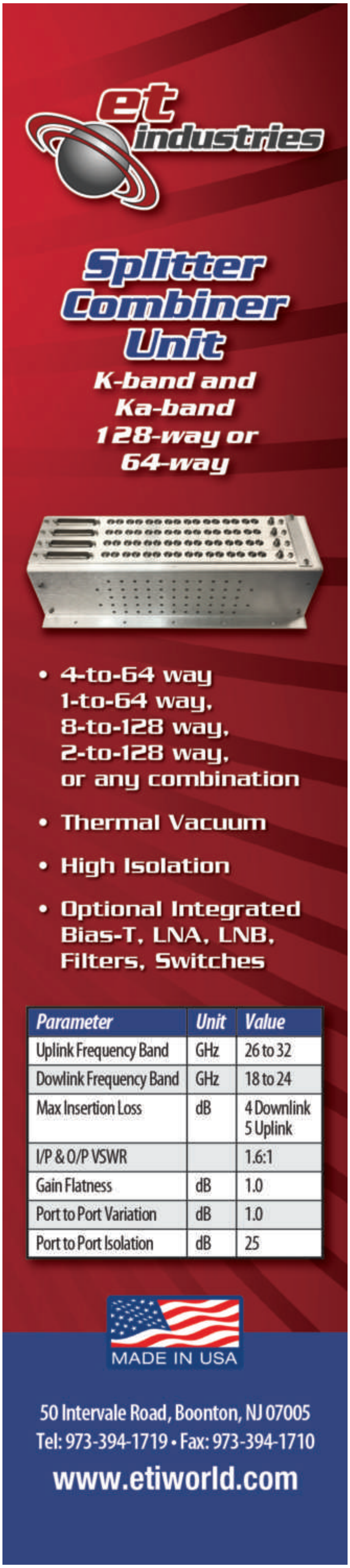

Boston Harbor (Source: MCAA).

dustry showcase and student paper finalists in an engaging social and technical evening event supported by the RFIC Symposium corporate sponsors.

On Monday and Tuesday, the RFIC Symposium will have multiple tracks of oral technical paper sessions. The 5G Summit technical sessions on Tuesday afternoon will provide high-level 5G overview presentations that will complement the 5G-focused RFIC technical sessions on Tuesday morning. Two enlightening panels will be featured during lunchtime on both days. The Monday panel session titled “The Internet of Things (IoT) – Back to the Future, or No Future?” will feature experts from the industry and academia pondering on how the future IoT market will be affected by the accelerated introduction of 5G and the developments in “big data” and artificial intelligence (AI). The Tuesday joint panel session with IMS2019 is titled “Will Artificial Intelligence (AI) and Machine Learning (ML) Take Away My Job as an RF/Analog Designer?” and our distinguished panelists from the academia, CAD/EDA and RF industries will debate on what we may expect to see in the future and how we should prepare ourselves for the inevitable realities. Please make sure to bring your engaging opinions and questions to both panel sessions.

ARFTG at Microwave Week

Ron Ginley, NIST

ARFTG covers anything related to RF/microwave and mmWave measurements. Originally ARFTG was a user’s forum for the early vector network analyzers (VNA). It has grown to encompass all aspects of precision microwave measurements. The most important part of the ARFTG experience is the opportunity to interact one-on-one with colleagues, experts and suppliers of the RF and microwave test and measurement community. Interesting topics include high-throughput production or one-of-a-kind metrology measurements, complex systems or simple circuit modeling, small-signal S-parameter or large-signal nonlinear measurements, phase noise or noise figure, DC or lightwave—there is something for everyone.

There is always ample opportunity at ARFTG conferences for detailed technical discussions with others facing similar test & measurement challenges. ARFTG also hosts a supplier exhibit focused on the measurement industry in a more relaxed setting. Given the informal and friendly atmosphere, members of ARFTG often find these interactions are their best source of ideas and information for their current projects.

There are several ways you can interact with ARFTG people at the International Microwave Week. ARFTG co-sponsors two workshops


Zakim Bridge (Source: MCAA).

during the Week. For IMS2019, these workshops will take place on Monday and are titled "Measurement Challenges in Over-The-Air (OTA) Testing" and "Measurement and Design Techniques for Next-Generation Communication Systems." ARFTG hosts a couple of user forums that are open to all. For IMS2019, there will be a Nonlinear Vector Network Analyzer Users' Forum that discusses the latest techniques and theories for nonlinear measurements and an On-Wafer Users' Forum which deals with issues related to high frequency on-wafer measurement techniques and theory. Finally, there is the main one-day ARFTG conference, where oral technical sessions are done in a single-track format. There are extended breaks that combine exhibits and an interactive forum to aid networking with vendors and among colleagues. All of these activities are great ways to learn about microwave measurements and interact with others in the field.

If you have interest in measurements from 1 kHz to 1 THz and beyond, be sure to add the ARFTG 2019 Conference to your plans in Boston this June. You will find our atmosphere informal and friendly, which enhances interactions and provides opportunities for you to learn new ideas and to discuss your own ideas with colleagues.

5G Summit Highlights Recent Microwave Hardware Developments

Andrew Zai, Raytheon

The 5G Summit is a special co-organized event between IEEE ComSoc and MTT-S that will be open to all IEEE, IMS and RFIC attendees for a nominal cost. It consists of a half-day of invited talks from industry speakers, as well as an evening panel session. The Summit is strategically scheduled to occur on the afternoon of Tuesday, June 4. It begins immediately following the lunchtime RFIC panel session, so that there is no overlap with the RFIC conference and the IMS2019 5G sessions taking place on Wednesday morning. Any attendee who wants to drink from the 5G firehose with viewpoints from MTT-S, RFIC and ComSoc can regis-


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T40/T50 Series
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High Reliability
& Accuracy
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ter for sessions spanning Sunday through Wednesday.

The 5G Summit has invited speakers from Qualcomm, Analog Devices, MACOM, Anokiwave, China Mobile and PHAZR. Qualcomm will talk about how 5G New Radio (NR) incorporates mmWave and massive MIMO to increase user experience. Analog Devices will educate attendees on the challenges and the evolution of technologies to address them, enabling the future bits-to-beams mmWave radios. MACOM will speak about the active work occurring in sub-6 GHz array development, and the associated challenges. Anokiwave will be discussing development efforts in mmWave phased arrays. China Mobile will give insight into how the interna-


Paul Revere Statue (Source: MCAA).

tional community is leading and participating in the development of 5G technology. Finally, PHAZR, recently acquired by JMA Wireless, will tell attendees about the cutting edge 5G innovations coming out of the startup community.

In addition to the invited speakers, the Summit will continue the popular 5G demos launched at IMS2018. This demonstration format complements the 5G lectures to show the latest hardware and software utilized in the real world to address 5G related design and measurement techniques. Take advantage of this informal and interactive learning opportunity by attending the 5G demos at IMS2019.

In a field moving this quickly, participating in events like this is the only way to stay informed. Be sure to register or buy a Superpass, as it is the best way to learn the latest in microwave development for 5G. As a bonus, the event will be holding a panel session during our industry-sponsored cocktail hour, comprised of our speakers and other invited panelists. Together they will help to answer the question, "How can we make 5G commercially viable?"

All of the chairs of the IMS2019 conferences welcome everyone to Boston for the International Microwave Week activities.■

IMS2019 Young Professionals and Women In Microwaves

Young Professionals: Competitive with the Pace of Innovation

Ryan Lagoy, Starry and
Janet Nguyen, Lockheed Martin

Famous for innovative startups, prominent university labs and most importantly as a pioneer of modern microwave engineering, Boston is an exceptional place for Young Professionals (YP) to network with one another and enjoy the unique culture that we have to boast. This year, the 2019 IEEE International Microwave Symposium (IMS) Steering Committee is focusing on providing engaging places and events for YP to feel inspired and learn valuable lessons from a diverse group of highly accomplished individuals in the field of microwaves. Aligned with the innovative culture of Boston, the overarching theme of our YP events is how to stay inventive and competitive in a world where technology is so rapidly evolving around us.

Coppersmith Restaurant and Bar.

To spark this conversation, an informal panel session will be held at the start of the conference where attendees can speak directly with carefully selected individuals who have made significant impacts with their careers. The panelists have unique backgrounds and include a technical director at a disruptive mmWave startup, an engineering manager at a large well-known social media company, a prominent professor and a DARPA program manager who is also the lead developer of software-defined radio (SDR) framework widely used today. Our panelists encompass high achievers in hardware and software, leadership, academia, government, industry and startups. The panel discussion will not be held in the typical "classroom" setting, but rather in a more open forum space, encouraging real opportunities for connection.

Immediately after the panel discussion, the YP will head off down the street to a recep-

tion at Coppersmith. Coppersmith is a popular restaurant and bar where everyone can unwind and continue conversations with our panelists and network with other attendees. Because IMS is a one-of-a-kind opportunity where people of diverse backgrounds have access to each other, the Steering Committee is committed to making this event accessible to everyone, so it will be held later in the day and is open to all.

New to IMS2019 is a lounge area dedicated specifically to YPs. The spacious YP Lounge, situated with views of Boston's Seaport District, will be open for the entire duration of the conference, and it will be the place to go to find attendees meeting over a lawn game, discussing a technical paper at one of the high-top tables or just finding a comfortable spot to relax or catch up on emails.

With these exceptional panelists and variety of exciting events planned, the Steering Committee is "wicked" excited to welcome YPs from around the world to meet and experience what Boston and IMS have to offer in the field of microwave engineering.

YP Lounge
Tuesday-Thursday, June 4-6

YP Panel
YP Lounge, Tuesday, June 4, 5:30-7:00

YP Reception
Coppersmith, Tuesday, June 4, 7:00-9:00

Challenges Still Facing Women in Microwaves

Janet Nguyen, Lockheed Martin and Erin Bernay, Raytheon

It is 2019, and you may be asking yourself, why does there need to be a specific "women's" category of events at IMS? According to research by the Society of Women Engineers, only 30 percent of women who earned bachelor's degrees in engineering still work in engineering 20 years later. Of the women who leave the engineering profession, 30 percent cite "organization climate" as their reason for leaving.

While some of us are fortunate enough to find mentors or others to help us navigate these struggles, it is highly dependent on individual personalities and situations, and is something that is still inconsistent throughout the industry. Having an event at a conference such as IMS is a great opportunity to allow people facing these challenges to realize they are not alone, get advice from a panel of highly accomplished individuals who can relate, help open the eyes of those who may not understand the magnitude of the issues and jump-start progress in fixing the problem from multiple angles.

Significant advancements have been made in the opportunities available to women in STEM, but women continue to endure unique, daunting challenges in a career field that is dominated by men. Along with extremely talented pioneering women, men have also played a pivotal role in the strides towards gender equality in STEM. For progress to happen, those in positions of authority and power need to be a part of the solution. Women and minorities need to communicate the realities of their challenges so that those who want to help can understand the situation and can work together for positive change. The Women in Microwaves (WiM) session is an opportunity for this communication and collaboration.

With the belief that we can all make a difference in building a better future for ourselves and each other, this year's WiM panel will focus on the topic of "Challenges still facing women in microwaves and how you can help." Please join us Wednesday, June 5 from 16:00 to 17:00 at the BCEC in Room 162A/B (check schedule on site in case there are changes). The panel consists of exceptional women who work in different aspects of STEM, have made their mark in the field and continue to inspire and mentor those around them. The discussion will fearlessly and honestly address the reasons we still need a special event like this, despite the progress that has been made for equality. Breaking down the barriers that systemically limit and disproportionately affect women can only improve the future of the field of microwaves. We hope all IMS2019 attendees—men, women and high school students—attend and participate in this panel session, and then continue the conversation afterwards at our reception at the beautiful Boston Lookout Rooftop Bar at the Envoy Hotel (18:00 to 21:00). We hope to have spirited and informative discussions that will inspire everyone to take the messages and lessons into their lives and make an even brighter future for all those who work in STEM.■


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IMS2019 Exhibition Overview

IMS2019 Exhibition

Pat Hindle,
Microwave Journal *Editor*

The annual IMS2019 Exhibition is the commercial focus of the International Microwave Symposium (IMS) 2019 taking place Tuesday, June 4 through Thursday, June 6 at the Boston Convention and Exhibition Center. The Exhibition consists of over 600 exhibiting companies who represent the state-of-the-art when it comes to materials, devices, components and subsystems, as well as design and simulation software and test & measurement equipment. It is the best place to find out about new products and services being offered in the RF/microwave industry. It is also the best place to network with industry experts to find out answers to your design, simulation and test & measurement challenges.

EXHIBITION DATES AND HOURS

Tuesday, June 4	9:30 to 17:00
Wednesday, June 5	9:30 to 17:00
Industry Hosted Reception	17:00 to 18:00
Thursday, June 6	9:30 to 15:00

The Exhibition also includes MicroApps and Exhibitor Workshops presented by IMS2019 exhibitors addressing new products, processes and applications of interest to the microwave community. There will be more than 65 15-minute presentations given by representatives of companies from around the world as part of the MicroApps program. The presenters are typically application engineers who work for companies that can solve the technical challenges you experience in your daily work. After the show, you can download all the presentations using the link you will receive at the MicroApp Theater.

The Industry Workshops are two-hours each in duration, with one or more presentations. They are awarded to a single company or group of companies to discuss a specific technical topic in much greater depth than the MicroApps seminars, possibly with live demonstrations and attendee participation. The Industry Workshops are held in a classroom setting, and are open to all registered IMS2019 attendees.

Microwave Journal is a proud sponsor of MicroApps and the press lounge located in Room 104AB of the Boston Convention and Exhibition Center. As a service to IMS2019 press attendees and exhibitors, IMS will provide a media interview room adjacent to the press lounge. We hope that everyone will attend IMS2019 in *Microwave Journal*'s headquarters' hometown of Boston.

New Startup Pavilion: Startups and Corporations Collaborate

Ryan Lagoy, Starry and Janet Nguyen, Lockheed Martin

New to IMS2019, the Boston Steering Committee is hosting the Startup Pavilion—a stand-out Exhibition floor space dedicated specifically for startup company booths. A series of events will also be held during the course of the week that embodies the excitement and passion startups are known for. With the rise of many successful startups, students, professionals and even large companies have shown interest in the unique contributions these companies have to offer. Since Boston is the hub for innovative, young companies and prominent entrepreneurs, IMS2019 is the perfect opportunity for the Steering Committee to kick off this new component of IMS.

The Startup Pavilion is centered around an exclusive space on the Exhibition floor for young companies to promote their products and technology through interactive demonstrations and open conversations with conference attendees, including other exhibitors. The Startup Pavilion is strategically located next to the popular and highly visible MicroApps Theater to ensure large crowds while the Exhibition floor is open. There will also be an Introduction to Intellectual Property (IP) talk given by patent agent Michele Moresco, Ph.D., including common misconceptions and best practices. He will address questions such as: What rights does a patent provide? When should I file a patent applic-tion? Can a patent be obtained worldwide?


BCEC Exhibition Floor (Source: MCAA).

In addition to the physical Pavilion booth space, there will be two startup-themed events that will be held in the afternoons at the adjacent MicroApps Theater: a panel session and mini startup pitching competition. The panel and Q&A session consists of carefully selected panelists who will discuss the mutual benefits of collaboration between large corporations and startup companies. The panel session is formatted to encourage dialogue with the audience, so please be ready to share your burning questions. Panelists will include representatives from Techstars Boston, Starry, BAE Systems and the government.

Finally, a one-hour mini startup competition, "The Next Top Startup," will be held, where small companies, students and even creative individuals can pitch their ideas to judges for prizes and fame in front of the MicroApps Theater audience. The judges are from all areas of the startup ecosystem, including investment firms, tech startup incubators and experts in RF technologies, including Cliff Hirsch from Pinestream Consulting, Jacques Benkoski from US Venture Partners and Craig Mullett from Branison Group LLC. The judges will provide valuable feedback from their wealth of experience, and the participants will get the opportunity to show off their products and ideas to Exhibition attendees. The startups will compete for various prizes and the title of "Best Startup of IMS2019."■

Startup Panel
MicroApps Theater, Tuesday, June 4, 3:45-5:00 p.m.

Startup Pitch
MicroApps Theater, Wednesday, June 5, 4:30-6:00 p.m.

IP101
YP Lounge, Thursday, June 6, 1:00-2:00 p.m.


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MASSACHUSETTS AV.
DARTMOUTH ST.
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Boston Public Garden
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Hynes Convention Center
TURNPIKE
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HUNTINGTON AV.
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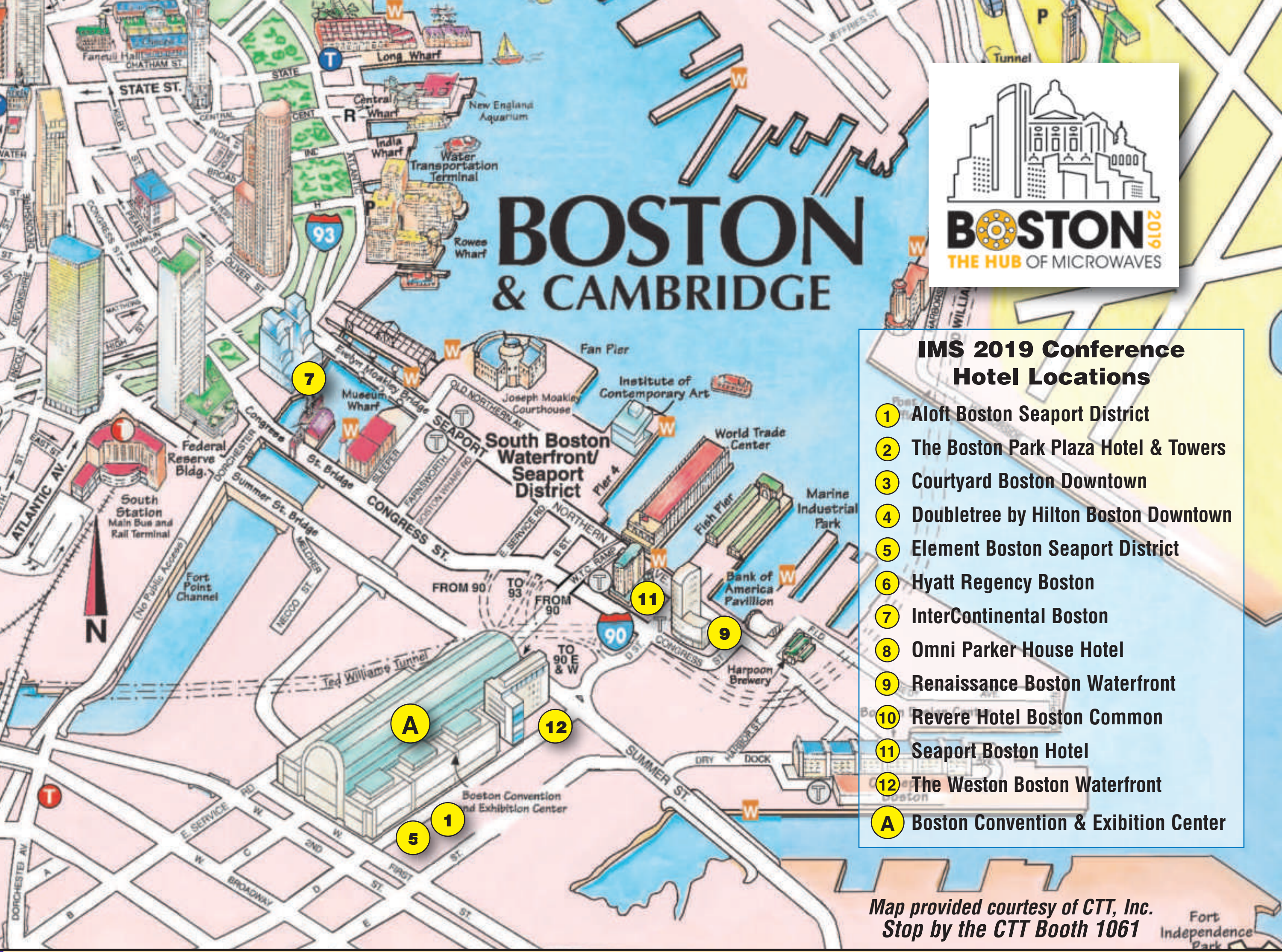

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EXHIBITOR LIST IMS2019

To access booth numbers, please visit www.ims2019.org
The following exhibitors are accurate as of 3/12/19.
Exhibitors in **BLUE** have an ad in this issue.

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3G Shielding Specialties
3RWAVE
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A.T. Wall Company
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ALPHA-RLH
Altair Engineering, Inc.
Altum RF
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American Standard Circuits, Inc.
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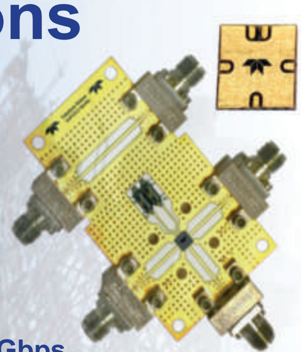
VIDA Products, Inc.
Viking Tech America Corp.
Viking Technology/Sanmina
Viper RF Limited
Virginia Diodes Inc.
Vishay Intertechnology, Inc.
W. L. Gore & Associates, Inc.
Waka Manufacturing Co., Ltd.
Wave Mechanics Pvt. Ltd
WAVEPIA Co., Ltd.
Wavetek Microelectronics Corporation
Wavice Inc.
weasic Microelectronics SA
Weinschel Associates
Wenzel Associates Inc.
Werlatone Inc.
West Bond Inc.
WEVERCOMM Co., Ltd.
Wiley
Wilkes University
WIN Semiconductors Corp.
Winchester Interconnect
WIPL-D
Wireless Telecom Group
Withwave Co., Ltd.
Wolfspeed, A Cree Company
Xi'an HengDa Microwave Technology Development Co., Ltd.
XIAN PRECISIONRF ELECTRONICS CO., LTD.
Xilinx
XMA Corporation
X-Microwave
Xpeedic Technology, Inc.
Yach.com
Yokowo Co., Ltd.
Z-Communications, Inc.
Zhejiang Jiakang Electronics Co., Ltd.
Zhejiang Wazam New Materials Co., Ltd.
Zhongjiang Lijang Electronics Company Ltd.
Zik, Inc.

The Leader in Switching Solutions

Everywhereyoulook™ Teledyne Relays provides high-bandwidth switching solutions for automated test equipment, telecommunications, signal processing, test & measurement instruments, and medical devices.
In addition to RF Electromechanical Relays and Coaxial Switches, the new InP1012-60 Active RF Switch provides DC-60 GHz bandwidth in a rugged compact package.



Signal Integrity Beyond 40 Gbps
DC- 60 GHz Bandwidth
Reflective SPDT Active RF Switch
3mm x 3mm x 1mm Package
- 65°C to +125°C Operating Temp
100 krads Radiation Tolerance

InP1012-60

MICROWAVE COAXIAL SWITCHES

- DC to 40 GHz
- SPDT, Transfer, Multi-Throw
- SP3T-SP10T
- Low PIM Switching
- 5M Cycle-life
- Custom products
- 50GHz SPDT Comming Soon!

ELECTROMECHANICAL RELAYS

- 40 Gbps Signal Integrity, DC-18GHz Bandwidth
- Loopback Relays with bypass path for ATE Applications
- SPDT, DPDT, 4PST Configurations
- Magnetic Latching and Failsafe Options

RF SWITCH MATRIX

- Multiple Standard and Custom configurations
- Failsafe, Latching, or Normally Open Configurations
- Integration with Filters, Attenuators, Splitters, Dividers, etc.

MINIATURE SWITCH MATRIX

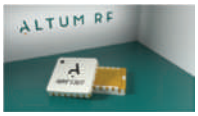
- DC-18GHz, 26.5 GHz, or 40 GHz options
- USB/Ethernet Mini-Switch Modules
- SPDT, Multi-throw, and Transfer switch options
- Multiple RF Connectors Available
- USB/Ethernet Controllable
- Off-The-Shelf Product, Short Lead Times

Come see us at Booth #1124

TELEDYNE RELAYS Everywhereyoulook™

TELEDYNE COAX SWITCHES Everywhereyoulook™

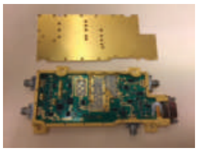
Altum RF
GaN Distributed Amplifier



Altum RF's ARF1307 is a packaged, GaN distributed amplifier for 2 to 20 GHz applications. The amplifier provides 25 dB small-signal gain, 10 W saturated output power with 16 dB of power gain and 25% power-added efficiency. The ARF1307 features a robust, lead-free and RoHS-compliant 7 × 7 mm ceramic QFN package with excellent thermal and electrical properties. The ARF1307 is suitable for higher performance commercial and defense related applications, such as test & measurement equipment, EW and commercial or defense radar systems.

www.altumrf.com

American Microwave Corp.
Baseband Amplifier



The baseband amplifier used in the ALR-85 radar warning receiver system is a form, fit, function replacement for a baseband module with two RF inputs P1 (direct input), P2 (with pre-amp), bandpass filtering on the inputs and covering 2 to 6 GHz frequency range with build-in digitally controlled attenuator (31 dB gain control). It has dual output P3 (for RF processing) and P4 (input to a DLVA which AMC also supplies). The baseband module and DLVA are form fit function replacement within Litton EW receivers.

www.americanmic.com

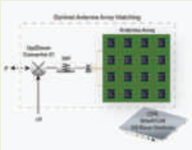
Amplical
Absorptive PIN Diode Switch

Amplical's SW2A101 SP2T 0.1 to 20 GHz miniature ultra-broadband absorptive PIN diode switch features 2 W CW hot-switching with low insertion loss, low VSWR, high isolation and fast switching speed. J1 and J2 ports are terminated in 50 Ω when switched in the isolation (off) state. All RF ports incorporate DC blocks. An on-board TTL-compatible driver provides convenient logic control. The compact design incorporates field replaceable SMA female connectors which can be removed. Applications include bypass switches used in communications, radar and EW systems, as well as test equipment and simulators.

www.amplical.com

Anokiwave, Inc.
Optimal Array Matching

VENDORVIEW



Anokiwave leads the mmWave market with its silicon based ICs for 5G, SATCOM and radar applications for high volume commercial deployments. Their latest 5G-Gen-3 IC family features complete RF signal chain functionality, supports dual pol architectures with new and enhanced features to make 3GPP compliant cutting-edge performance even easier. Their portfolio of IC options enables optimal array matching for powerful and efficient antennas for multiple use cases.

24/26 GHz Gen-3 5G IC

The 24/26 GHz 5G band is here. The newest IC in the 24/26 GHz family covers the 3GPP n258 (24.25 to 27.5 GHz) band and can operate as a dual polarization four channel beamformer IC or as a single polarization eight channel beamformer IC. With low-cost materials, embedded ZERO-CAL™, fast beam steering and KINETIC-GREEN™ technologies, field health monitors, as well as the continued drive to higher power efficiency, this IC will have a pronounced effect on making ubiquitous 5G a reality.

28 GHz Gen-3 5G IC

The newest IC in the 28 GHz family covers the 3GPP n257 and n261 (26.5 to 28.35 GHz) bands. The AWMF-0151 supports dual polarization architectures while adding new and enhanced features to make 3GPP compliant cutting-edge performance even easier. The system architecture behind the family allows multiple use cases ranging from infrastructure to consumer equipment. By harnessing the highest levels of integration, the company has enabled base stations and small cells to reach price points on par with Wi-Fi access points.

37/39 GHz Gen-3 5G IC

The newest IC in the 37/39 GHz family covers the 3GPP n260 (37 to 40 GHz) band. The AWMF-0158 supports dual polarization architectures while adding new and enhanced features to make 3GPP compliant cutting-edge performance even easier. The system architecture behind the family allows multiple use cases ranging from infrastructure to consumer equipment. With over five years of focused innovation, three generations of ICs and significant quantities of 5G ICs delivered, Anokiwave is making mmWave 5G a commercial reality.

K/Ka-Band SATCOM IC Family

The 2nd generation K/Ka-Band SATCOM beamformer IC family enables active antenna SATCOM ground terminals that can auto-align and auto-position supporting SATCOM-on-the-move using LEO/MEO/GEO satellites. The highly integrated AWMF-0132 K-Band Rx IC and the AWMF-0133 Ka-Band Tx IC both support four dual polarization radiating elements with full polarization flexibility. The IC family builds on their prior generations improving performance, reducing cost and providing a host of digital functionality that simplifies active antenna design. Look for a new family at Ku-Band soon.

www.anokiwave.com

Anritsu
Vector Network Analyzers

VENDORVIEW

Anritsu (Booth 542) continues to lead the way with its innovative, high performance vector network analyzer (VNA) solutions. The VectorStar™ MS4640B and ME7838 premium and broadband VNA series offers the broadest coverage to 145 GHz in a single instrument. The ShockLine™ family of VNAs provides best-in-class performance while optimizing cost-of-test with its 1-, 2- and 4-port options that offer frequency coverage to 43.5 GHz (55 to 92 GHz extended E-Band).

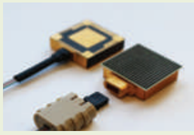
www.anritsu.com/test-measurement

For booth numbers, please visit www.ims2019.org.

API Weinschel
Programmable Attenuators

API Weinschel's 4209 Series Programmable Attenuators are available in 31.5 and 63 dB attenuation ranges with 0.5 dB step resolution. The 4209 series has a superior RF performance to 43.5 GHz with an extremely low insertion loss and VSWR over the entire frequency range. The units are supplied with an AUX connector for operation in I2C, SPI, UART or TTL compatible modes. Also included is API's LabView based USB Control Center Software.

Micro-Optical Transceiver



The new OPTO-FIRE™ micro-optical transceiver from API Technologies enables the improvement of critical data communication systems in airborne, naval and renewable energy applications. With a range of high speed data rates (20 Mbs to 25 Gbs), multiple-channels and protocol agnostic architecture, the OPTO-FIRE™ micro-optical transceivers are specifically designed for harsh environment applications. OPTO-FIRE™ is a major change in optical core technology which enables significant size and weight reductions. Available in customized rugged packaging styles to withstand harsh −58°F to +212°F operating temperature requirements.
www.apitech.com

AR RF/Microwave Instrumentation
Microwave Power Amplifiers

VENDORVIEW

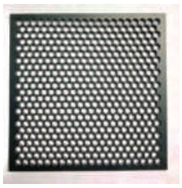
AR offers solid-state power amplifiers designed for various EW, EMC and communications applications. You can have chip and wire hybrid modules from 0.7 to 6 GHz to 100 W or benchtops designs up to 500 W CW. Benchtop units from 6 to 18 GHz are also available in 20 and 40 W CW Class A models. For added versatility, AR can supply dual band single housed units covering the full 1 to 18 GHz band with a high-power of 60 W up to 6 GHz and 40 W from 6 to 18 GHz.
www.arworld.us/html/12200_microwave_amplifier.asp

Arance Electronics
1 mm Connector Cable Assembly

Arance's self-developed 1 mm connector cable assembly can operate up to 110 GHz. Phase and amplitude stable, good flexibility, lighter weight. Reliable in connection and

testing applications. Length and armor can be customized according to a customer's requirement.
www.arance-rf.com

ARC Technologies
Thermoplastic Vent Material



ARC Technologies, a Hexcel company, presents their patented Thermoplastic Vent Material. These vents are designed to reduce radiated emissions at higher frequencies, through dielectric loss, than traditional metal vents allow. Through the use of absorptive materials, their patented vent technology reduces emissions while maintaining ample airflow for heat dissipation. Come visit ARC Technologies LLC at IMS2019 in Booth 130 to learn more.
www.arc-tech.com

Besser Associates, Inc.
RF Technology Certification

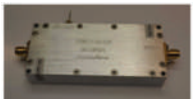
RF Technology Certification is an online course designed for professionals who need a solid background in the fundamentals of RF and wireless technology and products. The four-part program provides the student with a thorough understanding of RF analytical tools, communication signals, RF devices and test instruments. The program was developed by Besser Associates, a worldwide leader in RF and wireless training.
www.besserassociates.com

Cadence Design Systems
Integrated IC/Package/Module Design Flow

The new Cadence® Virtuoso® RF Solution increases productivity and eliminates design failures caused by poorly integrated tools. It streamlines the RF design flow by using a single "golden" schematic to drive layout implementation, simulation and physical verification of the RF module while enabling simultaneous editing of multiple RFIC on the complex RF module. The environment also includes smart integration of electromagnetic (EM) analysis tools that automates hours of manual work required to run EM simulations. Visit Cadence at Booth 942.
www.cadence.com

Cernex Inc.
Active Frequency Multipliers

VENDORVIEW



Cernexwave's (Booth 508) CFM series active frequency multipliers cover the frequency range of 10 MHz to 500 GHz. They can be designed to multiply an RF signal 2, 3, 4 or as many as 36 times with the company's custom multiplier chain assemblies. These multipliers utilize state of the art MIC and MMIC technologies to provide highly stable, reliable and efficient frequency extenders for system applications.
www.cernex.com

Charter Engineering Inc.
5G RF Switches from DC to 40 GHz

CEI introduces a new series of RF switches operating from DC to 40 GHz utilizing 2.92 mm female connectors. The switches feature outstanding characteristics in insertion loss of 0.6 dB max and return loss of 1.5:1 max. The highly repeatable RF switches are targeted to 5G applications and are available in a variety of configurations including failsafe, latching and normally open.
www.ceiswitches.com

Ciao Wireless
Highly Integrated Amplifiers

Ciao Wireless (Booth 736) features a line of highly integrated amplifiers for SATCOM and military/defense. Model CA0022-351560ADTCS exemplifies this product line with instantaneous frequency coverage from 10 MHz to 22 GHz, 35 dB gain, +15 dBm P1 dB PT, low noise figure and includes temp comp, voltage variable gain attenuation (15 dB), integrated wideband output coupler and detected output with 10 dB min dynamic range and settling speed of 50 µs. Proven fielded reliability.
www.ciaowireless.com

Cobham Advanced Electronic Solutions
SPST Through SP6T and Transfer Switches

VENDORVIEW

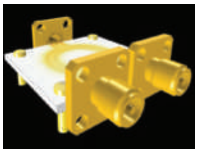
Cobham Advanced Electronic Solutions offers thousands of standard high performance SPST through SP6T and Transfer Switches. Spanning a frequency range of 10 MHz to 18 GHz, the S-Series PIN diode switches are available with absorptive or reflective input ports and characterized by

low insertion loss, low VSWR, high isolation and fast switching and feature internal DC blocks on all RF ports. They are available in frequency ranges from cost-effective narrowband to high performance broadband.
www.cobham.com/switches

Coilcraft
Ceramic Wirewound Chip Inductors

Coilcraft 0402DC Series ceramic wirewound chip inductors offer the industry's highest Q factors in an 0402 size up to 159 at 2.4 GHz. They are available in 112 inductance values from 0.8 to 120 nH, including 0.1 nH increments between 2.8 and 10 nH. Twenty samples of all 112 values are included in Coilcraft's C472-2 Designer's Kit, the perfect resource when designing impedance matching circuits for antennas in both lowband (700 to 960 MHz) and highband (1710 to 2700 MHz) applications.
www.coilcraft.com/0402dc.cfm

COMSOL Inc.
RF Module



The RF Module, an add-on product to COMSOL Multiphysics® enables engineers to analyze RF, microwave, mmWave and THz designs in multiphysics scenarios. The latest version features the following updates: postprocessing workflows and variables for antenna array radiation pattern analysis; simulation domain transformation utilizing time-to-frequency and frequency-to-time fast Fourier transform (FFT); expanded material library for microwave and mmWave circuit boards; and application library updates through the deployment of commercially available connectors in the RF Part Library.
www.comsol.com

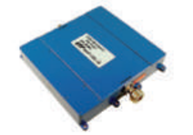
Copper Mountain Technologies
2-Port 2-Path M Series VNAs

The new 2-port 2-path M series VNAs deliver highly accurate measurements with the ideal feature set for many applications in one affordable package. All CMT VNAs include excellent customer service, automation support and years of engineering expertise at your disposal. The M series is an attractive option for users who want the metrology-grade performance provided by CMT without some of the advanced features.
www.coppermountaintech.com

Crane Aerospace & Electronics
Microwave Solutions

Crane Aerospace & Electronics (Booth 960) designs and manufactures high performance RF, IF and mmWave components, subsystems and systems for commercial aviation, defense and space. With over 60 years of experience, Crane has proven capabilities in major military, communications, EW, radar and satellite systems. Product capabilities: beamformers, component and single function devices, integrated microwave assemblies, Multi-Mix® multi-fabrication technology, space qualified products switch matrices.
www.craneae.com

CTT
X-Band Radar Power Amplifier



CTT's new X-Band solid-state GaN-based power amplifier, Model AGN/098-5864-P, is designed specifically to meet the demands of the latest synthetic aperture radar (SAR) requirements. Providing more than 600 W pulsed (10% duty) at 9.5 GHz, in a compact package, 6.17 × 6.6 × 0.82 in. This new power amplifier design makes an especially attractive choice for new SAR designs where SWaP is at a premium, including many UAV applications. Visit CTT in Booth 1061 at IMS2019.
www.cttinc.com

Custom Microwave Components
Non-Blocking Switch Matrix

A non-blocking switch matrix with 72 inputs and 32 outputs used to configure RF environments for carrier end-to-end backhaul and hand-over testing. Intuitive browser graphical user interface, easy to network and use API to support automated testing, solid-state reliability and repeatability, modular line-replaceable active units with built-in spares, distributed hot-swappable redundant supplies, system health monitoring and reporting, ultra-low operating power (< 85 W), ultra-quiet operation, frequency: 0.7 to 3 GHz (optional 0.7 to 6) GHz, insertion loss: 30 dB max. Visit at IMS2019 in Booth 307.
www.customwave.com

Custom MMIC
Low Noise Amplifier
VENDORVIEW

The CMD283C3 is a broadband MMIC low noise amplifier housed in a leadless 3 × 3 mm surface mount package. The CMD283C3 is ideal for EW and communications systems where small size and low-power consumption are needed. The

device is optimized for broadband performance and delivers 27 dB of gain with a corresponding noise figure of 0.6 dB at 4 GHz. The CMD283C3 is a 50 ohm matched design which eliminates the need for external DC blocks and RF port matching. Visit at IMS2019 in Booth 1350.
www.CustomMMIC.com

Dalicap
Hi-Q MLCC

Dalicap is the source of RF/microwave high-Q (> 10,000) MLCC, and also dedicated to designing, manufacturing customized products, such as MLCC c/w microstrip, ribbon and so on. After years of development, Dalicap is one of the leading suppliers of Hi-Q MLCC, which is being widely used in 5G power amplifier, MRI coil, semiconductor RF power, high speed railway, filter, plasma igniter, television and broadcast transmitters industries. Visit at IMS2019 in Booth 889.
www.dalicap.com

dB Control
mmWave High-Power Amplifiers

dB Control offers five mmWave high-power amplifiers, including the dB-3860 traveling wave tube amplifier. This rack-mount TWTA features a 34.5 to 35.5 GHz frequency range and operates at 700 W peak power (10% duty cycle). It is designed for radar applications. Additionally, the dB-3201 is a conduction-cooled MPM featuring 26.5 to 40 GHz and operating at 125 W pulsed to CW. It is suitable for electronic countermeasures and EW simulation. dB Control will be in Booth 1416.
www.dBControl.com

dBm Corp., Inc.
Advanced Channel Emulator

dBm will exhibit its ultra-high band (600 MHz) Advanced Channel Emulator (ACE) which offers full link emulation with programmable phase continuous changing delay, carrier/signal doppler, path loss/attenuation, phase shift, atmospheric scintillation, 12 path multipath and AWGN. In addition to link emulation mode, the ACE offers a suite of powerful modeling tools allowing full payload/hardware-in-the-loop emulation. Impairments such as programmable group delay, phase noise, amplifier compression, AM/AM, AM/PM distortion and IMUX/OMUX simulation may also be inserted in the RF link communications channel.
www.dbmcorp.com

PRODUCT SHOWCASE
IMS2019

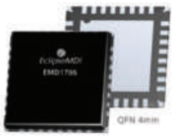
Ducommun
E-Band Diplexer

Ducommun's (Booth 1146) E-Band diplexer comprises of two waveguide bandpass filters designed to pass at the frequency spectrum of 71 to 76 and 81 to 86 GHz respectively. The nominal insertion loss of the diplexer is 0.5 dB and the minimum isolation is 55 dB. The E-Band diplexer's features include: low insertion loss, high isolation and a small footprint. It is available in waveguide and connectorized.
www.ducommun.com

Dynawave Inc.
DynaTest™ HD for High Density Testing

The power of repeatable and reliable performance! DynaTest™ HD cable assemblies are ideal for testing switch matrices or high density backplanes. They feature < 0.5 in. spacing on centerlines, SMA hex/knurl coupling nuts to facilitate quick mating, and stainless steel connectors. DynaTest HD assemblies are highly flexible, have excellent strain relief at cable-connector junction and are 100% RF tested with low insertion loss and VSWR DC to 40 GHz.
www.dynawave.com

Eclipse MDI
MMIC Driver Amplifier



Eclipse Microdevices (Booth 1210) announces the EMD1706 MMIC driver amplifier with operation from DC to 24 GHz. The 1706 provides an output power of 22 dBm and a typ. gain of 15 dB with typ. sat. power of 23.5 dBm. The EMD1706 requires only a 8 V supply and consumes just over 1 W of power. The 1706 is available in a QFN 4 mm hermetically sealed plastic package and is ideal for commercial, military, SATCOM and telecom applications.
www.eclipsemicrowave.com

Empower RF
GaN Module
VENDORVIEW

Empower RF announces the release of model 1219, a single band solid-state GaN module delivering a min. 30 W (40 W typ.) across its entire 0.6 to 6 GHz band. Empower RF is the first amplifier manufacturer to cover this bandwidth with an affordable COTS product. The 1219 utilizes 50 V GaN on SiC transistors which have lower leakage currents and higher thermal conductivity and is a more reliable technology than GaN on Si. Visit Booth 659 to learn more.
www.EmpowerRF.com

Exodus Advanced Communications
VENDORVIEW
Solid-State Power Amplifier System

Exodus Advanced Communications is pleased to highlight their AMP2030 high power 1 to 6 GHz 300 W amplifier. Exodus AMP2030 provides > 300 W with a min. power gain of 53 dB. The unit has excellent gain flatness, < 5 usec switching speeds for enable/disable functions. Available are amplifier monitoring parameters for forward/reflected power, as well as voltage, current and temperature sensing for optimum reliability and ruggedness for all applications. Nominal weight is < 90 lbs. and dimensions of 19 × 22 × 8.75 in.
www.exoduscomm.com

GLOBALFOUNDRIES
22FDX® Technology

GLOBALFOUNDRIES' 22FDX® technology delivers future-ready performance, power and area advantages for demanding 5G communications and automotive mmWave applications through a potent combination of ruggedness, best-in-class ft/fmax and high self-gain, power efficiency and integration. Harness RF-optimized features and body biasing while packing more function into smaller chips in radar-optimized SoCs for ADAS solutions and 5G smartphone and infrastructure solutions that incorporate integrated FEMs and transceivers, along with ADC/DACs. Visit Booth 624 to learn more.
www.globalfoundries.com

Gowanda Components Group
High Current Conicals

Gowanda's new broadband conicals provide current ratings up to 10 amps DC—the highest level in the industry. The four new series—C305FL, C550FL, C750FL, C1000FL—offer performance ranges for inductance from 0.30 to 22 µH, Q from 30 to 66, DCR ohms from 0.02 to 0.265 and current rating mA DC from 1300 to 10,500. Communication applications: bias tees, broadband chip manufacturing, communication platforms, high frequency, microwave circuitry, RF test set-ups, test & measurement, test gear, test instrumentation and transmission amplifiers. Visit at IMS2019 in Booth 236.
www.gowandacomponentsgroup.com

Herotek
Limiter

Herotek offers a wide range of high-power limiters. Model LS00105P200A is a 200 W CW limiter operating from 10 to 500 MHz with 1 kW peak, 1 ms pulse width limiting protection. It has a low insertion loss of 0.8 dB and 2.2:1 VSWR with typical leakage of 20 dBm at 200 W CW input. This limiter has built-in input and output DC blocks. It comes in a hermetically sealed package with removable connectors for drop-in assembly and designed for both military and commercial applications.
www.herotek.com

Holzworth
VENDORVIEW
Real-Time Phase Noise Analyzer

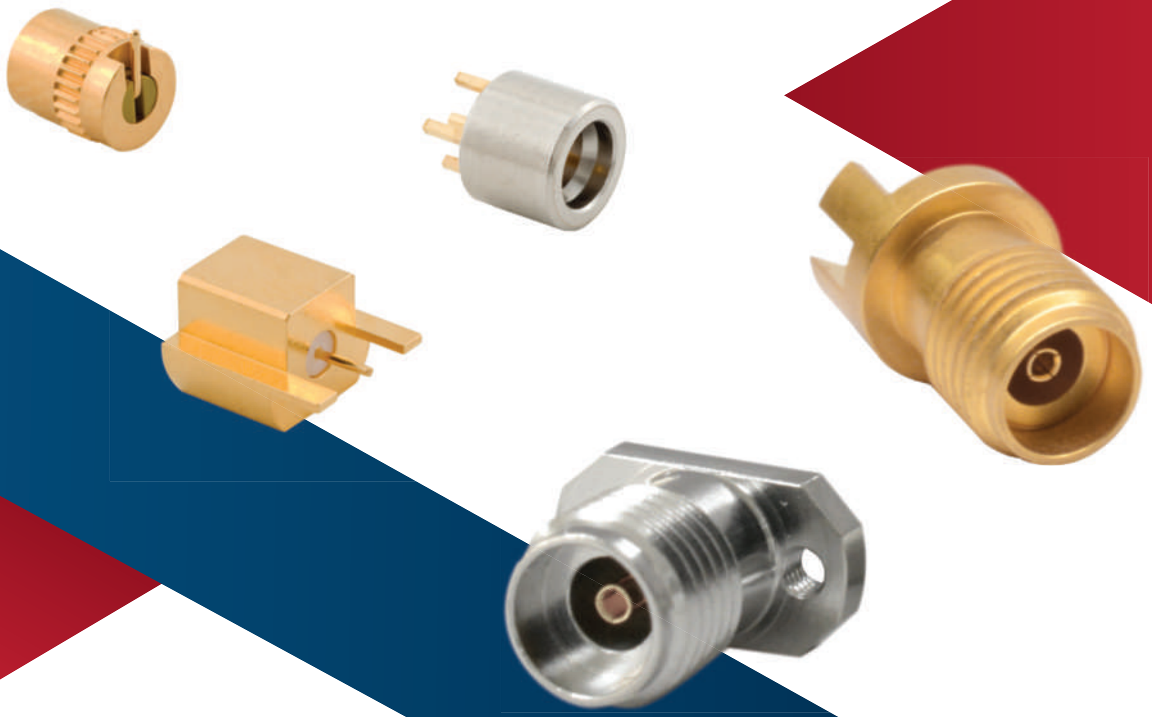
The HA7062D 40 GHz real-time phase noise analyzer is designed to support manufacturing ATE and R&D applications where high speed data acquisition is critical. The HA7062D is the only phase noise analyzer available with real-time FFT data analysis that covers the entire 100 MHz measurement bandwidth. In addition to pure measurement speed, Holzworth's phase noise analyzers focus on data accuracy, repeatability and reliability. Visit Holzworth at IMS2019 Booth 679 to test drive the new HA7062D along with Holzworth's new 40 GHz synthesizer products.
www.HOLZWORTH.com

HYPERLABS
Broadband, Resistive Pick-Off Tee

The HYPERLABS HL9465 is a broadband, resistive pick-off tee featuring rise-times of < 9 ps. The HL9465 showcases excellent through-line insertion and return loss and pick-off stability from DC to over 40 GHz. The pick-off port output is an estimated 0.3 scale duplicate of the signal passing through the tee. The HL9465M is sold as a matched pair for differential applications requiring equal propagation delays. Visit Booth 1376 at IMS2019 to learn more.
www.hyperlabsinc.com

Integra Technologies Inc.
RF and MW Power Semiconductor and Pallet Solutions

Integra Technologies Inc. (Booth 1207) announces a new GaN/SiC RF power transistor designed to meet the demanding needs of modern S-Band radar systems. The IGN2729M400R2 operates at the instanta-



neous frequency range of 2.7 to 2.9 GHz, delivers a min. peak output power of 400 W at 50 V drain bias voltage and > 18 dB of gain, achieving 63% efficiency at 100 ms pulse width, 10% duty cycle.
www.integratech.com

ITEQ
RF Product Solutions

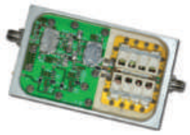
ITEQ's (Booth 484) RF product solutions are compatible with FR-4 for hybrid applications and designed for use in automotive radar, mmWave antennas, base station antennas and emerging 5G applications. ITEQ's RF products have Dk and Df stable over frequencies, temperatures and humidity. Other features include: standard FR-4 PCB processes, high-power handling capability due to higher thermal conductivity, stability of dielectric properties with temperature and aging, excellent copper peel strength and low cost of ownership.
www.iteq.com.tw

JQL Electronics
MINI-SMT Circulators

VENDORVIEW

JQL Electronics introduces the new series of MINI-SMT circulators for both 5G and radar applications. The world's smallest SMT X-Band circulator with 0.205 in. (5.2 mm) diameter delivers impressive up to 200 W pulse power handling. It is an ideal component for high-power radar. JQL's MINI-SMT family also includes the smallest 0.276 in. (7 mm) circulator for 3.4 to 3.6 GHz tailored for 5G MIMO antenna. Custom design MINI-SMT isolators/circulators are available from 800 MHz to 40 GHz.
www.jqlelectronics.com

K&L Microwave, Inc.
Pre-Filtered LNA Assemblies



K&L Microwave offers a line of pre-filtered LNA assemblies. Initially covering GPS in any combination of L1, L2 or L5. Gains available span 16 to 37 dB in 3 dB increments with a low 3 dB noise figure. DC power can be provided through hermetic feed throughs or on the RF path using an internal bias tee. The sealed package typically measures 2 × 1.5 × 0.45 in. Custom designs are available covering 10 MHz to 18 GHz. Contact K&L for your pre-filtered LNA assemblies.
www.klmicrowave.com

Knowles Precision Devices
Filter Technology

Knowles Precision Devices (DLI) filter technology addresses the challenge of implementing high performance filters, couplers and dividers at mmWave frequencies 26, 28 and 39 GHz. Catalog filters provide 3 GHz of bandwidth, > 50 dB rejection, are 20× smaller than current alternatives while implemented in surface mount packages for standard tune-free assembly and provide temperature stable operation from −55°C to +125°C. Off the shelf catalog designs are available to 42 GHz and custom design services are available.
www.knowlescapacitors.com

Kratos General Microwave
Solid-State Power Amplifiers

Kratos General Microwave's cutting-edge, field proven SSPAs are designed and built for the harshest environment conditions, including hostile temperatures, shock, vibration, moisture, altitudes and G-forces. The custom and off-the-shelf SSPAs in X- and Ku-Bands, utilize the latest GaN and GaAs technologies and provide high-power density in a compact footprint to meet critical space and weight requirements in high frequencies. All of their SSPAs can be supplied to meet the most stringent environmental requirements.
www.kratosmed.com

Krytar
Directional Coupler

VENDORVIEW

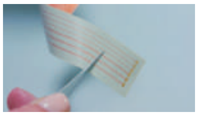
KRYTAR's new coupler, Model 1100110010, exhibits excellent coupling over a ultra-broadband frequency range of 10 to 110 GHz. This compact coaxial directional coupler maintains flat 10 dB coupling and low mainline insertion loss with consistent directivity across a 100 GHz bandwidth. The coupler offers frequency sensitivity of ±1.25 dB, insertion loss of less than 2.5 dB, directivity of greater than 10 dB and max VSWR is 1.8. The directional coupler comes with 1 mm SMA female connectors. Visit KRYTAR at IMS2019 in Booth 825.
www.krytar.com

LadyBug Technologies
Pulse Profiling Power Sensor

VENDORVIEW

See LadyBug Technologies' thermally stable LB480A USB pulse profiling power sensor at IMS2019 in Booth 1255. The power sensor provides high accuracy NIST traceable RF power measurements to below −60 dBm. Includes software and ATE support. Pulse profiling capability along with over 2,000 average measurements per second and no buffer latency. Connector options allow placement directly on the DUT to achieve the best match and accuracy. In-stock for immediate shipment.
www.LadyBug-Tech.com

Lark RF Technology
Complex RF Integrated Solutions and Custom RF Components



Lark RF Technology, a Benchmark company, is a global provider of complex RF integrated solutions and custom RF components, SMT, hybrid and micro-electronics assembly and packaging and substrate to system design for high speed and RF circuit fabrication. Their innovation differentiators include electronics miniaturization utilizing high performance materials such as liquid crystal polymer, design and testing of wireless 5G products at frequencies up to 110 GHz and vertical integration with U.S. and Asia sites for global scale.
www.larkengineering.com

LPKF Laser & Electronics
ProtoMat S104

The LPKF (Booth 1224) ProtoMat S104 for PCB prototyping is fully equipped for the electronics laboratory, perfect for military and defense contractor R&D labs. The system is suitable for RF applications, thin laminates and substrates with sensitive surfaces (conductor path widths as small as 100 μm). The system software considers the special requirements of RF materials.
www.lpkfusa.com/products/pcb_prototyping/machines/protomat_s104/

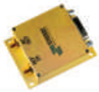
MACOM
Wideband Amplifier

MACOM's MAAM-011238-DIE is an easy-to-use, wideband amplifier that operates from 100 kHz to 67.5 GHz. The amplifier provides 14 dB gain, 4.5 dB noise figure and 33 dBm of P3dB output power at 30 GHz.

Ultra Low Phase Noise

Phase Locked Clock Translators

Up to 3.0 GHz

Model	Frequency	Ref. Input	DC Bias	Typical Phase Noise (dBc/Hz)				Package
	(MHz)	(MHz)	(VDC)	100 Hz	1 kHz	10 kHz	100 kHz	
FCTS800-10-5	800	10	+5, +12	-87	-116	-144	-158	
KFCTS800-10-5	800	10	+5, +12	-87	-116	-144	-158	
FCTS1000-10-5	1000	10	+5, +12	-75	-109	-140	-158	
FCTS1000-10-5H	1000	10	+5, +12	-84	-116	-144	-160	
FCTS1000-100-5 *	1000	100	+5, +12	-75	-109	-140	-158	
KFCTS1000-10-5 *	1000	10	+5, +12	-75	-109	-140	-158	
FCTS2000-10-5 *	2000	10	+5, +12	-80	-105	-135	-158	
FCTS2000-100-5 *	2000	100	+5, +12	-80	-105	-135	-158	
KFCTS2000-100-5 *	2000	100	+5, +12	-80	-105	-135	-158	
FSA1000-100	1000	100	+3.3, +5, +12	-105	-115	-145	-160	
KFSA1000-100	1000	100	+12	-105	-115	-145	-160	
FXLNS-1000	1000	100	+5, +12	-120	-140	-149	-154	
KFXLNS-1000	1000	100	+12	-120	-140	-149	-154	

** New for 2018*

Features

- Cost Effective
- Replaces Noisy Frequency Multipliers
- No Programming Required
- Lead Free RoHS Compliant

Applications

- Scanning & Radar Systems
- ADC & DAC Fast Clocking & Sampling
- Test & Measurement Equipment
- High Performance Frequency Converters
- Base Station Applications
- Front End Converter LO's

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Phone: (973) 881-8800 | Fax: (973) 881-8361
E-mail: sales@synergymwave.com | Web: www.synergymwave.com
Mail: 201 McLean Boulevard, Paterson, NJ 07504

It is matched to 50 Ω with typical return loss better than 12 dB. The amplifier requires only positive bias voltages and would typically be operated at 6 V and 135 mA. MAAM-011238-DIE is suitable for a wide range of applications in instrumentation and communication systems, available as 2.1 × 1.05 mm die.
www.macom.com

Maury Microwave
High-Power Pulsed SMUs

AMCAD's AM3100 high-power pulsed SMUs are the perfect pulsed-bias supply and acquisition instrumentation for pulsed load pull and general-purpose test and measurement applications. The AM3100 can operate up to 120 V and 30 A pulsed with pulse widths down to 1 μs. It includes internal and external synchronization and triggering and can be controlled through direct SCPI commands via USB or Ethernet. The AM3100 includes multiple levels of protection circuitry including a fast short-circuit current breaker (e-fuse). Visit at IMS2019 in Booth 618.

Active Load Pull for 5G and Wi-Fi

Maury's (Booth 618) MT2000 mixed-signal active harmonic load pull system has been designed for 5G FR1 and FR2 device characterization up to 40 GHz. The MT2000 enables wideband impedance control over a bandwidth up to 1000 MHz for multi-channel 5G load pull measurements, and can accurately measure power, efficiency ACPR and EVM with its low noise floor and receiver sensitivity. The MT2000 offers the simplest configuration and ease-of-use based on a fully integrated and turnkey architecture.
www.maurymw.com

MCV Microwave
5G and ATC Radar Ceramic Filter

VENDORVIEW

MCV Microwave (Booth 1074) introduces a series of miniature high performance ceramic filters suitable for 5G NR MIMO base stations, UNII band Wi-Fi and ATC radar applications covering major communications bands—UHF, L-Band, 3.5 GHz, lower C- to Ku- and Ka-Band. In addition to low insertion loss, MCV ultra-miniature 3 mm ceramic filters track well in a series of 11 filter family from 630 to 1325 MHz with the same −1, −6 and −60 dBc bandwidths.
www.mcvmicrowave.com

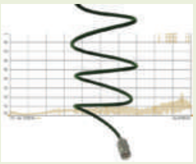
MECA Electronics, Inc.
mmWave 2-Way Power Divider

MECA expanded offering of 5G mmWave products. Featuring 2-way power dividers covering 18 to 40 GHz with 2.92 mm interfaces. Specifications of 1.3:1 V typ./1.8 max VSWR, 22 typ./14.5 dB min. isolation, 1.25 dB typ./1.8 max insertion loss and 0.3 typ./0.5 dB max amplitude balance. Also available are attenuators, terminations, bias tees, DC blocks and adapters. Additionally octave and multi-octave models covering up to 50 GHz built by J-Standard certified assemblers and technicians. Made in U.S. with a 36-month warranty.
www.e-MECA.com

MIcable
T26 Test Cable

MIcable (Booth 316) T26 series are super flexible and durable test cable assemblies. The cable assemblies go to the frequency of 26.5 GHz, the typical VSWR is 1.2:1 at 26.5 GHz, loss is 2.52 dB/m at 26.5 GHz, phase stability over flex. is ±2 degrees at 26.5 GHz and amplitude stability is ±0.04 dB at 26.5 GHz. Even after 150K harsh bending cycles, shaking and twisting, the cable assemblies have negligible phase and amplitude variation. They are the cost saving replacements of other existed test cables.

C29F Microwave Cable Assemblies



MIcable (Booth 316) C29F Series cable assemblies are specially developed for 5G testing and connecting application. They use 0.086 in. flexible 80% propagation velocity low loss phase stable cable, special rugged low cost stainless steel connector design and advanced assembling technology. The cable assemblies have VSWR typical 1.35:1 at 50 GHz, phase stability vs. flexture ±5 degrees at 50 GHz, amplitude stability ±0.13 dB at 50 GHz and phase stability 500 ppm over −40°C to +70°C. Micable can offer 2.4, 2.92, SMP, multi-pins connectors, also phase matching and tracking options are available.
www.micable.cn

Mician
Software Products

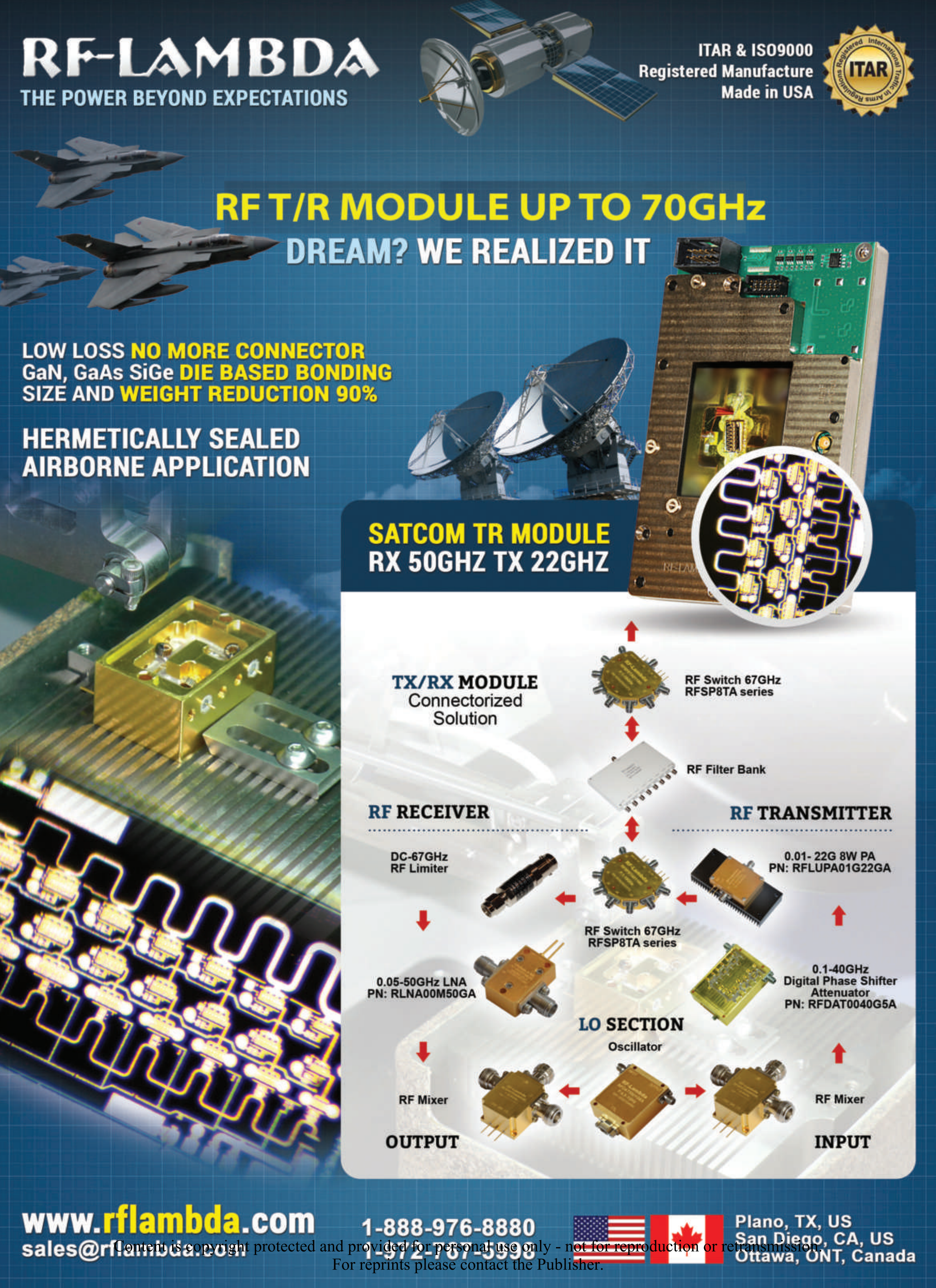
Mician software products are geared towards rapid development of passive RF components in aerospace and telecommunications. The μWave Wizard EDA suite is a powerful tool for synthesis, analysis and optimization of microwave assemblies. μWave Wizard's hybrid EM solver guarantees fast and accurate simulation of passive components, feed networks and antennas. Typical applications include horn and reflector antennas, feed clusters, OMTs, polarizers, circulators, waveguide and combline filters, multiplexers, couplers and more. Integrated COM/VBA interfaces support external control and third-party add-ons.
www.mician.com

Micro Lamba Wireless
Bench Test Filters

The MLBF-Series bench test filters are ideal for production test sets, laboratory tests and test equipment racks where filtering of microwave signals is essential. These bench top filter assemblies provide either bandpass or band reject (notch) filter types depending on application. Frequency coverage is dependent on which production filter type is chosen. Frequency coverage for bandpass models range from 500 MHz to 50 GHz while the band reject models cover 350 MHz to 20 GHz.
www.microlambdawireless.com

Milliwave Silicon Solutions
mmWave Test Fixtures

MilliBox (Booth 2000) is a highly modular and economical product line of mmWave test fixtures. The MBX family consists of lab bench sized radiation pattern chambers. Three sizes give 80, 140 or 200 cm far-field measurement distance. The GIM family consists of 3D gimbals controlled using Python over USB. They are used for radiation pattern or beam forming performance measurements and come with various DUT load capacities and rotational velocities. The ISO family consists of desktop isolation chambers for mmWave firmware and SQA developers.
www.milliwavess.com


RF-LAMBDA
THE POWER BEYOND EXPECTATIONS
ITAR & ISO9000
Registered Manufacture
Made in USA
ITAR
International Traffic in Arms Regulations Registered
RF T/R MODULE UP TO 70GHz
DREAM? WE REALIZED IT
LOW LOSS NO MORE CONNECTOR
GaN, GaAs SiGe DIE BASED BONDING
SIZE AND WEIGHT REDUCTION 90%
HERMETICALLY SEALED
AIRBORNE APPLICATION
SATCOM TR MODULE
RX 50GHZ TX 22GHZ
TX/RX MODULE
Connectorized
Solution
RF Switch 67GHz
RFSP8TA series
RF Filter Bank
RF RECEIVER
RF TRANSMITTER
DC-67GHz
RF Limiter
0.01- 22G 8W PA
PN: RFLUPA01G22GA
RF Switch 67GHz
RFSP8TA series
0.05-50GHz LNA
PN: RLNA00M50GA
0.1-40GHz
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PN: RFDAT0040G5A
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Plano, TX, US
San Diego, CA, US
Ottawa, ONT, Canada

Mini-Circuits

Tiny MMIC Gain Slope Equalizers

VENDORVIEW

Mini-Circuits' EQY-5-24+ is an absorptive MMIC gain equalizer with a negative 5.1 dB slope versus frequency from DC to 20 GHz. Fixed slope MMIC equalizers are useful for flattening negative gain slope in wideband amplifiers, receivers and transmitters in applications from wireless communications to broadband/optical, satellite, defense and more. This model is capable of handling up to +34 dBm RF input power and provides 20 dB typical return loss across its full bandwidth. Fabricated using highly repetitive GaAs IPD technology, this equalizer provides outstanding repeatability of performance, making it suitable for volume production. It comes housed in a 2 × 2 mm 8-lead QFN package, saving board space and minimizing the effect of parasitics. EQY-series MMIC gain slope equalizers are available with a wide range of slope values to meet your needs.

High Dynamic Range MMIC Amplifier

Mini-Circuits' TSS-13LN+ ultra-high dynamic range MMIC amplifier provides industry-leading noise figure and IP3 from 1 MHz to 1 GHz. An internal shutdown feature protects the amplifier in the presence of pulsed signals while keeping the power supply at constant voltage to minimize DC power consumption. This model provides 1.1 dB noise figure and +39.2 dBm IP3, making it ideal for maximizing sensitivity and dynamic range in high performance receiver applications. It delivers 22.8 dB typical gain with ±3 dB flatness and +19 dBm output power at 1 dB compression. The amplifier is fabricated using E-PHEMT technology with excellent repeatability. It operates on a single 8 V supply, and comes housed in a tiny 12-pad 3 × 3 mm QFN package.

Tiny High-Rejection LTCC Low Pass Filter

Mini-Circuits' LFCG-530+ is an LTCC lowpass filter with a passband from DC to 530 MHz. This model provides 1 dB typical passband insertion loss and stopband rejection of 30 dB typ. The filter is capable of handling up to 4 W RF input power and provides a wide operating temperature range from −40°C to 85°C. Housed in a tiny 0805 ceramic form factor with wraparound terminations, the LFCG-530+ is ideal for dense PCB layouts with minimal performance variation due to parasitics.

Tiny LTCC Dual/Differential Low Pass Filter

Mini-Circuits' DLFCV-1600+ is a dual lowpass filter with a passband from DC to 1600 MHz designed into a single 1210 ceramic package. This design allows customers to use a single unit in systems where two filters of the same passband are required, saving board space. The dual filter can also be used as a differential filter in differential circuits where interference and noise must be minimized. This model provides 1.5 dB passband insertion loss, 50 dB stopband rejection and RF input power handling up to 3 W (each filter). It supports a wide range of applications and is ideal for minimizing interference at amplifier inputs and ADC outputs.

Ultra-Low Noise D-PHEMT Transistor

Mini-Circuits' TAV1-331+ is a MMIC D-PHEMT transistor with an operating frequency range from 10 to 4000 MHz, supporting a wide range of wireless communications bands. This model provides a unique combination of low noise (0.6 dB) and high gain (24.1 dB), resulting in lower overall system noise. It also provides high IP3 performance of +31.8 dBm, making it ideal for sensitive receiver applications. Manufactured using highly repeatable D-PHEMT technology, the unit comes housed in a tiny 1.4 × 1.2 mm MCLP package. This model requires external biasing and matching.

Coaxial Adapter Mates 1.85 mm-F to 2.92 mm-F Connectors

Mini-Circuits' 185F-KF+ is a coaxial 1.85 mm-F to 2.92 mm-F adapter, supporting a wide range of applications from DC to 40 GHz. This model provides 1.05:1 VSWR, and 0.13 dB insertion loss with flat response over its full frequency range. The unit features rugged, passivated stainless steel construction and measures 0.82 in. in length.

N-Type Coaxial 50 W Termination

Mini-Circuits' TERM-50W-183N+ is a coaxial termination capable of absorbing signals up to 50 W from DC to 18 GHz. It provides excellent return loss of 29 dB up to 18 GHz, effectively dissipating signal power with minimal signal reflections. This model features a passivated stainless steel N-type male connector with a rugged, anodized aluminum heat sink. TERM-series coaxial terminations are available with a variety of power ratings and connector types to meet your needs.

Waveguide Bandpass Filters

Mini-Circuits and Virginia Diodes have teamed together to offer a new series of high performance, high fidelity waveguide bandpass filters for mmWave applications. WVBP-series filters are available in various passbands spanning 27 to 86 GHz and are offered with standard WR waveguide interfaces. Built with precise machine tolerances and outstanding quality plating, WVBP-series filters provide low insertion loss in the passband, outstanding return loss and high stopband rejection with fast roll-off.

Wideband, DC Pass Directional Coupler

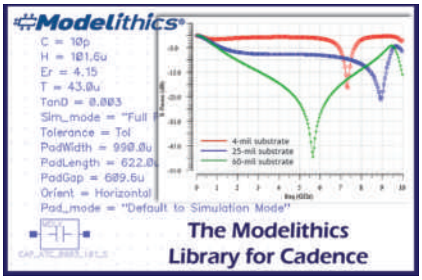
The Mini-Circuits ZCDC13-01263-S+ wideband directional coupler offers exceptional performance operating over 1 to 26.5 GHz. This coupler has excellent coupling flatness, good directivity and power handling. It is ideal for lab testing applications as well as for power monitoring over wide bands, among other applications.

Low Current, Wideband, Ceramic Monolithic Amplifier

The CMA-183L+ is a low current, wideband gain block that operates up to 20 GHz fabricated using highly reliable GaAs HBT process. This Darlington pair amplifier delivers excellent gain flatness, good return loss, low current with acceptable P1dB and OIP3 across a wide bandwidth without the need of external matching network. It has highly repeatable performance from lot to lot and it is packaged in an LTCC hermetic package utilizing fully automated and highly reliable manufacturing processes. CMA-series amplifiers are capable of meeting MIL requirements for gross leak, fine leak, thermal shock, vibration, acceleration, mechanical shock and HTOL. The tests can be performed if requested.

www.minicircuits.com

Modelithics
The Modelithics® Library of Scalable Microwave Global Models
VENDORVIEW

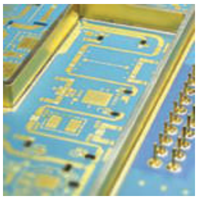


The Modelithics® Library of scalable Microwave Global Models™ is now formatted for Cadence® Spectre® RF Option and Virtuoso® RF Solution. The initial library version has over 300 models for discrete (off-chip) capacitor, inductor and resistor families from over 25 vendors, representing over 17,000 components. High frequency circuit designers using Cadence software can integrate the models into their SIP and module designs and can specify part-value, pad size and substrate properties. The models will accurately simulate parasitics based on the input properties, eliminating the need for generating S-parameters for modeling each time the design changes. Visit at IMS2019 in Booth 507.
www.modelithics.com

Morion Inc.
Ultra-Low Phase Noise OCXO

Morion's (Booth 205) MV317 100 MHz OCXO is now available with improved G-sensitivity up to 2E-10/G. Frequency stability vs. temperature to 5E-8 is available, with aging to 1E-7/year. Phase noise < −140 dBc/Hz at 100 Hz and < −180 dBc/Hz at 100 kHz. MV317 OCXO is available with 5 and 12 V voltage supply and SIN output. Package is 25 × 25 × 10.6 mm.
www.morion-us.com

MST-Micro Systems Technologies
Advanced Electronic Modules



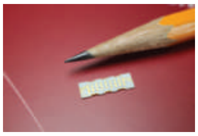
The MST group is specialized in developing and manufacturing integrated electronic module solutions with highest reliability from one source. The capabilities include highly complex HDI/microvia PCBs in flexible, rigid-flex and rigid versions, LCP and LTCC substrates, semiconductor packaging processes as well as advanced assembly in the field of SMT and chip & wire. Visit MST in Booth 1332.
www.mst.com

National Instruments (AWR)
Software Product Family

AWR

Two new releases to the NI AWR software product family include 14.02 of the NI AWR Design Environment EDA platform and 3.1 of AntSyn™ EM-based antenna synthesis and optimization software. The software delivers improved user productivity with enhancements in design automation for 5G component and system development, antenna arrays and PA and filter designs as well as for RF PCBs. In particular, AntSyn software now offers more than double the starting templates offered for antenna designs. Visit Booth 930 at IMS2019 to learn more.
www.awrcorp.com

Networks International Corp.
Thin Film Filters

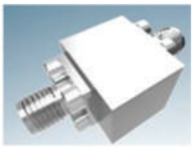


NIC's engineering expertise in hi-reliability RF products and integrated assemblies includes a specialty in thin film filters that span from 1 to 20 GHz. These high performance filters are built on industry standard substrates such as alumina and titanate, and are offered in a compact package size with low profile of < 0.08 in. The filters also offer high selectivity and out of band rejection of > 60 dB. Please stop by Booth 411 for additional information.
www.nickc.com

Norden Millimeter
Custom Transceivers
VENDORVIEW

Norden (Booth 1306) designs custom transceivers for military and commercial applications including Airborne, UAV and EW. They have "catalog" models which provide wideband RF and up to 1.5 GHz IF with low phase noise. Norden can provide custom designs which incorporate temperature compensation, variable gain and meet military environmental requirements. Norden also offers models in a low-SWaP 3U VPX module which includes a built in LO. Norden engineers utilize proven designs to provide low risk, cost-effective solutions.
www.nordengroup.com

Nova Microwave Inc.
26.5 to 40 GHz Broadband Isolator



Nova Microwave Inc., a manufacturer of high-quality passive RF/microwave circulators and isolators announces the release of the DKIU3325 broadband isolator. The new DKIU3325 isolator operates from 26.5 to 40 GHz and it can handle 5 W of forward average power. This high performance isolator is available with 2.92 mm (K) connectors.
www.novamicro.com

NSI-MI Technologies
The Vector Field Analyzer™

The Vector Field Analyzer™ (VFA) incorporates the latest technology for making antenna, radome and electromagnetic field probing measurements. This simultaneous multi-channel precision measurement receiver adds powerful new capabilities to display polarization parameters. When used with a dual polarized probe, the VFA measures both polarization ports and calculates key polarization parameters. Results include axial ratio, tilt angle, sense of rotation and displays of the polarization ellipse. The VFA combines the best RF performance, fastest measurement speed and most advanced features available in the industry.
www.nsi-mi.com/vector-field-analyzer

OML
5G Sub-Harmonic Pumped Mixer Module

OML (Booth 728) has developed an economical sub-harmonic pumped mixer down-converter module for the 5G market. M28H2ADC operates from 24 to 40 GHz with an IF bandwidth > 5 GHz. Its compact size is well suited for both field and lab uses. The M28H2ADC can be connected directly to portable handheld instruments such as Keysight FieldFox and Anritsu Spectrum Master or it can be configured to use with bench-top instruments. It is powered via USB port.
www.omlinc.com

Pasternack
Military-Grade RF Cable Assemblies
VENDORVIEW

Pasternack has introduced a new line of military-grade MIL-DTL-17 RF cable assemblies that are ideal for avionics, military electronics, satellite ground stations and autonomous vehicles. Pasternack's new series of military-grade cable assemblies consist of 124 basic configurations from six different cable types for a total of more than 700 part numbers that are all available for same-day shipment. These cables provide operating frequencies of up to 12.4 GHz and VSWR as low as 1.3:1 per connector.
www.pasternack.com

PicoTechnology
PicoScope 9404

Recently introduced, the PicoScope 9404 SXRTO (Sampler eXtended Real Time Oscilloscope) features four 5 GHz 12-bit channels, each supported by real-time sampling to 500 MS/s per channel and up to 1 TS/s (1 ps) equivalent-time sampling. Both the voltage and timing resolution specifications are characteristics of the highest performance broadband oscilloscopes.
www.picotech.com

Planar Monolithics Industries Inc.
P16T-100M50G-100-T-DEC
VENDORVIEW

PMI Model P16T-100M50G-100-T-DEC is a SP16T Absorptive Switch that operates from 0.1 to 50 GHz. This model offers a typical insertion loss of 16 dB while maintaining a typical isolation of 70 dB. It operates at 20 dBm CW, 100 ns switching speed and is controlled with TTL logic. Power requirements are +12 VDC at 800 mA max, −12 VDC at 720 mA max. Other features include 2.4mm connectors, nickel plated finish and 12 × 5.5 × 0.65 in. package size.

www.pmi-rf.com/product-details/p16t-100m50g-100-t-dec

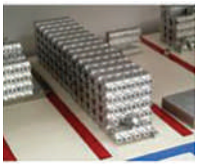
Qorvo
MMIC PA

Qorvo's TGA2222 MMIC PA delivers the industry's highest power for 32 to 38 GHz applications. It is a wideband PA GaN on SiC MMIC which provides 40 dBm (10 W) of saturated output power and 16 dB of large-signal gain while achieving > 22% PAE. It employs a balanced architecture to minimize performance sensitivity to load variation. Its RF ports are DC coupled to ground for optimum ESD performance. It can support a wide range of operating conditions, including CW operation, making it well-suited for both commercial and military systems such as EW, point-to-point communications, radar, SATCOM and more.
www.qorvo.com

Quarterwave
Traveling Wave Tube Amplifiers
VENDORVIEW

Quarterwave announces its new Traveling Wave Tube Amplifiers—the Compact Commercial Series. These units specialize in low noise, high PRF and are available for rugged applications. Upgraded with a modern exterior chassis, the Compact Commercial Series features better durability, improved control system and optional touch-screen interface. Amplifiers are high-powered for pulsed CW operations, mid-range from 8 to 18 GHz, with high PRF options from 1 to 3 MHz. Units are fully customizable to meet customer project needs.
www.quarterwave.com

Quest Microwave
Ferrite Devices



Quest Microwave provides a broad range of ferrite devices for the global microwave electronics marketplace. Standard and custom designs are available for both commercial and military applications. With over 60 years of combined experience, the company's engineering staff can design and develop ferrite devices for virtually any application. They are there to provide you with a world class microwave components solution.
www.questmw.com

Reactel Inc.
Small Form Factor Filters
VENDORVIEW

Reactel will showcase their line of small form factor filters at IMS2019. These units are suitable for densely populated boards, portable systems or any application where size is at a premium. Available technologies include Discrete Component, ceramic, cavity or combline designs. With profiles as low as 1/8 in. these robust units pack all of the performance of their larger counterparts into a much smaller package. They are available across a frequency range of 100 MHz to 20 GHz with bandwidths of 5 to 100% and are available in 4 to 12 sections. Visit Booth 471 to meet with their engineers.
www.reactel.com

Register by 31 May 2019 and Save!
Use the MWJ19EX to Register for the IMS Exhibition for Free!

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Apple App Store

Google Play Store

WWW.IMS-IEEE.ORG

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Exhibition Dates: 4-6 June 2019 • Symposium Dates: 2-7 June 2019

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MTT-S

IMS2019 and RFIC 2019 Keynote Speakers

RFIC Plenary Session Speaker
Sunday, 2 June 2019

Dr. Greg Henderson – *Senior Vice President Automotive, Communications and Aerospace & Defense, Analog Devices, Inc.*

"The Digital Future of RFICs"

RFIC Plenary Session Speaker
Sunday, 2 June 2019

Dr. Ir. Michael Peeters – *Program Director, Connectivity + Humanized Technology, imec*

"Do the Networks of the Future Care about the Materials of the Past?"

IMS Plenary Session Speaker
Monday, 3 June 2019

Dr. William Chappell – *Director of the Microsystems Technology Office (MTO), Defense Advanced Research Projects Agency (DARPA)*

"The Mind and Body of Intelligent RF"

MTT-S Awards Banquet Speaker
Wednesday, 5 June 2019

Dr. Ryan C.C. Chin – *CEO and Co-founder, Optimus Ride Inc.*

IMS Closing Session Speaker
Thursday, 6 June 2019

Dr. Dina Katabi – *Andrew & Erna Viterbi Professor of Electrical Engineering and Computer Science at MIT, Leader of NETMIT research group at CSAIL, Director of the MIT Center for Wireless Networks and Mobile Computing*

The IMS Welcome Reception will be held on Monday, 3 June 2019 at the Seaport World Trade Center Headhouse in Boston. The reception immediately follows the conclusion of the IMS Plenary Session.

For the latest on IMS and Microwave Week visit www.ims-ieee.org

RFIC Technical Sessions, Monday, 3 June 2019

All technical sessions will take place at the Boston Convention and Exhibition Center (BCEC)

Time	151AB	153AB	156AB	157BC	252AB	254AB	257AB	259AB
08:00 – 09:40					**Session Mo1A** RF Receiver Building Blocks	**Session Mo1B** Advanced Devices, Characterization, and Modeling for Millimeter-Wave Applications	**Session Mo1C** Millimeter-Wave Radar and Imaging Systems	
09:40 – 10:10	AM Coffee Break							
10:10 – 11:50					**Session Mo2A** 5G and Millimeter-Wave Beamforming Building Blocks	**Session Mo2B** Digitally Assisted Front-Ends for Emerging Wireless Applications	**Session Mo2C** RF-Inspired Emerging Technologies and Applications	
13:30 – 15:10					**Session Mo3A** Millimeter-Wave Integrated Subsystems	**Session Mo3B** Blocker Tolerance and Interference Cancellation	**Session Mo3C** High-Performance Energy-Efficient Oscillators and Frequency Synthesizers	
15:10 – 15:55	PM Coffee Break							
15:55 – 17:15					**Session Mo4A** Millimeter-Wave PAs for 5G and Phased Arrays	**Session Mo4B** Receiver Circuits in CMOS-SOI Technology	**Session Mo4C** Mixed Signal Circuits for High Speed RF and Optical Transceivers	

Also on Monday: Workshops, Short Courses, RF Boot Camp, RFIC Panel Session, Three Minute Thesis (3MT) Competition, IMS Plenary and Welcome Reception

For the latest on IMS and Microwave Week visit www.ims-ieee.org

RFIC and IMS Technical Sessions, Tuesday, 4 June 2019

All technical sessions will take place at the Boston Convention and Exhibition Center (BCEC)

Time	151AB	153AB	156AB	157BC	252AB	254AB	257AB	259AB
08:00 – 09:40	**Session Tu1A** Tunable and Active Filters	**Session Tu1B** Novel Techiques and Effects in Wave Propagation, Scattering, and Modeling	**Session Tu1C** Advances in Material Characterization and Processing	**Session Tu1D** HF/VHF/UHF Technology and Applications	**Session Tu1E** **Special Session** 5G Circuits and Systems	**Session Tu1F** Energy-Efficient Wake-Up Receivers and IoT Transceivers		
09:40 – 10:10	AM Coffee Break							
10:10 – 11:50	**Session Tu2A** Reconfigurable Filters with Transfer Function and Stopband Reconfiguration Capability	**Session Tu2B** Time-and Frequency-Domain Numerical Modeling for Advanced Applications	**Session Tu2C** Advancement in Biomedical Radar Technology	**Session Tu2C** Advanced Components for Low-Noice Applications	**Session Tu1E** **Special Session** 5G Millimeter Wave Beamforming Systems	**Session Tu2F** Broadband, Reconfigurable, and Multimode PAs and Transmitters		
13:30 – 15:10	**Session Tu3A** Tunable/ Reconfigurable Electromagnetic Structures	**Session Tu3B** Behavioral and Statistical Device Modeling Techniques	**Session Tu3C** Novel Microwave for Biomedical Diagnostics	**Session Tu3D** Advances in Frequency Conversion Techniques	**Session Tu3E** **Focus Session** Microwaves in Quantum Computing	**Session Tu3F** Microwaves in Quantum Computing	**Session Tu3G** Advances in Radar Sensors	**Session Tu3H** Advances in Silicon-Integrated Power Amplifiers
15:10 – 15:55	PM Coffee Break							
15:55 – 17:15	**Session Tu4A** Advanced Transmission and Transitions and Interfaces	**Session Tu4B** Complexity Reduction for Statistical Analysis and Design Optimization	**Session Tu4C** Advancement in Biomedical Sensing Systems	**Session Tu4D** High Frequency Low Phase Noise Oscillator Techniques		**Session Tu4F** Chipless RFID	**Session Tu4G** Novel Radar Technologies	

Technical Track Key: Field, Device and Circuit Tech. | Passive Components | Active Components | Systems & Applications | Emerging Technical Areas | Focus or Special Sessions | RFIC Sessions

Also on Tuesday: IMS Exhibition, IMS Student Design and Student Paper Competitions, IMS Panel Session, Startups 101 Panel Session, RFIC Interactive Forum, 5G Summit and Evening Panel Session, MicroApps, Industry Workshops, YoPros Panel and Networking Event, Amateur (HAM) Radio Talk and Reception

For the latest on IMS and Microwave Week visit www.ims-ieee.org

IMS Technical Sessions, Wednesday, 5 June 2019

All technical sessions will take place at the Boston Convention and Exhibition Center (BCEC)

Time	151AB	153AB	156AB	157BC	252AB	254AB	257AB	259AB
08:00 – 09:40	**Session We1A** Power Combiners and Transformers	**Session We1B** Oscillator Analysis, Power Amplifier Design, and MIMO System Characterization	**Session We1C** Enabling Technologies for mm-Wave 5G Communication	**Session We1D** mm-Wave and THz Systems for Sensing and Communications		**Session We1F** Microwave Acoustic Components and Applications	**Session We1G** Recent Advances in Radar Systems Applications	**Session We1H** Advanced GaN Power Amplifiers
09:40 – 10:10	AM Coffee Break							
10:10 – 11:50	**Session We2A** Advances in Passive Components	**Session We2B** Nonlinear Modeling Methods for Novel Microwave Components	**Session We2C** 5G Technologies and Evaluation Techniques	**Session We2D** mm-Wave Building Blocks and Transceivers		**Session We2F** Phase Change, Ferroelectric and Ferrite Control Devices	**Session We2G** Advances in Broadband Transceiver Chips for Radar and Communication Systems	**Session We2H** Wideband GaN Power Amplifiers
13:30 – 15:10	**Exhibit Hall Only Time, No Technical Sessions**							
15:10 – 15:55	PM Coffee Break							
15:55 – 17:15	**Session We3A** Substrate-Integrated Waveguide Bandpass Filters	**Session We3B** Multi-GHz CMOS Mixed-Signal Circuits and Systems	**Session We3C** High-Capacity Wireless Communications Systems	**Session We3D** Microwave-through-THz Photonics Devices and Systems		**Session We3F** Advanced MEMS Component Technologies, Characterization Techiques and Packaging	**Session We3G** Recent Advances in Non-Destructive Microwave Near-Field Sensing	

Technical Track Key: Field, Device and Circuit Tech. | Passive Components | Active Components | Systems & Applications | Emerging Technical Areas | Focus or Special Sessions

Also on Wednesday: IMS Exhibition, IMS Interactive Forum, IMS Panel Session, MicroApps, Industry Workshops, Startup Pitch Competition, Women in Microwave Panel Session and Networking Reception, Industry Hosted Reception, MTT-S Awards Banquet

For the latest on IMS and Microwave Week visit www.ims-ieee.org

IMS Technical Sessions, Thursday, 6 June 2019

All technical sessions will take place at the Boston Convention and Exhibition Center (BCEC)

Time	151AB	153AB	156AB	157BC	252AB	254AB	257AB	259AB
08:00 – 09:40	**Session Th1A** Planar Multi-Band Filter Synthesis and Design	**Session Th1B** Recent Advances in Packing, Interconnects and Multi-Chip Modules	**Session Th1C** Active Phased Arrays Systems	**Session Th1D** Innovative Systems and Applications	**Session Th1E** Nanoscale Devices for RF to THz Applications	**Session Th1F** Emerging Millimeter-Wave Transistor Technologies for 5G and DoD Applications	**Session Th1G** Design and Characterization of Wireless Power Transfer	**Session Th1H** PA Design Techniques and Baseband Terminations
09:40 – 10:10	AM Coffee Break							
10:10 – 11:50	**Session Th2A** Non-Planar Filters 1	**Session Th2B** 3D-Pritned RF Components and Interconnects	**Session Th2C** Beamforming Architectures, Components and Calibration Techniques	**Session Th2D** mm-Wave and THz Power Amplifiers	**Session Th2E** Measurement at the Limits	**Session Th2F** Advances in CMOS, and HBT Technologies for Monolithic ICs	**Session Th2G** Microwave and Millimeter Wave Wireless Energy Harvesting	**Session Th2H** Load Modulated Power Amplifiers
13:30 – 15:10	**Session Th3A** Non-Planar Filters 2	**Session Th3B** 3D Printed Wireless Modules and Systems			**Session We3E** The Art of Large Signal Measurement and Calibration	**Session Th3F** GaN Semiconductor Devices and Monolithic ICs	**Session Th3G** Novel Techniques and Applications for Near Field Wireless Power Transfer	
15:55 – 17:15								

Technical Track Key: Field, Device and Circuit Tech. | Passive Components | Active Components | Systems & Applications | Emerging Technical Areas | Focus or Special Sessions

Also on Thursday: IMS Exhibition, IMS Interactive Forum, MicroApps, Industry Workshops, IMS Panel Session, MTT-S Student Awards Luncheon, IMS Closing Session and Reception

For the latest on IMS and Microwave Week visit www.ims-ieee.org

Workshops, Short Courses

Day	Code	Length	Title
Sunday	SSA	Full day	The Dynamics, Bifurcation, and Practical Stability Analysis/Design of Nonlinear Microwave Circuits and Networks
Sunday	SSB	Full day	Build a 1GHz FMCW Radar in a Day
Sunday	WSA	Full day	Microwave Materials: Enabling the Future of Wireless Communication
Sunday	WSB	Full day	RF Circuit Design: Technologies for Tomorrow
Sunday	WSC	Full day	Recent Advances in Integrated Antenna-in-Package and Antenna-on-Chip Technologies and Techniques for 5G, Radar, and Emerging Millimeter-Wave Applications
Sunday	WSD	Half day	State-of-the-Art RF Receivers: Leading Edge Industrial Architectures and New Systems on the Horizon
Sunday	WSE	Full day	Analog and RF Hardware Security: Motivation, Challenges, and Solutions
Sunday	WSF	Full day	5G mmW to sub-THz Circuit and System Techniques
Sunday	WSG	Full day	Electronic-Photonic Integrated Systems for LIDAR and Sensing
Sunday	WSH	Full day	Power amplifier and transmitter designs for emerging sub-6 GHz 5G communications
Sunday	WSI	Full day	Design Challenges in 5G IoT
Sunday	WSJ	Full day	Quantum Computing for RFIC Engineers: Concepts, Devices, Systems, and Opportunities
Sunday	WSK	Full day	Efficient Millimeter-Wave Power Amplifier Design for 5G and Wireless Broadband Transmitters
Sunday	WSL	Full day	Integrated phased array ICs for 5G and beyond
Sunday	WSM	Full day	Sensors and Connectivity Enabling Autonomous Cars
Monday	SMA	Full day	Demystifying Noise Parameter Measurements and Model Extraction
Monday	WMA	Full day	Exploratory Semiconductor Devices for the 5G mm-Wave Era and Beyond
Monday	WMB	Full day	Low Phase Noise Oscillator and Frequency Synthesizer Techniques
Monday	WMC	Full day	5G: mmW Power Amplifiers & Technology Benchmarking
Monday	WMD	Full day	Measurement and Design Techniques for Next-Generation Communication Systems
Monday	WME	Full day	Millimeter Wave Power Amplifier Design Innovations
Monday	WMF	Full day	Measurement Challenges in Over-The-Air Testing
Monday	WMG	Half day	Advanced Packaging Technologies for High-Performance 5G Front-End Modules
Monday	WMH	Half day	Recent Advancement and Trends in 3D heterogeneous integration for mmW 5G and Terahertz
Monday	WMI	Full day	Digital Signal Processing for Radio Frequency Identification
Monday	WMJ	Full day	Advanced Non-Reciprocal Technologies for High-Frequency Applications based on Novel Approaches and Nanoscale Concepts
Monday	WMK	Full day	RF Integrated Magnetics – Devices, Integration and Applications
Friday	WFA	Full day	Electroceuticals: technologies and modeling for electromagnetically-mediated medical treatments
Friday	WFB	Full day	The Analog vs. Digital Battle – A Fight of Paradigms to Optimize Systems & PA Solutions for Wireless Infrastructure in 5G and beyond
Friday	WFC	Full day	Towards one Chip Solution for GaN Front-Ends
Friday	WFD	Full day	In-Band Full-Duplex Technologies and Applications
Friday	WFE	Full day	System Concepts and Digital Signal Processing for Advanced Microwave Sensors and Imagers
Friday	WFF	Full day	Advanced Radar Systems for Industrial, Medical and Consumer Applications
Friday	WFG	Half day	Microwave Engineering Applications of Machine Learning: Past, Present and Future
Friday	WFH	Half day	Challenges for mm-Wave Remote Radio Units in 5G Infrastructure

For the latest on IMS and Microwave Week visit www.ims-ieee.org

Exhibition Overview

The Exhibition consists of over 600 exhibiting companies who represent the state of the art materials, devices, components, and subsystems, as well as design and simulation software and test/measurement equipment. Whatever you are looking to acquire, you will find the industry leaders ready and willing to answer your purchasing and technical questions.

MicroApps and Industry Workshops

The Microwave Application seminars (MicroApps) are presented by technical experts from IMS2019 exhibitors with a focus on providing practical information, design, and test techniques that practicing engineers and technicians can apply to solve the current issues in their projects and products.

The Industry Workshops are in-depth industry-led presentations featuring hands-on, practical solutions often including live demonstrations and attendee participation.

For more information on MicroApps and Industry Workshops please visit www.ims-ieee.org/exhibition.

5G Summit, Tuesday, 4 June 2019

5G Summit Speakers:

- John Smee, Qualcomm Inc.
- Thomas Cameron, Analog Devices, Inc.
- Walter Honcharenko, MACOM
- Alastair Upton and Nitin Jain, Anokiwave
- Chih-lin I, China Mobile
- Farooq Khan, PHAZR

Panel Sessions, Monday, 3 June 2019 - Thursday, 6 June 2019

- **The Internet of Things (IoT)- Back to the Future or No Future?**
- **100 Gb/s Wireless Link: How do We Get There and What are the Future Applications?**
- **In-Band Full-Duplex: Is It Really Going To Happen?**
- **Will Artificial Intelligence (AI) and Machine Will Artificial Intelligence (AI) and Machine Learning (ML) take away my job as an RF/Analog Designer?**

RF Boot Camp, Monday, 3 June 2019

This one-day course is ideal for newcomers to the microwave world featuring the following topics:

- The RF/Microwave Signal Chain
- Network Characteristics, Analysis and Measurement
- Fundamentals of RF Simulation
- Impedance Matching & Device Modeling Basics
- Introduction to RF and Microwave Filters
- Spectral Analysis and Receiver Technology
- Signal Generation
- Modulation and Vector Signal Analysis
- Microwave Antenna Basics
- Introduction to Radar and Radar Measurements


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For more information visit, www.ims-ieee.org
IEEE
MTT-S
Get the entire pulse of the Microwave and RF industry in just a few days:
• The world's largest Microwave/RF component test & measurement, software and semiconductor exhibition featuring over 600 companies
• Over 75 technical sessions, workshops and panel sessions
• RF Bootcamp, a special course designed specifically for newcomers to the micro-wave world
• 5G Summit featuring experts from industry, government and academia
• Student forums such as design competitions, paper competition, PhD Initiative and Project Connect
• Special interest groups such as Women in Microwaves and Young Professionals
• Countless networking opportunities
• Special focus on startup companies with the first ever Startup pavilion, Startup panel session and Next Top Startup competition

RelComm Technologies Inc.
High Performance 1P4T Coaxial Relay

RelComm Technologies Inc. compliments its product line with a high performance 1P4T coaxial relay configured with "7-16 DIN" type connectors providing excellent RF performance to 3 GHz. Power rating is 4000 W CW to 250 MHz, 1400 W CW to 1 GHz, 1100 W CW to 2 GHz and 900 W CW to 3 GHz. Operating temperature range is −25°C to +70°C. The relay measures 4.75 in. square and is less than 4 in. tall and weighs under 3.5 lbs. It is fitted with a standard DE9P or DB15P for ease of wire up and is fully RoHS compliant. The relay is available in both failsafe and latching configurations with 12 and 28 V DC operation. Options include auxiliary position indicators, splash proof sealed and TTL controlled input.

www.relcommtech.com

Remcom Inc.
EM Simulation Software

VENDORVIEW

Remcom's complementary EM simulation products work together to provide complete end-to-end design of complex devices and wireless communication systems. Features include: high frequency antenna modeling for intricate devices, wireless communication and 5G network planning, massive MIMO beamforming and fixed wireless access and drive test simulation of automotive radar sensors. Visit Remcom at Booth 1012 for a demo of the new simulation platform.

www.remcom.com

RFMW/Ampleon
Advanced Rugged Transistors

VENDORVIEW

Ampleon introduces ART2K0FE, the first of its LDMOS Advanced Rugged Transistors (ART). The device is rated for 2000 W CW and handles > 65:1 VSWR without degradation or damage. It is designed to withstand the harshest conditions often found in applications such as industrial lasers, plasma generators and MRI RF amplifiers and can be used up to 65 V. The full ART portfolio will cover ceramic and plastic packages with a minimum longevity commitment of 15 years.

www.ampleon.com
www.rfmw.com

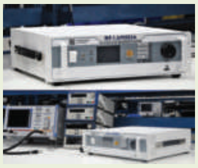
RFMW/Integrated Device Technology
600 to 4200 MHz RF Amplifier

VENDORVIEW

IDT's F0424 flexible 600 to 4200 MHz RF amplifier delivers high linearity and Zero-Distortion™ broadband performance for Rx and Tx applications. > 17.3 dB gain from a single, 5 or 3.3 V supply drawing 70 mA and OIP3 measures +40 dBm with 2.3 dB noise figure. The combination of low noise and high linearity allows transceiver solutions in repeaters, point-to-point radios, DAS and public safety applications. Available in a 2 × 2 mm package, its I/O matched to 50 Ω for ease of integration.

www.idt.com
www.rfmw.com

RF-Lambda
Benchtop Power Amplifiers



RF-Lambda introduces a new fully integrated high efficiency, high linearity wide band power amplifier. This model supports 26.5 to 34 GHz with up to 20 W of average power. The unit comes in a compact benchtop or rackmount package and is equipped with features such as input overdrive, over-current and over-temperature protection as well as temperature compensation. Ideal for aerospace/military, wireless infrastructure as well as EMC test and lab applications.

Absorptive SP8T RF Switch

RF-Lambda offers an extensive line of absorptive wide band switch matrices that are ideal for RF and microwave testing and phased array applications. This switch matrix is first of class with 8 channels covering frequencies from 0.5 to 43.5 GHz and switching speeds that are 50 to 100 ns. This switch comes equipped with a standard package for controlled environments up to 30,000 ft. As an added option, the switch is also available in a hermetically sealed package up to 60,000 ft. (MIL-STD-810/883) that is available upon request.

Wideband Solid-State Power Amplifiers

RF-Lambda announces a new high-power wideband solid-state power amplifier that is currently in stock. This unit features high efficiency, high linearity wideband performance from 18 to 47 GHz with up to 1 W of power. RF-Lambda's amplifiers are equipped with features such as input overdrive, over-current and over-temperature protection, as well as temperature compensation, making them ideal for EMC, Vsat, testing and radar applications.

www.rflambda.com

RFMW/Qorvo

VENDORVIEW

Wideband Driver Amplifier

The QPA2213 is ideal for commercial and military radar applications. This packaged GaN on SiC wideband driver amplifier covers 2 to 20 GHz bands. The QPA2213 provides > 2 W of saturated output power and 16 dB of large-signal gain while achieving > 23% power-added efficiency. This GaN driver can support a variety of operating conditions to best support system requirements. With good thermal properties, it can support a range of bias voltages.

www.qorvo.com
www.rfmw.com

RFHIC Corp.
GaN on SiC Power Amplifier

RFHIC Corp. introduces its latest 5 W (avg. power), GaN on SiC power amplifier (RTH353705X) designed for 5G massive MIMO and small cell applications. This fully matched 2-stage, Doherty GaN on SiC power amplifier has an exceptional power-added efficiency of 42% (PAPR 7.5 dB). The RTH353705X has 26 dB of typical gain at frequencies from 3.5 to 3.7 GHz and is packaged in a surface mount hybrid package. Custom designs are available upon request, with an average developmental period of 2 to 3 weeks.

rfhic.com

Richardson RFPD
Wideband RF Transceiver

Analog Devices' 75 MHz to 6 GHz ADRV9009 is the only transceiver with the bandwidth and RF performance to create a clear path to 5G, and the versatility to support all 2G, 3G and 4G cellular standards. It is part of ADI's RadioVerse™ technology and design ecosystem that gets customers through the entire radio design process—from idea, to proof of concept, to production—as fast as possible.

www.richardsonrfpd.com

RLC Electronics
SPDT Switches

RLC Electronics is offering DC to 65 GHz SPDT switches, made available with customization options including your choice of control voltage, operating mode, indicators and TTL or BCD drivers, as well as special mating/power connectors. These switches exhibit low loss (< 1 dB) and maintain high isolation (> 50 dB) over the full passband. Manually controlled options are available as well which are hand-driven utilizing a toggle on the top of the switch. Some typical applications for the 65 GHz switches include collision avoidance test systems and 5G products.

www.rlcelectronics.com

Rogers Corp.
Laminates, Bonding Materials and Foils

Rogers Corp. introduced a set of next-generation products designed to meet the existing and emerging needs of advanced mmWave multi-layer designs. RO4835T™ laminates are 3.3 Dk, low loss, spread glass reinforced, ceramic filled thermoset materials designed for inner-layer use in multilayer board designs. RO4450T™ bonding materials are 3.2 to 3.3 Dk, low loss, spread glass reinforced, ceramic filled bonding materials. CU4000™ and CU4000 LoPro® Foils are sheeted foil options for designers looking for foil lamination builds, and provide good outer layer adhesion when used with RO4000 products.

www.rogerscorp.com

Rohde & Schwarz USA Inc.
High-End Vector Network Analyzers

VENDORVIEW

Rohde & Schwarz presents the R&S ZNA, a new generation of high-end vector network analyzers (VNA) offering outstanding RF performance and a unique hardware concept that simplifies measurement configuration. Its excellent measurement stability and trace noise enable users to perform demanding measurements on active and passive components and modules. Thanks to its innovative, DUT-centric approach, the world's first purely touch-operated VNA reduces configuration times to a minimum. It comes with four independent sources, eight parallel receivers and two integrated local oscillators.

www.rohde-schwarz.com/product/zna

Roos Instruments
ATE System

Be ready for 5G testing requirements now with the future proof RI Cassini modular ATE system with hot-swappable banded building block instruments. RI fuses this flexible instrument framework with patent pending fixturing technology learned from 30 years of system integration experience to deliver seamless multi-functional test. Cassini scales efficiently from DC to 100 GHz, supporting AiP and OTA devices while providing the broadest production proven full 5G NR test capability. Visit at IMS2019 in Booth 880.
www.roos.com

Rosenberger
Series RPC-1.35 Connectors

Rosenberger introduces a new precision connector series to meet the increasing demand for proper RF-connections up to 90 GHz. The newly developed RPC-1.35 connector series—the "E connector"—is characterized by a highly robust mechanical design, min. 3000 mating cycles, high connector repeatability, max return loss values. The product range covers semi-rigid and flexible cable assemblies, PCB connectors, test PCBs, cable connectors, in-series and inter-series adaptors, test port, floating and waveguide-to-coaxial adaptors, as well as gauge and calibration kits. The interface standardization is in progress.
www.rosenberger.com

SignalCore Inc.
6 GHz RF Signal Source

The SC5507A and SC5508A are from SignalCore's PSG line of signal sources, providing tunable frequency range from true DC to 6.2 GHz, with resolution of 1 MHz. Their amplitude range is typically between −50 to 15 dBm stepping in 0.01 dB, and harmonics are typically < −35 dBc. Phase noise at 5 GHz CW is better than −126 dBc/Hz at 10 kHz. These devices incorporate a 1 MHz to 6 GHz power sensor whose measurement range is −30 and 15 dBm with accuracies of better than 0.25 dB.
www.signalcore.com

Signal Hound
Headless RF Spectrum Analyzer

The new SM200A is an affordable, compact and capable spectrum analyzer for a range of applications. Tuning from 100 kHz to 20 GHz, the analyzer has an instantaneous bandwidth of 160 MHz and a high dynamic range of 110 dB. A sustained sweep speed of 1 THz/s and ultra-low phase noise means the SM200A introduces only 0.1% error to EVM measurements. Ready to ship. Visit at IMS2019 in Booth 123.
www.signalhound.com/sm200a

Signal Microwave
Solderless Board Launch Connectors and Test Boards

Signal Microwave (Booth 1141) introduced new types of solderless board launch connectors and test boards. Compared to current vertical mount connectors on the market, this new TLF40-002 connector has the same footprint and mounting configuration as the current industry standard connectors. A simple to design board level transition is all that is required to achieve performance equal to that which before could only be achieved by edge launch connectors.
www.signalmicrowave.com

Southwest Microwave
Board-Mounted Vertical Launch Connectors

Providing excellent signal integrity for microstrip and grounded coplanar waveguide designs, Southwest Microwave vertical launch connectors are reusable and can be installed without soldering. The newest edition is the industry's first 1 mm board-mounted vertical launch connector, achieving low insertion loss and VSWR to 110 GHz. The connectors are also available in 1.85 and 2.92 mm configurations, covering DC to 67 and DC to 40 GHz, respectively. Visit Southwest Microwave at IMS2019 in Booth 344.
www.southwestmicrowave.com/interconnect

Spectrum Elektrotechnik GmbH
New Miniature Phase Adjusters

Spectrum Elektrotechnik GmbH has added a series of miniature phase adjusters, the LS-0040-KFKM, using 2.92 mm connectors, the LS-0050-HFHM, using 2.4 mm connectors, the LS-0050-HFVM, using 2.4 mm and 1.85 mm connectors and the LS-0065-VFVM, using 1.85 mm connectors, covering the frequency range from DC to 63 GHz. The products maintain impedance of 50 ohms over the full adjustment range, positive resettable locking mechanism, low VSWR and rugged construction. Please ask for the new 100-page catalog.
www.spectrum-et.com

SV Microwave
LiteTouch Solderless PCB Connectors

SV now offers a complete line of extreme frequency surface mount PCB connectors that meet the industry need for high performing solderless connectors for precision thin substrate mounting. As frequencies increase and board substrates become thinner, the standard solderless PCB compression mount connectors can create undesirable results on thin (< 0.010 in.) dielectric PCB. SV's LiteTouch connector addresses this issue by maintaining a solderless connection while keeping the board material intact.
www.svmicrowave.com

Synergy Microwave Corp.
SAW Based Fixed Frequency Sources

The FCTS-series of SAW resonator based, fixed frequency phase locked oscillators (PLO) is available in frequencies that operate at 800 MHz, 1 and 2 GHz. The phase noise is −144 dBc/Hz at 10 kHz offset for the 800 MHz model, and −135 dBc/Hz at 10 kHz offset for the 2 GHz model, making these sources ideal for low jitter main clocking in A/D and D/A converters. This series is surface mount packaged and RoHS compliant. Contact Synergy Microwave sales for further information and pricing.

Surface Mount DRO Oscillators

The SDRO-series of surface mount, dielectric resonator based oscillators now includes models centered at 8, 9, 10 and 10.24 GHz. These are supplied in a surface mount package of only 0.75 in. square by 0.53 in. high with ENIG terminations. The 8 GHz DRO exhibits low phase noise of −114 dBc/Hz at 10 kHz offset and −170 dBc/Hz at 10 MHz offset and the 10.24 GHz oscillator boasts low noise of −105 dBc/Hz at 10 kHz offset and −165 dBc/Hz at 10 MHz offset.
www.synergymwave.com


strand25
Thank you for an amazing 25 Years.
Strand would like to thank our fantastic clients, their insanely smart customers, and our dedicated partners like the Microwave Journal, for twenty-five years of success.
It's been our mission to create the most engaging and provocative campaigns in the business. So we humbly share this milestone with you and the billions around the world who've benefited from your shared innovations.
StrandMarketing.com

MICRO-ADS

Teledyne Relays
Indium Phosphide Active RF Reflective SPDT

Teledyne Relays (Booth 1124) introduces the InP1012-60 active RF SPDT. This InP HEMT has a DC to 60 GHz bandwidth and 40+ Gbps signal integrity. With low insertion loss, high linearity and 100 ns switching time, InP1012-60 is ideal for ATE and 5G telecom/datacom applications. The InP1012-60's compact 3 × 3 × 1 mm package is shock and vibration resistant, operates from –65°C to 125°C and can tolerate 100 krads—making this an excellent choice for military and space applications.
www.teledynerelays.com

Teledyne Storm Microwave
E- & W-Band Connectivity Solutions

Teledyne Storm's SF047EW cable offers the proven durability and robustness of their Storm Flex® 047 cable, enhanced with improved insertion loss stability with flexure that exceeds VDI/VDE 2622 Part 19 requirements. Small and flexible enough to accommodate a variety of test setups, the SF047EW is optimized for broadband connectivity, operating to 110 GHz with a 1 mm connector or WR10 and WR12 waveguide adapters. A new 1.35 mm connector option will soon be available, offering additional capabilities to 90 GHz.
www.teledynestorm.com

Telegartner Inc.
RF Coaxial Connector Solutions

Telegartner Inc. is the U.S. affiliate of Telegaertner Karl Gartner GmbH. Telegartner has been producing and providing RF coaxial connector solutions for over 70 years and can meet all the technical demands and requirement needs whether quantities are large or small. Telegartner is the ideal supplier and development partner for customers who demand and expect the best connector solutions for their success.
www.telegaertner.us

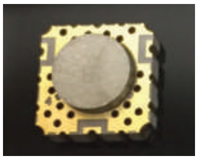
Times Microwave Systems
Coax Test Cables

Times Microwave introduces its new Clarity™ Series of 18, 26.5 and 40 GHz coax test cables. Clarity™ boasts steel torque, crush and overbend protection with abrasion resistance, while not compromising flexibility. The cable is ultra-stable through 40 GHz with exceptionally low attenuation. The design includes an ergonomic, injection molded strain relief and Times' new, SureGrip™ coupling nut to significantly improve the user's everyday experience. Clarity™ is appropriate for use as VNA test port extension, R&D lab, production test or system interconnect cables.
www.timesmicrowave.com

Transline Technology
Printed Circuit Boards

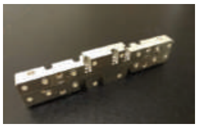
Transline Technology has been working side-by-side with visionary engineers in the RF/microwave industry for over 20 years to produce innovative PCB. TTI offers rigid, rigid-flex and flex PCB fabrication services as well as photo-chemical etching and forming. The company stocks Rogers, Taconic and Arlon materials with the ability to turn product in as little as 24 hours. Visit at IMS2019 in Booth 415.
www.translinetech.com

TTM Technologies
Surface-Mount Circulator



The TTM XCIR85100 is a high performance surface-mount circulator designed for phased array radar antennas, EW and communication systems. The patented device operates over a frequency range of 8.5 to 10 GHz and offers 20 dB isolation with an industry-best 0.2 dB insertion loss and RF power handling up to 30 W CW. This device has a small 0.35 in. sq. form factor, available in volume tape and reel, and withstands typical MIL ground and airborne environments. Also available in C-Band 5 to 6 GHz.
www.ttm.com

Universal Microwave Technology Inc.
D-Band Diplexer



Universal Microwave Technology Inc. announced a new product line for D-Band diplexer. The diplexer works for 141 to 148 and 156 to 163 GHz with low insertion loss and good flatness in passband. The diplexer also offers more than 60 dB rejection for both TX and RX band. Universal Microwave Technology Inc. provides other microwave components up to D-Band.
www.umt-tw.com

Vaunix
Bidirectional, 8-Channel Digital Attenuator

VENDORVIEW

The LDA906V-8 is a highly accurate, bidirectional, 8-channel digital attenuator.

The LDA-906V-8 provides calibrated attenuation from 200 to 6000 MHz with a step size of 0.1 dB and typical accuracy of < 0.25 dB over 90 dB of control range. The attenuator is specifically designed for errorless attenuation transitions in ultra-high speed 5G, Wi-Fi and PTP networks. This Lab Brick uses a native USB HID interface to avoid the difficulties inherent in using older serial or IEEE-488 interfaces implemented over USB.

www.vaunix.com

Velocity Microwave
Repairable VNA Cables

Velocity Microwave provides another industry first. If your Vector VNA cable becomes damaged or worn and needs repair, you can get a loaner by the next business day. Why buy VNA cables that cannot be repaired? Why buy other "repairable" cables you might get back in 6 to 8 weeks? Velocity has your back. Vector VNA cables have a best-in-class two-year warranty and exclusive Hot Swap program for 10 more years.

www.velocitybygte.com/vector

Wenzel Associates
OCXO + Rubidium Ruggedized Frequency Source

Wenzel Associates' is now offering QRb Sync series products, which includes a low noise OCXO coupled with a very stable disciplined Rubidium oscillator, all combined within a small ruggedized housing. This combination offers exceptional phase noise performance as well as excellent stability. There are many options to choose from, depending on the application, including HF and VHF frequencies from 10 to 100 MHz as well as low g-sensitivity and internal vibration isolation.

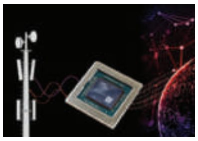
www.wenzel.com

West Bond
Wire Bonders

Introducing the most flexible, complete wire bonders system available today. 7KE and 4KE series wire bonders: bonding at 45 degree feed for tail control, 90 degree for ribbon and deep access and ball bonding without changing heads. Wedge bonding Au, Al, Cu; ball bonding Au, Cu, Automatic, semiautomatic and manual all ESD protected. Ultrasonic, thermosonic and thermocompression wire/ribbon bonders; eutectic and epoxy die bonders, insulated wire bonders and pull testers. Visit at IMS2019 in Booth 856.

www.westbond.com

Xilinx
Adaptable, Intelligent 5G Infrastructure

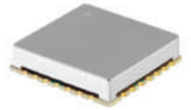


Xilinx (Booth 194) is the engine behind 5G radio and mMIMO deployment. Only Xilinx provides adaptable 5G communication platforms, with highly integrated silicon featuring RF ADC and DACs, accelerated 5G NR and the highest efficiency performance for mMIMO radios, macro base station and small cell deployments. This IMS2019 conference, with Xilinx experts, customers and partners, learn the latest about the innovative Xilinx Zynq® UltraScale+ RFSoC portfolio and how it is being deployed in 5G NR.

www.xilinx.com

Z-Communications
PLL Synthesizer

VENDORVIEW



The RFS12000C-LF is a fixed frequency PLL synthesizer which encompasses an internal 10 MHz reference clock to produce a low noise output signal at 12 GHz. It operates off a 5 and 3.3 VDC supply while drawing 95 and 15 mA, respectively, all while delivering phase noise of −90 dBc/Hz at 10 kHz offset. It is housed in a 1 × 1 × 0.22 in. package and operates over the industrial temperature range of −40°C to 85°C. Visit at IMS2019 in Booth 155.

www.zcomm.com

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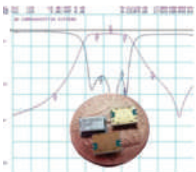
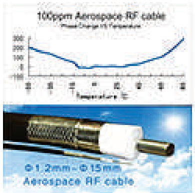
3H Communication Systems
Leadless, Pico Series Filters



3H's new Pico Series is a miniature, leadless, SMT, Ku-Band, bandpass filter offering low passband insertion loss. 3H Pico series filters are custom designed to meet its customer specifications and can be packaged in a 0.25 × 0.18 × 0.08 in. housing. The filter is manufactured for automated assembly processes and is designed to meet Mil-Std-202 conditions. Available in RoHS and non-RoHS packages. 3H Pico Series filters are available from 5 to 25 GHz.
www.3Hcommunicationsystems.com

Advanced Microwave Technology (AMT)
DC to 110 GHz Connect Solution



AMT is a company in R&D, designing, manufacturing and distribution of RF, microwave and mmWave 50 Ω coaxial cables, connectors, adapters, cable assemblies and passive devices. With 10 years rapid development, more than 200 types of cables are available. Special products include phase stable cables with out-meter covers from mini 1.2 to 12 mm enduring high-power and ultra-stable phase cables whose phase vs. temperature is 100 PPM at –10°C to +55°C.
www.advancedmicrowave.net

Exceed Microwave
Waveguide Group Delay Equalizer

VENDORVIEW

Do you ever have too much group delay variation in your passband? Exceed Microwave's waveguide group delay equalizer can distort the group delay with minimum impact on the amplitude. Provide the shape of your current group delay and Exceed will inversely match the shape to help flatten out the overall group delay response.
www.exceedmicrowave.com/index.php/products/equalizers

Fairview Microwave Inc.
Low-PIM Coaxial Cables

Fairview Microwave Inc., an Infinite Electronics brand, has released a new series of low-PIM coaxial cable assemblies in standard and custom lengths that are ideal for distributed antenna systems (DAS) and are available with same-day delivery. The over 100+ standard configurations that make up Fairview Microwave's new line of low-PIM coaxial cable assemblies deliver PIM levels of less than –160 dBc. These high-quality cables provide excellent VSWR and low insertion loss.
www.fairviewmicrowave.com

Integrated Microwave
Developer's Kits

Integrated Microwave introduces four developer's kits for 5G applications. Each kit includes four bandpass filters consisting of customer's choice of four bandwidths: 50, 100, 200 and 400 MHz. Adjusting the center frequency to different band centers within the proximity of a specified N-Band range is an available option. Filters measure 1.9 × 0.5 × 0.425 in. excluding connectors, and offer high-Q, highly selective temperature compensation and 70 dB out-of-band rejection.
www.imcsd.com

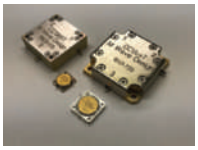
Kaelus
Cable & Antenna Analyzer

The iVA Series Cable and Antenna Analyzer (560 to 2750 MHz) enables accurate measurement of return loss sweeps, distance-to-fault and cable loss in RF infrastructure. The iVA is a rugged, battery-operated module that can be remotely controlled with any Bluetooth-enabled tablet or laptop computer. Possessing a simple to operate user interface with the unique ability to generate and submit complete test reports onsite, the iVA used Class 1 Bluetooth functionality for remote control up to 100 m.
www.kaelus.com

MilesTek
High-Temp Ethernet Cables

MilesTek's high-temp cable assemblies feature FEP jackets that are rated for a wide temperature range of –55°C to +150°C and a double shielded cable with both 100% foil and 85% braid shields that provide maximum EMI and RFI protection. These cables are offered off-the-shelf in Cat6a, Cat5e and Cat5e slim construction versions and comply with all RoHS directives. Furthermore, the fire properties of these Ethernet cables meet FAR (Federal Aviation Regulation), Airbus and Boeing requirements.
www.milestek.com

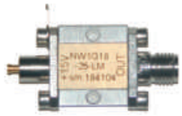
M Wave Design Corp.
High Power T/R (AESA) Circulators



The M Wave Design Corp. has developed small for, high-power circulators for AESA Radar systems. These products cover the common UHF, L-, S-, C- and X-Band applications. Their small footprint with high-power handling and low insertion loss will improve the dynamic range of your radar design. See what their design team can do for you.
www.mwavedesign.com

NoiseWave
Miniature Calibrated Noise Source

NoiseWave announces the NW1G18-LM miniature calibrated noise source. The NW1G18-LM features broadband frequency coverage from 1 to 18 GHz. Designed in an industry standard small package, 0.53 × 0.62 × 0.25 in. excluding field replaceable connectors, the NW1G18-LM offers a minimum of 25 dB ENR with spectral flatness of ±1.25 dB. The unit operates from +15 VDC and typically draws less than 15 mA. Custom models welcome. NoiseWave serves the defense, aerospace, communications, test and instrumentation markets.



www.noisewave.com

PolyPhaser
Coaxial DC Block RF Surge Protection

The IS-B50 Series are designed to protect against lightning events and are ideal for HF, UHF and VHF radios. The IS-B50 family of RF protectors can be used for general radio use with frequency ranges between 1.5 to 1000 MHz, the series offers frequency ranges from 1.5 to 1000 MHz and connectors available in N-Type and UHF.
www.polyphaser.com

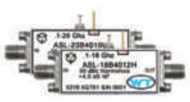
Seven Associates
Digital Cut-Off Saw

The T-500D digital cut-off saw is designed for production cutting of semi-rigid coaxial cable. This saw runs at 8000 max RPM and uses a 3 in. solid carbide blade to produce clean, precise cuts with no significant smear or burr. The saw cuts 0.141 in. diameter coax and all smaller sizes using interchangeable guide blocks. This tool is designed for cable assemblies that rely on extremely precise cut length. It will consistently hold a 0.0005 in. tolerance.
www.sevenassociates.com

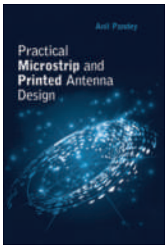
Spacek Labs
Broadband Bandpass Filter

Spacek Labs Fc2-625-9 is a WR-15 broadband bandpass filter. This series is offered from 18 to 110 GHz with bandwidths from 30 to 100% of the band. These waveguide filters combine exceptional performance lowpass filter and highpass filter technologies. Model Fc2-625-9 has a passband from 48 to 72 GHz. Lower and upper 20 dB rejection is 45 and 74 GHz respectively, rejecting > 30 dB out to 110 GHz. Insertion loss is 1 dB typ., 2 dB max.
www.spaceklabs.com

Wright Technologies (WT)
Broadband Harmonics



Models ASL-18B4012H, ASL-20B4010H are 0.1 to 18, 0.1 to 20 GHz LNAs that offer great harmonic signal purity of > 30 dBc while being tested at –35 dBm. The typical noise figure is below 3 dB across the frequency bands, with a 3.8 dB NF at 18 GHz, and 4.5 dB NF at 20 GHz. The gain blocks available are 30 and 40 dB. Output P1dB is 12 and 10 dBm, backed with the four-year warranty program. This type of service can give WT customers the support they need for long term uses between costly replacements.
www.wrighttec.com



Practical Microstrip and Printed Antenna Design

Anil Pandey

This comprehensive resource presents antenna fundamentals balanced with the design of printed antennas. Over 70 antenna projects, along with design dimensions, design flows and antenna performance results are discussed, including antennas for wireless communication, 5G antennas and beamforming. Examples of smartphone antennas, MIMO antennas, aerospace and satellite remote sensing array antennas, automotive antennas and radar systems and many more printed antennas for various applications are also included. These projects include design dimensions and parameters that incorporate the various techniques used by industries and academia.

This book is intended to serve as a practical microstrip and printed antenna design guide to cover various real-world applications. All antenna projects discussed in this book are designed, analyzed and simulated using full-wave electromagnetic (EM) solvers. Based on several years of the author's research in antenna design and development for RF and microwave applications, this book offers an in-depth coverage of practical printed antenna design methodology for modern applications.

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FABS and LABS

MACOM—Partners from RF to Light

MACOM was launched in the summer of 1950 as Microwave Associates by four ex-Sylvania engineers—Vessarios Chigas, Louis Roberts, Hugh Wainright and Richard Walker—as a consulting and research company for mmWave technology. The company branded itself as the first name in microwave for many years, as an early company to the growing microwave industry. It has acquired and spun off many other famous companies, such as Linkabit, which included Irwin Jacobs and Andrew Viterbi who launched Qualcomm, Omni Spectra and Adams Russell, before being re-launched as an IPO in 2012 after its breakup by Tyco Electronics a few years prior.

The company started in Boston but moved into several suburbs, as it expanded its operations around the Boston area. In 1984, MACOM established the Advanced Semiconductor Operation in Lowell, Mass. to focus on GaAs ICs. The Lowell facility recently underwent a large expansion and building update to accommodate its growth.

The new 280,000 square foot headquarters includes the heart of the company, its original wafer fabrication facility, which contains 34,000 square feet of clean room manufacturing space outputting 2,000 wafers per month. The IC fabrication includes Silicon, GaAs and InP devices for both RF/microwave and optical applications ranging from diodes to highly integrated circuits. The company also makes use of external foundries for other processes and additional capacity.

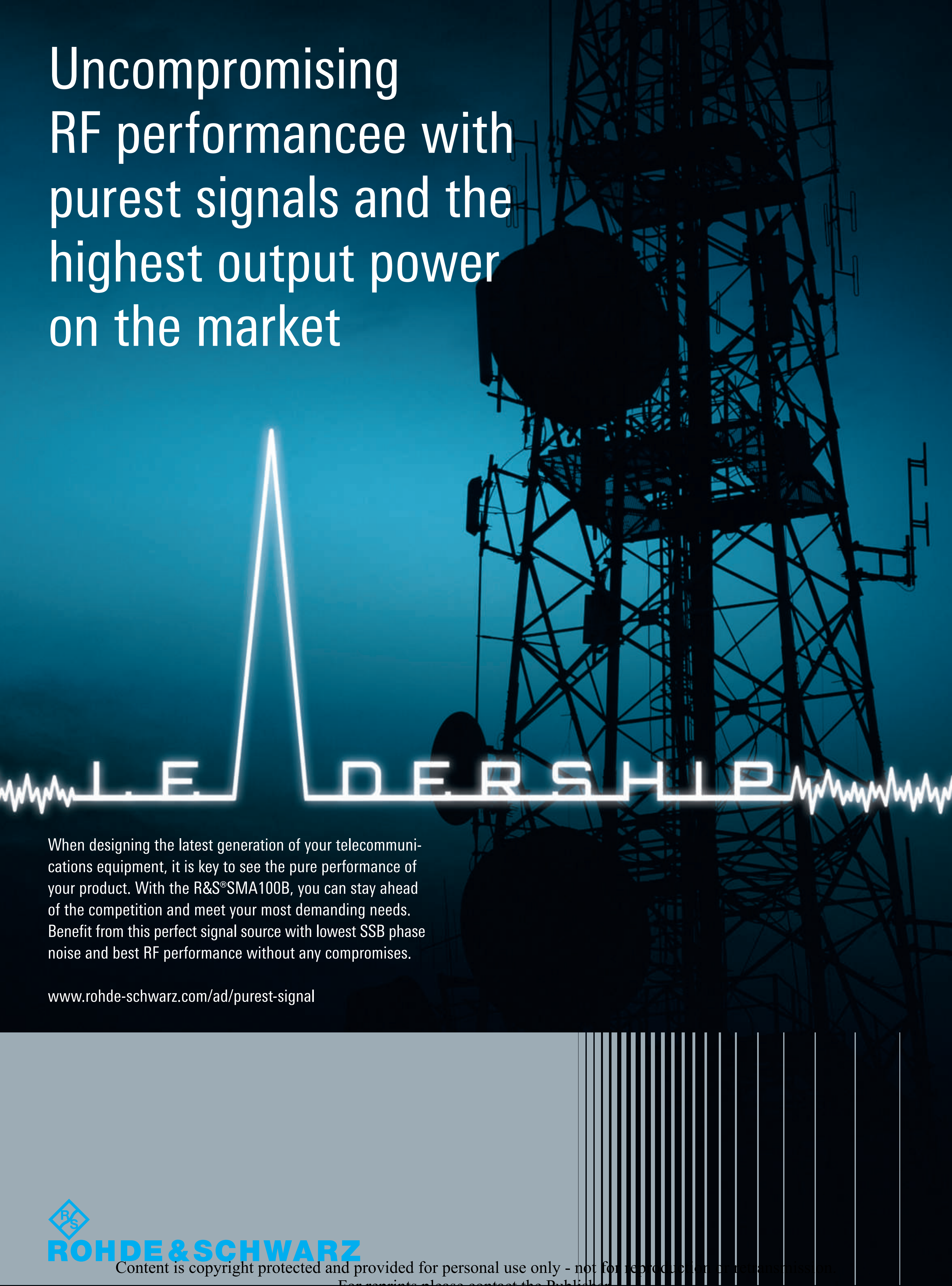
The Lowell wafer fabrication equipment set includes i-line steppers with TEL coaters, E-beam system for fine line lithography, contact aligners, evaporators, medium current implanter, rapid thermal anneal system, multiple grind and polish tools, various state-of-the-art dry etchers, saw/scribe for wafer singulation, dual chamber epitaxial reactors and wafer bonders for PIN diodes. MACOM maintains an annual capital budget for new equipment and building renovations to continuously improve the Fab environment and capabilities.

Process control and proper inspection are key attributes of MACOM's operation. The facility includes automated optical inspection, Zeiss Analytical SEM with EDX, Hitachi CD SEM, 3D optical interferometry and laser imaging, spectrophotometry, photoluminescence, acoustic micro imaging and surface charge analyzer. The company makes use of outside labs for more exotic analysis such as SIMS, FIB, EMMI, EDX line scans, etc. The facility is ISO9001 certified with Trusted Foundry and DLA Certifications.

MACOM uses the eight disciplines as a way of business and culture to handle manufacturing issues. First they establish a team of people with product/process knowledge. Then they describe the problem: who, what, where, when, why, how. Next they develop an interim containment plan before proceeding to determine and verify the root causes and escape points. Next they verify permanent corrections followed by defining and implementing corrective actions. At the end of the process, they prevent recurrence and system problems by modifying the management systems, operation systems, practices and procedures. And most importantly, the final step, to congratulate the team.

Today, MACOM is not only a leading microwave components company, but also a leader in the optical components area through several acquisitions. They recently announced a partnership with STMicroelectronics to process 6 in. GaN on Silicon wafers for high volume RF/microwave power products and plan to advance to 8 in. wafers in the near future. The plan is to drive down the cost of GaN devices for wide commercial adoption from telecom to RF energy applications. MACOM remains aggressive in market driving for change in the way traditional markets are approached—just as they did in 1950 to push mmWave technology to the forefront of the industry.

www.macom.com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Directional Couplers

Model	Type	Frequency (MHz)	Power (W CW)	Coupling (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
C8740	Dual	20-512	200	40	0.3	Tabs	1.5 x 0.95 x 0.55
C9655	Dual	20-1000	100	30	0.7	Tabs	1.5 x 0.95 x 0.55
C8631	Dual	20-1000	150	40	0.35	Tabs	1.5 x 0.95 x 0.55
C10561	Dual	20-1000	250	50	0.1	SMT	1.35 x 1.0 x 0.15
C8025	Bi	500-3500	125	30	0.3	Drop-In	1.3 x 1.0 x 0.07
C8098	Bi	800-2000	200	30	0.25	Drop-In	1.3 x 1.0 x 0.07

0° (In-Phase) Combiners/Dividers

Model	Type	Frequency (MHz)	Power (W CW)	Isolation (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
D9888	2-Way	1000-3000	500	15	0.35	SMT	2.8 x 2.2 x 0.27
D9922	2-Way	2000-6000	200	15	0.35	SMT	1.4 x 1.1 x 0.14

90° & 180° Hybrids

Model	Type	Frequency (MHz)	Power (W CW)	Amp. Bal. (±dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
QH9056	90°	30-520	400	1.2	0.80	Drop-In	4.0 x 1.7 x 0.29
QH9304	90°	60-1000	150	1.0	1.0	Drop-In	2.0 x 1.0 x 0.16
QH8849	90°	80-1000	250	1.0	0.65	Drop-In	2.9 x 2.1 x 0.31
QH11489	90°	80-1000	600	0.8	0.6	Drop-In	3.33 x 2.25 x 0.31
QH8100	90°	100-512	250	0.5	0.45	Drop-In	3.3 x 1.52 x 0.28
QH8922	90°	150-2000	100	1.0	0.75	SMT	1.47 x 1.13 x 0.16
QH11643	90°	200-1000	200	0.55	0.4	SMT	2.8 x 0.75 x 0.16
QH10900	90°	380-2500	150	0.6	0.55	Drop-In	1.3 x 1.3 x 0.15
QH7900	90°	450-2800	125	0.45	0.55	SMT	1.5 x 1.1 x 0.095
QH7622	90°	500-3000	150	0.6	0.55	Drop-In	1.65 x 1.1 x 0.09
QH11687	**90°**	**500-6000**	**150**	**0.7**	**0.75**	**SMT**	**1.28 x 1.08 x 0.13**
QH11113	90°	600-4000	150	0.7	0.5	SMT	1.29 x 0.99 x 0.12
QH10756	90°	700-6000	100	0.6	0.55	SMT	0.75 x 0.45 x 0.09
QH10541	90°	700-6000	150	0.6	0.5	SMT	0.86 x 0.66 x 0.09
QH10089	90°	800-2800	200	0.4	0.35	SMT	1.25 x 0.55 x 0.08
QH11805	90°	800-3200	200	0.5	0.4	Drop-In	2.2 x 0.8 x 0.174
QH8105	90°	800-4200	150	0.5	0.55	Drop-In	1.5 x 1.08 x 0.09
H10125	180°	1000-3000	350	0.3	0.5	SMT	2.31 x 1.21 x 0.25
QH10827	90°	1000-7500	100	0.7	0.65	SMT	0.86 x 0.61 x 0.09
QH10828	90°	1000-8000	100	0.7	0.9	SMT	0.65 x 0.5 x 0.07
QH10148	90°	2000-6000	100	0.5	0.3	SMT	0.75 x 0.45 x 0.08
H10126	180°	2000-6000	100	0.4	0.8	SMT	1.15 x 0.6 x 0.14

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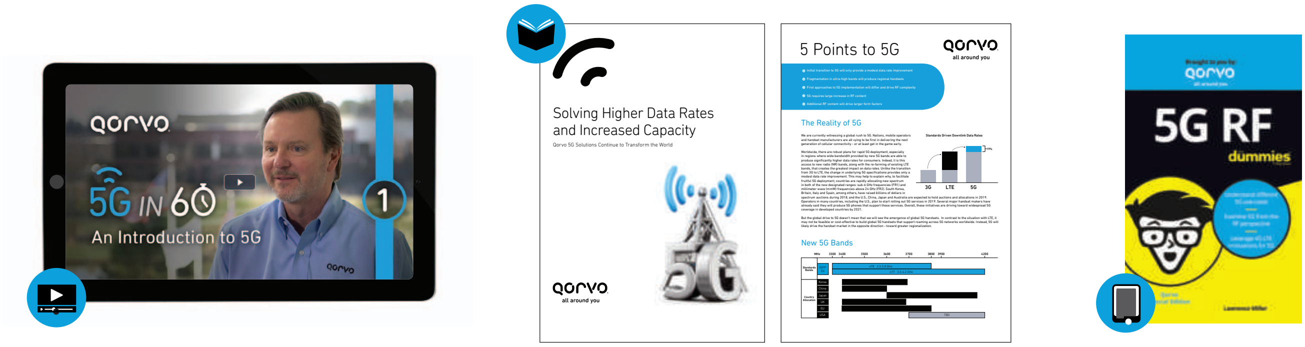

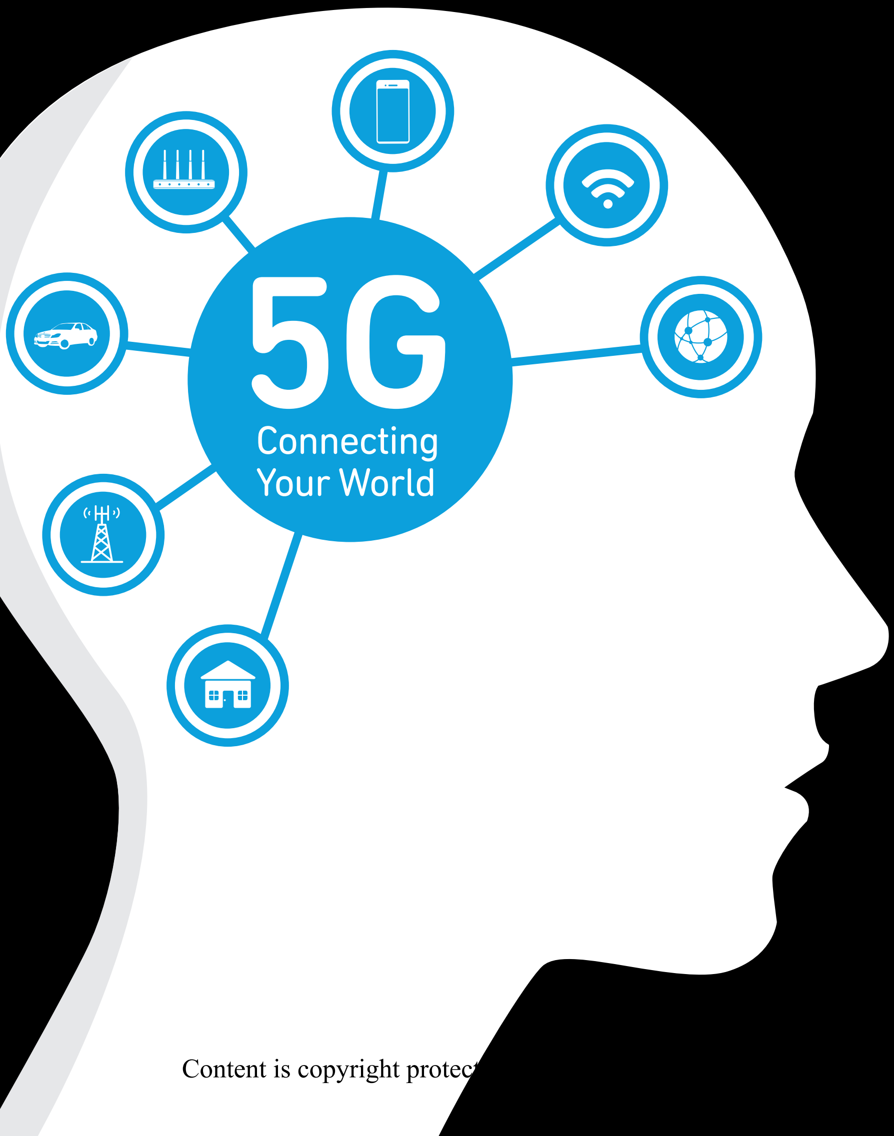

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What is 5G?

5G is massively broadband

Reaching into frequencies never previously thought of for mobile wireless — above 3.4 GHz, and even to 30 GHz and beyond.

5G is ultra efficient

For streaming data, taking full advantage of carrier aggregation and massive MIMO.

5G is fixed wireless

Giving more choices to get 1 Gb/s connections to your home and business.

5G is the backbone of the Internet of Things

Connecting more than a trillion devices to the internet in the next 10 years.

5G is wireless infrastructure

Using beam steering and high-power GaN, based on the technologies in phased-array antennas for defense.

5G is low-latency

For real-time connections enabling autonomous vehicles and augmented/virtual reality.

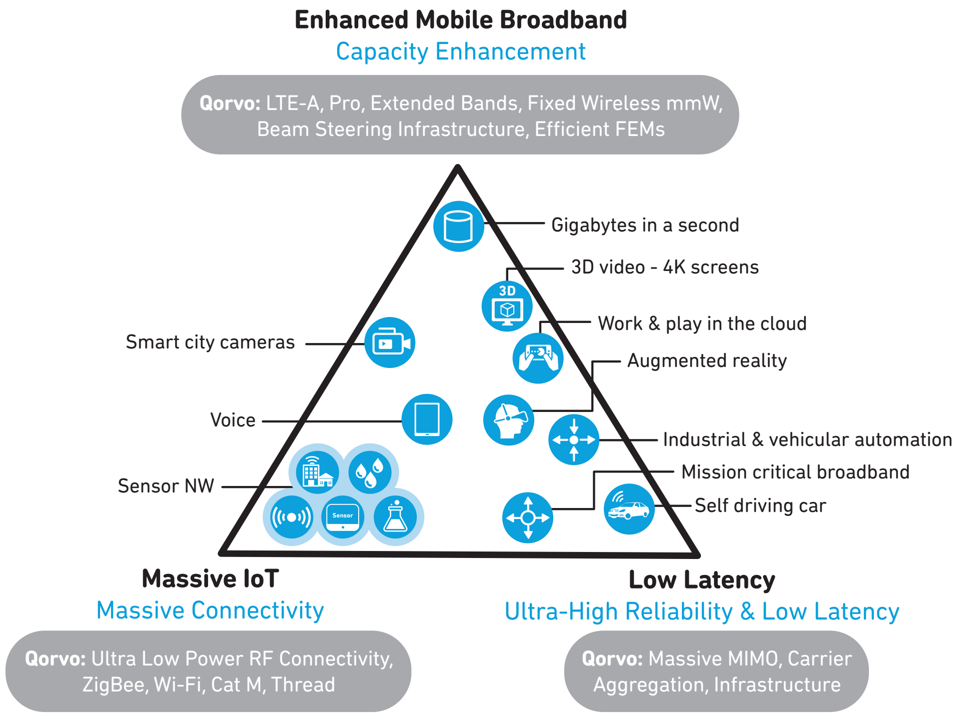
Qorvo is the standard setter – participating in standards bodies and partnering with wireless carriers – to define 5G RF for the future.

5G Complements the 4G LTE Network

- 5G will start as an overlay of the 4G LTE network.
- The 5G radio specification (called 5G NR for "new radio") will have both non-standalone (NSA) and standalone (SA) operation.
- NSA is an evolutionary step for carriers to offer 5G services without building out a 5G core network, until they add the full SA 5G core later.
- Starting in 2019, 5G will encompass major new capabilities.

Connecting the Uses of 5G

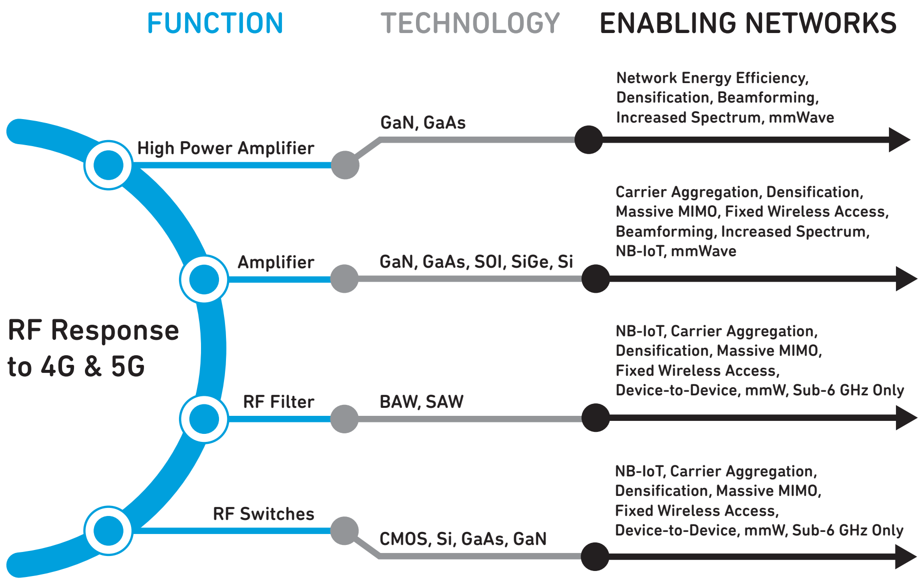
Qorvo connects RF for all 5G use cases — more than just cellular and Wi-Fi.



(Source: Qorvo, Inc., from ITU-R IMT 2020 requirements)

RF Communication Technologies By Use Case

5G will overlay the 4G LTE network in the coming years. The RF function, frequency band, power level and other performance requirements determine which semiconductor technology is the best fit.



5G Fixed Wireless Access Array and RF Front-End Trade-Offs

The vision of next-generation 5G networks is to deliver an order-of-magnitude improvement in capacity, coverage and connectivity compared to existing 4G networks, all at substantially lower cost per bit to carriers and consumers. The many use cases and services enabled by 5G technology and networks are shown in **Figure 1**. In this first phase of 5G new radio (NR) standardization, the primary focus has been on defining a radio access technology (RAT) that takes advantage of new wideband frequency allocations, both sub-6 GHz and above 24 GHz, to achieve the huge peak throughputs and low latencies proposed by the International Mobile Telecommunications vision for 2020 and beyond.

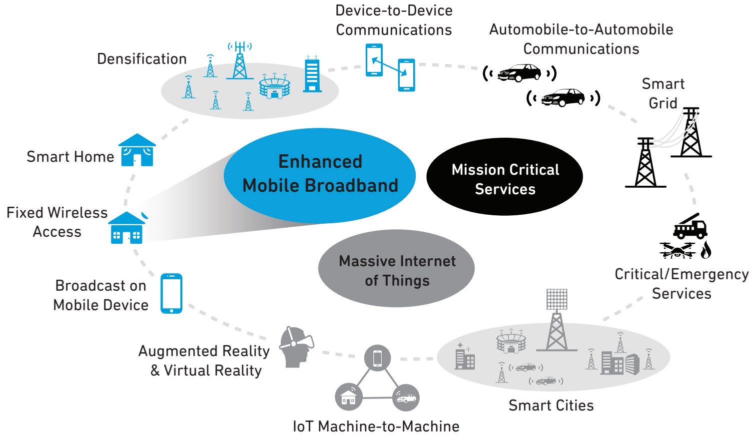


Figure 1 5G use case.

Mobile network operators are capitalizing on the improvements introduced by NR RAT, particularly in the mmWave bands, to deliver gigabit fixed wireless access (FWA) services to houses, apartments and businesses, in a fraction of the time and cost of traditional cable and fiber to the home installations. Carriers are also using FWA as the testbed toward a truly mobile broadband experience. Not surprisingly, Verizon, AT&T and other carriers are aggressively trialing FWA, with the goal of full commercialization in 2019.

In this article, we analyze the architecture, semiconductor technology and RF front-end (RFFE) design needed to deliver these new mmWave FWA services. We discuss the link budget requirements and walk through an example of suburban deployment. We address the traits and trade-offs of hybrid beamforming versus all-digital beamforming for the base transceiver station (BTS) and analyze the semiconductor technology and RFFE components that enable each. Finally, we discuss the design of a GaN-on-SiC front-end module (FEM) designed specifically for the 5G FWA market.

FWA Deployment

A clear advantage of using mmWave is the availability of underutilized contiguous spectrum at low cost. These bands allow wide component carrier bandwidths up to 400 MHz and commercial BTSs are being designed with carrier aggregation supporting up to 1.2 GHz of instantaneous bandwidth. Customer premise equipment (CPE) will support peak rates over 2 Gbps and come in several form factors: all outdoor, split-mount and all indoor desktop and dongle-type units. Mobile-handset form factors will follow.

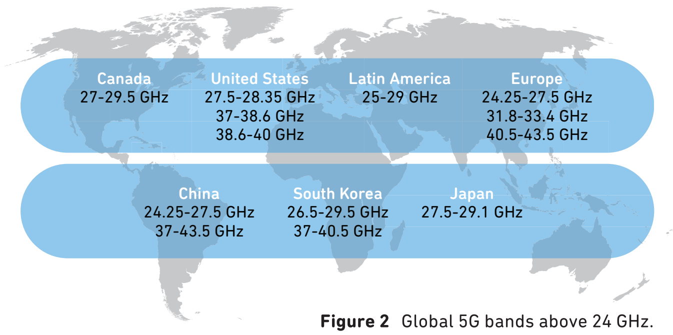


Figure 2 Global 5G bands above 24 GHz.

Global mmWave spectrum availability is shown in **Figure 2**. In the U.S., most trials are in the old block A LMDS band between 27.5 and 28.35 GHz, but the plan-of-record of carriers is to deploy nationwide in the wider 39 GHz band, which is licensed on a larger economic area basis. These candidate bands have been assigned by 3GPP and, except for 28 GHz, are being harmonized globally by the International Telecommunications Union.

FWA describes a wireless connection between a centralized sectorized BTS and numerous fixed or nomadic users (see **Figure 3**). Systems are being designed to leverage existing tower sites and support a low-cost, self-install CPE build-out. Both are critical to keeping initial deployment investment low while the business case for FWA is validated. Early deployments will be mostly outdoor-to-outdoor and use professional roof-level installations that maximize range, ensure initial customer satisfaction and allow time for BTS and CPE equipment to reach the needed cost and performance targets.

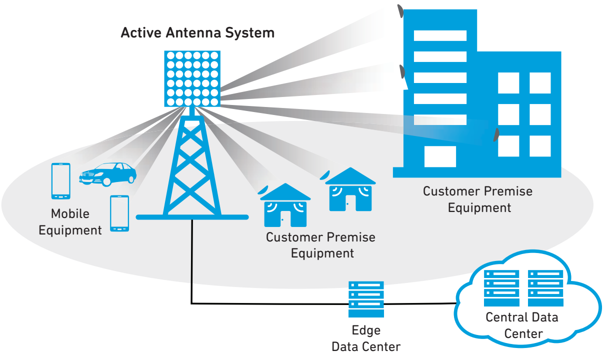


Figure 3 End–to–end FWA network.

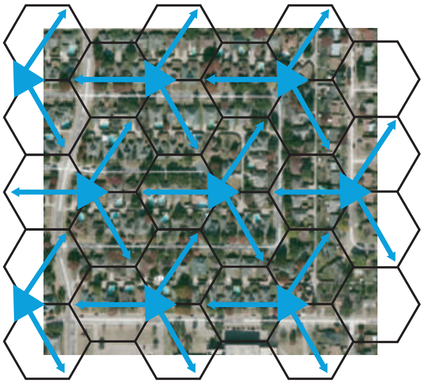


Figure 4 FWA in a suburban environment.

Large coverage is essential to the success of the FWA business case. To illustrate this, consider a suburban deployment with 800 homes/km2, as shown in **Figure 4**. For BTS inter-site distance (ISD) of 500 m, we need at least 20 sectors, each covering 35 houses from nine cell sites. Assuming 33 percent of the customers sign up for 1 Gbps service and a 5x network over subscription ratio, an average aggregate BTS capacity of 3 Gbps/sector is needed. This capacity is achieved with a 400 MHz bandwidth, assuming an average spectral efficiency of 2 bps/Hz and four layers of spatial multiplexing. If customers pay $100 per month, the annual revenue will be $280,000/km2/year. Of course, without accounting for recurring costs, it is not clear FWA is a good business, but we can conclude that as ISD increases, the business case improves. To that end, carriers are driving equipment vendors to build BTS and CPE equipment that operate up to regulatory limits to maximize coverage and profitability.

In the U.S., the Federal Communications Commission has defined very high effective isotropic radiated power (EIRP) limits for the 28 and 39 GHz bands, shown in **Table 1**. The challenge becomes building systems that meet these targets within the cost, size, weight and power budgets expected by carriers. Selecting the proper front-end architecture and RF semiconductor technology are key to getting there.

Table 1
FCC Power Limits for 28 and 39 GHz Bands

Equipment Class	Power (EIRP)
Base Station	75 dBm/100 MHz
Mobile Station	43 dBm
Transportable Station	55 dBm

FWA Link Budget

The standards community has been busy defining the performance requirements and evaluating use cases over a broad range of mmWave frequencies. The urban-macro scenario is the best representation of a typical FWA deployment: having large ISD of 300 to 500 m and providing large path-loss budgets that overcome many of the propagation challenges at mmWave frequencies. To understand the needed link budget, consider a statistical path-loss simulation using detailed large-scale channel models that account for non-line-of-site conditions and outdoor-to-indoor penetration, like those defined by 3GPP.

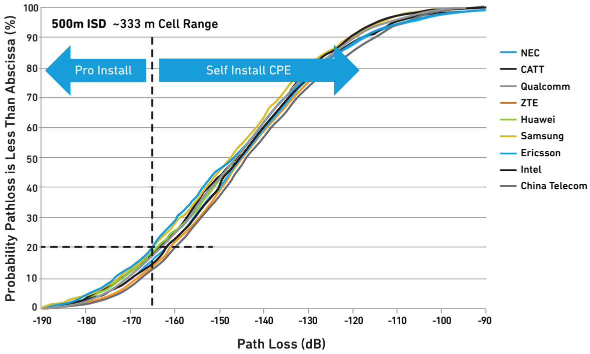


Figure 5 Statistical path loss simulation for urban-macro environment with 500 m ISD.

Figure 5 shows the result for a 500 m ISD urban-macro environment performed by equipment vendors and operators. For this simulation, 28 GHz channel models were used with 80 percent of the randomly dropped users falling indoors and 20 percent outdoors. Of the indoor users, 50 percent were subject to high penetration-loss models and 50 percent lower loss. Long-term, carriers desire at least 80 percent of their potential users to be self-installable to minimize more expensive professional roof-level installations. The distribution curve shows the maximum system path loss to be 165 dB.

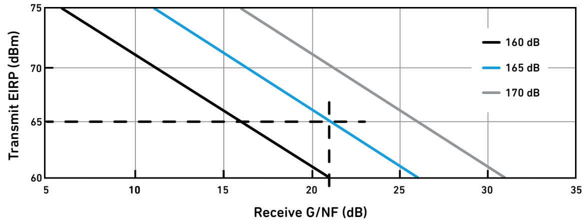


Figure 6 Transmit EIRP and receive G/NF vs. path-loss for 1 Gbps edge-of-coverage throughput.

Closing the link depends on many variables, including transmit EIRP, receive antenna gain, receiver noise figure (NF) and minimum edge-of-coverage throughput. To avoid overdesign of the cost-sensitive CPE equipment and shift the burden toward the BTS, the link design begins at the CPE receiver and works backward to arrive at the BTS transmitter requirements. In lieu of the conventional G/T (the ratio of antenna gain to system noise temperature) figure-of-merit (FOM), we define a more convenient G/NF FOM: the peak antenna gain (including beamforming gain) normalized by the NF of the receiver.

Figure 6 illustrates the required EIRP for the range of receive G/NF to overcome a targeted path loss delivering an edge-of-coverage throughput of 1 Gbps, assuming the modulation spectral efficiency is effectively 2 bps/Hz and demodulation SNR is 8 dB. From the graph, the BTS EIRP for a range of CPE receiver's G/NF can be determined. For example, 65 dBm BTS EIRP will be needed to sustain a 1 Gbps link at 165 dB of path loss when the CPE receiver G/NF is ≥ 21 dBi.

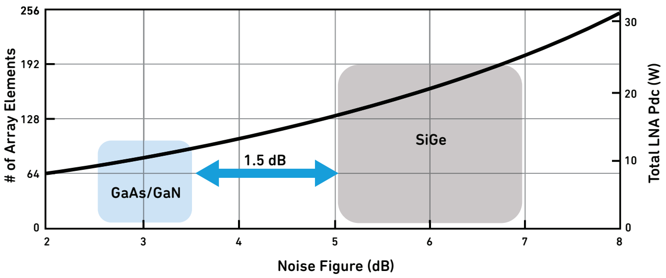


Figure 7 Array size vs. front-end NF and power consumption for G/NF = 21 dB.

Next, we consider the impact of receiver NF by plotting the minimum number of array elements needed to achieve G/NF of 21 dB (see **Figure 7**). We also plot the total low noise amplifier (LNA) power consumption. By adjusting the axis range, we can overlap the two and see the impact NF has on array size, complexity and power. For this example, each LNA consumes 40 mW, which is typical for phased arrays. The NFs of RFFEs, including the T/R switch losses, are shown for 130 nm SiGe BiCMOS, 90 nm GaAs PHEMT and 150 nm GaN HEMT at 30 GHz. The compound semiconductor technology provides ≥ 1.5 dB advantage, translating to a 30 percent savings in array size, power and, ultimately, CPE cost.

To explore architecture trades that are key to technology selection and design of the RFFE components, we start by understanding the antenna scanning requirements. We highlight the circuit density and packaging impact for integrated, dual-polarization receive/transmit arrays. Finally, we investigate all-digital beamforming and hybrid RF beamforming architectures and the requirements for each.

1D or 2D Scanning

The number of active channels in the array depends on many things. Let's start by first understanding the azimuth and elevation scanning requirements and whether two-dimensional beamforming is required for a typical FWA deployment or if a lower complexity, one-dimensional (azimuth only) beamforming array is sufficient. This decision impacts the power amplifier (PA). **Figure 8** shows two FWA deployment scenarios.

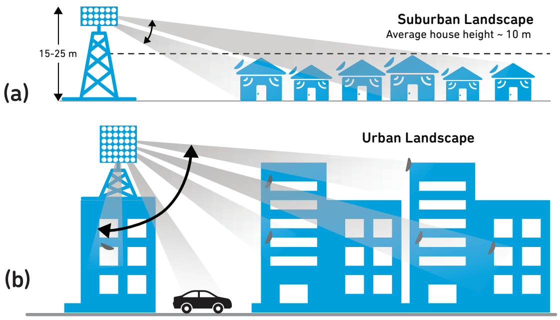


Figure 8 Array complexity depends on the scanning range needed for the deployment: suburban (a) or urban (b).

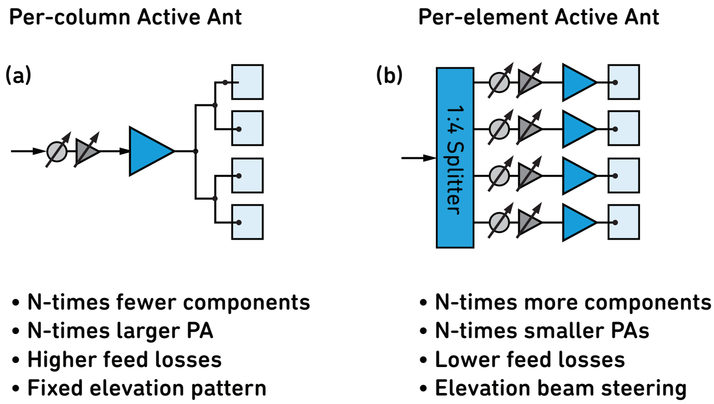


Figure 9 Column-fed (a) and per-element (b) active arrays.

In the suburban deployment, the tower heights range from 15 to 25 m and the cell radius is 500 to 1000 m, with an average house height of 10 m. Just as with traditional macro cellular systems, there is no need for fully adaptive elevation scanning. The elevation beam can be focused down by corporately feeding several passive antenna elements, as shown in **Figure 9a**. This vertically stacked column of radiating elements is designed to minimize radiation above the houses and fill in any nulls along the ground. Further, the gain pattern is designed to increase at relatively the same rate as the path loss. This provides more uniform coverage for both near and far users. The nominal half-power beamwidth can be approximated as 102°/NANT and the array gain by 10log10(NANT) + 5 dBi. With passively combined antennas, the elevation beam pattern is focused and the fixed antenna gain increases, as shown in **Table 2**. For the suburban FWA deployment, a 13 to 26 degree beamwidth is sufficient, with the passively combined column array from four to eight elements. In the urban scenario, however, the elevation scanning requirements are greater, and systems will be limited to one or two passive elements.

Figure 9b illustrates the per-element active array. Both the per-element and column-fed array architectures have the same antenna gain, but the column-fed array has a fixed elevation beam pattern. The per-element array supports wider scan angles but needs 4x as many PAs, phase shifters and variable gain components for an antenna with four elements. To achieve the same EIRP, the PA driving a column-fed array with four antennas will need to provide at least 4x the output power, which can easily change the semiconductor selection. It is reasonable to assume a suburban BTS will use antennas with 6 to 9 dB higher passive antenna gain compared to an urban deployment. As a result, the phased array needs far fewer active channels to achieve the same EIRP, significantly reducing active component count and integration complexity.

Table 2
Approximate Performance for Corporately Fed Elements

Column Array Size	Beamwidth (°)	Gain (dB)
Single Element	102	5
2-Element	51	8
4-Element	26	11
8-Element	13	14

Array Front-End Density

Early mmWave FWA BTS designs used separate, single-polarization transmit and receive antenna arrays, which allowed significantly more board area for components. These designs avoided the additional insertion loss and linearity challenges of a T/R switch. However, a major architecture trend is integrated T/R, dual-polarization arrays (see **Figure 10**), which is driving RFFE density. The key reason is spatial correlation. Adaptive beamforming performance depends on the ability to calibrate the receive and transmit arrays relative to one another. As such, it is important to integrate the transmit and receive channels for both polarizations, so the array shares a common set of antenna elements and RF paths. The net result is a requirement for the RFFE to have 4x the circuit density of earlier systems.

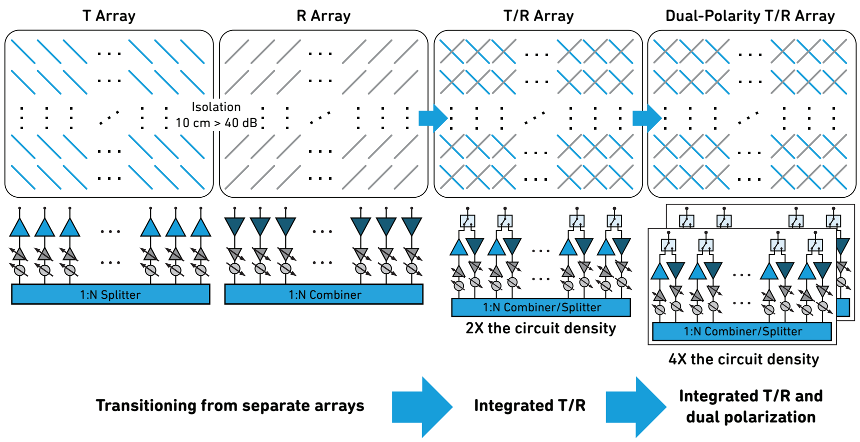


Figure 10 FWA antenna arrays are evolving from separate T and R arrays to integrated T/R arrays with dual polarization.

At mmWave frequencies, the lattice spacing between phased-array elements becomes small, e.g., 3.75 mm at 39 GHz. To minimize feed loss, it is important to locate the front-end components close to the radiating elements. Therefore, it is necessary to shrink the RFFE footprint and integrate multiple functions, either monolithically on the die or within the package, using a multi-chip module. Tiling all these functions in a small area requires either very small PAs, requiring a many-fold increase in array size, or using high-power density technologies like GaN. Further, it is critical to use a semiconductor technology that can withstand high junction temperatures. The reliability of SiGe degrades rapidly above 150°C, but GaN on SiC is rated to 225°C. This 75°C advantage in junction temperature has a large impact on the thermal design, especially for outdoor, passively-cooled phased arrays.

All Digital vs. Hybrid Arrays

It was natural for BTS vendors to first explore extending the current, sub-6 GHz, all-digital beamforming, massive MIMO platforms to mmWave. This preserves the basic architecture and the advanced signal processing algorithms for beamformed spatial multiplexing. However, due to the dramatic increase in channel bandwidths offered by mmWave and the need for many active channels, there is a valid concern that the power dissipation and cost of such a system would be prohibitive. Therefore, vendors are exploring hybrid beamformed architectures, which allows flexibility between the number of baseband channels and the number of active RF channels. This approach better balances analog beamforming gain and baseband processing. The following sections analyze the two architectures and discuss the RFFE approaches needed for each.

Digital Beamforming

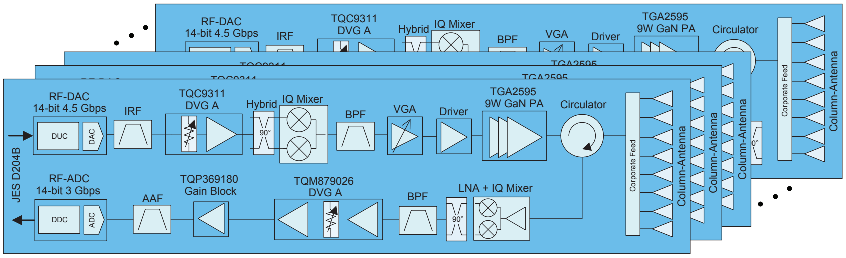


Figure 11 Array design using digital beamforming and commercial, off-the-shelf components.

Assuming large elevation scanning is not required for suburban FWA and a well-designed, column antenna provides gain of up to 14 dBi, we start with a mmWave BTS transceiver design targeting an EIRP of 65 dBm and compute the power consumption using off-the-shelf point-to-point microwave radio components that have been available for years, including a high-power, 28 GHz GaN balanced amplifier. The multi-slat array and transceiver are shown in **Figure 11**. Assuming circulator and feed-losses of 1.5 dB, the power at the antenna port is 27 dBm. From the following equations, achieving 65 dBm EIRP requires 16 transceivers that, combined, provide 12 dB of digital beamforming gain:

$$EIRP = G_{BF}\ (dB) + G_{ANT}\ (dBi) + P_{AVE\_TOTAL}\ (dBm)$$

$$EIRP = 10log10(N_{COLUMNS}) + 10log10(N_{PAS}) + G_{ANT} + P_{AVE/CHANNEL}\ (dBm)$$

The power consumption for each transceiver is shown in **Figure 12**. The total power dissipation (P_{DISS}) at 80 percent transmit duty cycle for all 16 slats will be 220 W per polarization, and a dual-polarized system will require 440 W. For all outdoor tower-top electronics, where passive cooling is required, it is challenging to thermally manage more than 300 W from the RF subsystem, suggesting an all-digital beamforming architecture using today's off-the-shelf components is impractical.

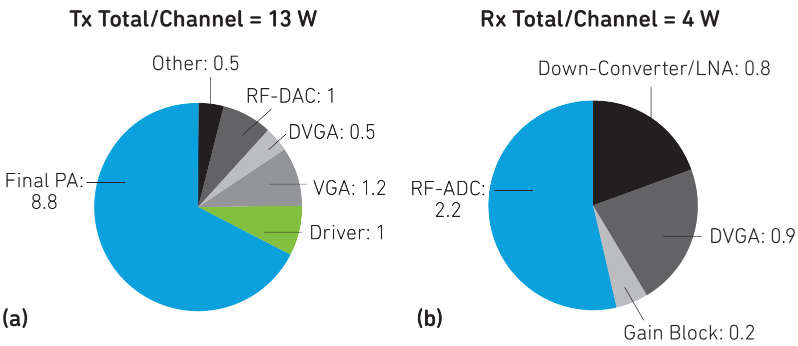


Figure 12 Power dissipation of the transmit (a) and receive (b) chains.

However, new GaN FEMs are on the horizon to help address this. As shown in **Figure 13**, the GaN PAs integrated in the FEM apply the tried-and-true Doherty efficiency-boosting technique to mmWave. With Doherty PAs, digital pre-distortion (DPD) is needed; however, the adjacent channel power ratio (ACPR) requirements defined for mmWave bands are significantly more relaxed, enabling a much "lighter" DPD solution. The estimated power dissipation of a 40 dBm P_{SAT}, symmetric, multi-stage Doherty PA can be reduced more than 50 percent. In the above system, this improvement alone drops the total P_{DISS} below 300 W. Combined with power savings from next-generation RF-sampling digital-to-analog and analog-to-digital converters, advancement in mmWave CMOS transceivers and increased levels of small-signal integration, it will not be long before we see more all-digital beamforming solutions being deployed.

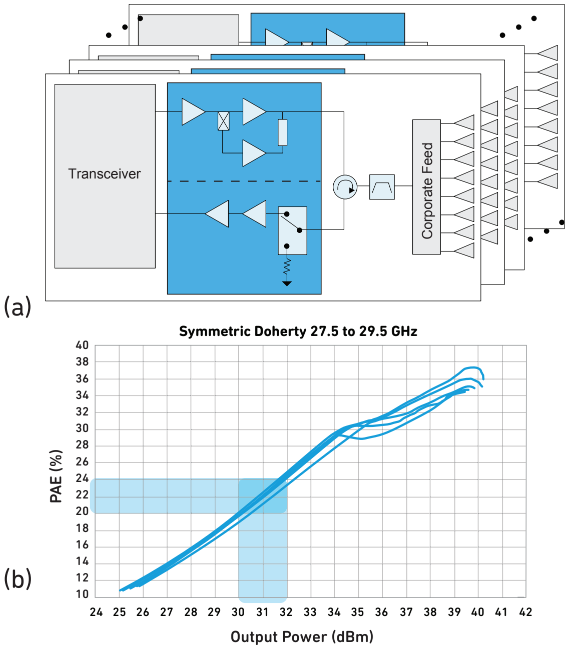


Figure 13 Integrated FEM with symmetric GaN Doherty PA and switch-LNA (a) and PA performance from 27.5 to 29.5 GHz (b).

Hybrid Beamforming

The basic block diagram for a hybrid beamforming active array is shown in **Figure 14**. Here, N baseband channels are driving RF analog beamformers, which divide the signal M-ways and provide discrete phase and amplitude control. FEMs drive each M-element subarray panel. The number of baseband paths and subarray panels is determined by the minimum number of spatial streams or beams that are needed. The number of beamformer branches and elements in each subarray panel is a function of the targeted EIRP and G/NF. While a popular design ratio is to have one baseband path for every 16 to 64 active elements, it really depends on the deployment scenario. For example, with a hot-spot small cell (or on the CPE terminal side), a 1:16 ratio single panel is appropriate. A macro BTS would have two to four subarray panels with 64 active elements, where each panel is dual-polarized, totaling four to eight baseband paths and 256 to 512 active elements. The digital and analog beamforming work together, to maximize coverage or independently, to provide spatially separated beams to multiple users.

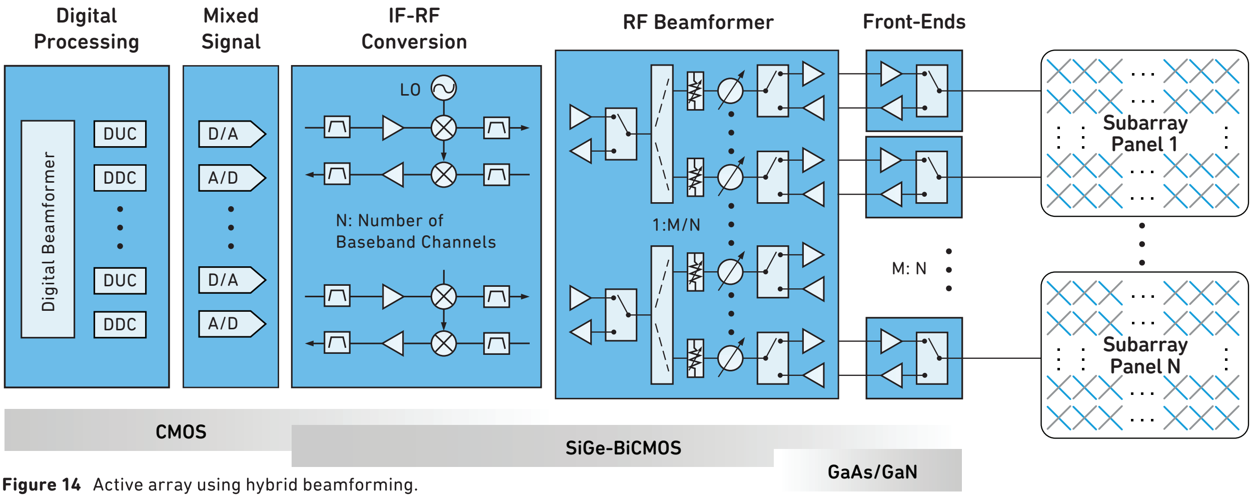


Figure 14 Active array using hybrid beamforming.

There is an important trade unfolding, whether SiGe front-ends can provide sufficient output power and efficiency to avoid the need for higher performance III-V technology like GaAs or GaN. With good packaging and integration, both approaches can meet the tight antenna lattice-spacing requirements.

Front-End Semiconductor Choices

The technology choice for the RFFE depends on the EIRP and G/NF requirements of the system. Both are a function of beamforming gain, which is a function of the array size. To illustrate this, **Figure 15** shows the average PA power (P_{AVE}) per channel needed as a function of array size and antenna gain for a uniform rectangular array delivering 65 dBm EIRP. The graph is overlaid with an indication of the power ranges best suited for each semiconductor technology. The limits were set based on benchmarks of each technology, avoiding exotic power-combining or methods that degrade component reliability or efficiency. As array size gets large (more than 512 active elements), the power per element becomes small enough to allow SiGe, which can be integrated into the core beamformer RFIC. In contrast, by using GaN for the front-end, the same EIRP can be achieved with 8 to 16x fewer channels.

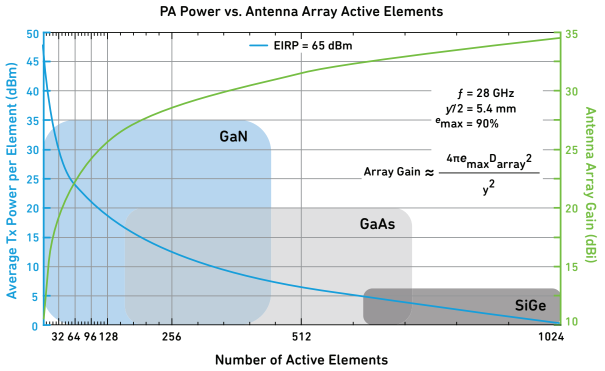


Figure 15 Optimum RFFE technology vs. array size.

System Power Dissipation

For an array delivering 64 dBm EIRP, **Figure 16** shows an analysis of the total P_{DISS} of the beamformer plus the front-end as a function of the number of active elements in each subarray panel. The P_{DISS} is shown for several error vector magnitude (EVM) levels, since the EVM determines the power back-off and efficiency achieved by the front-end. We assume each beamformer branch consumes 190 mW, which is the typical power consumption of core beamformers in the market. The system on the far right of the figure represents an all-SiGe solution with 512 elements, with an output power per element of 2 dBm and consuming approximately 100 W. Moving left, the number of elements decreases, the P_{AVE} per channel increases and P_{DISS} is optimized to a point where beamforming gain starts to roll off sharply, and the P_{DISS} to maintain the EIRP rapidly increases. The small steps in the dissipation curves represent where the front-end transitions from a single stage to two-stage and three-stage designs to provide sufficient gain. As stages are added, the efficiency drops with the increase in power dissipation.

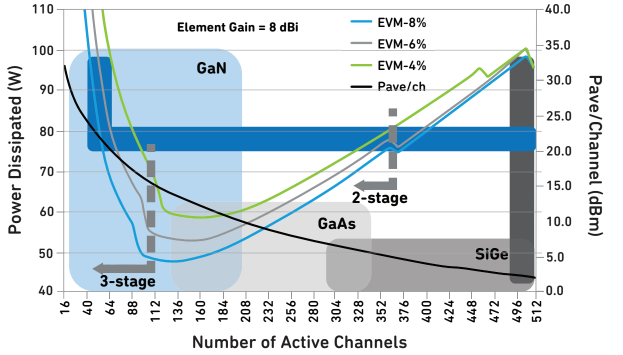


Figure 16 System power dissipation vs. array size and EVM for 64 dBm EIRP.

Designing to optimize system P_{DISS} without regarding complexity or cost, an array of about 128 elements with a two-stage, 14 dBm output PA (24 dBm P1dB) is the best choice. However, if we strive to optimize cost, complexity and yield for a P_{DISS} budget of under 100 W, the optimum selection is the range of 48 to 64 active channels using a three-stage GaN PA with an average output power of 20 to 23 dBm, depending on the EVM target. The trends shown in Figure 16 are less a function of PA efficiency and more a function of beamformer inefficiency. In other words, the choice to increase array size 8x to allow an all-SiGe solution comes with a penalty, given that the input signal is divided many more ways and requires linearly biased, power consuming devices to amplify the signal back up.

Cost Analysis

The cost of phased arrays include the RF components, printed circuit board material and the antennas themselves. Using compound semiconductor front-ends allows an immediate 8x reduction in array size with no increase in P_{DISS}. Even with lower-cost printed antenna technology, this is a large saving in expensive antenna-quality substrate material. Considering component cost, the current die cost per mm2 of 150 nm GaN on SiC fabricated on 4-inch wafers is only 4.5x the cost of 8-inch 130 nm SiGe. As 6-inch GaN production lines shift into high volume, the cost of GaN relative to SiGe drops to 3x. A summary of the assumptions and a cost comparison of the relative raw die cost of the two technologies is shown in **Table 3**. Using a high-power density compound semiconductor like GaN on 6-inch wafers can save up to 35 percent in the raw die cost relative to an all-SiGe architecture. Even though the cost of silicon technologies is lower per device, the cost of the complete system is significantly higher.

GaN Front-End Modules

To validate the concept of a GaN FEM for mmWave FWA arrays, Qorvo set out to design the highest power, lowest NF FEM for the 37 to 40 GHz band. To support the trend to integrated transmit/receive arrays, the front-end includes a PA, integrated T/R switch and a low NF LNA. The module was designed with sufficient gain to be driven by core beamformer RFICs, which have a typical drive level of 2 dBm. The FEM's P_{AVE} of 23 dBm was selected from an analysis similar to that shown in Figure 16, and the P_{SAT} was determined by analyzing the needed headroom to support a back-off linearity of ≥ 33 dBc ACPR, EVM ≤ 4 percent and a 400 MHz orthogonal frequency-division multiple access (OFDMA) waveform.

Table 3
Relative Cost of All SiGe and SiGe Beamformer with GaN FEM

Parameter	Units	All SiGe	GaN + SiGe
Average Output Power per Channel	dBm	2	20
Power Dissipation per Channel	mW	190	1329
Antenna Element Gain	dBi	8	8
Number of Active Channels	–	512	64
EIRP	dBmi	64	64
Total Power Dissipation	W	97	97
Beamformer Die Area per Channel	mm^2	2.3	2.3
Front-End Die Area per Channel	mm^2	1.2	5.2
Total SiGe Die Area	mm^2	1752	144
Total GaN Die Area	mm^2	0	334
	Die Cost	**Units**	**Notes**
All SiGe System Die Cost	1752	$/x	–
GaN + SiGe System Die Cost (4-inch GaN)	1647	$/x	4-inch GaN = 4.5x
GaN + SiGe System Die Cost (6-inch GaN)	1146	$/x	6-inch GaN = 3x

A key design decision was determining if GaAs or GaN or a combination of both were needed. The die size for a GaAs PA would not allow the FEM to meet the tight 3.75 mm lattice spacing at 39 GHz. The equivalent output power GaN PA is 4x smaller with no sacrifice in gain and a slight benefit in efficiency. Considering the LNA, the 90 nm GaAs P_{HEMT} process was favored due to its slightly superior NF. However, the net improvement was only a few tenths of a dB once the additional bond wires and 50 Ω matching networks were considered. The trade-off analysis concluded it was better to stay with a monolithic GaN design that allowed co-matching of the PA, LNA and T/R switch. Such a design was lower risk, easier to assemble and test, and the MMIC was as compact as possible. The system thermal analysis indicated that the higher junction temperature offered by GaN-on-SiC was critical for passively-cooled arrays.

As shown in **Figure 17**, the 39 GHz FEM integrates two of the multi-function GaN MMICs into an air-cavity, embedded heat-slug, surface-mount package, sized to meet the array element spacing at 39 GHz. Each of the GaN MMICs contains a three-stage linear PA, three-stage LNA and a low-loss, high-linearity SPDT switch. The FEM covers 37.1 to 40.5 GHz and provides 23 dBm average output power, which supports 256-QAM EVM levels, with 24 dB transmit gain. In receive mode, the NF is 4.1 dB, and receive gain is 16 dB. The package size is 4.5 mm × 6.0 mm × 1.8 mm.

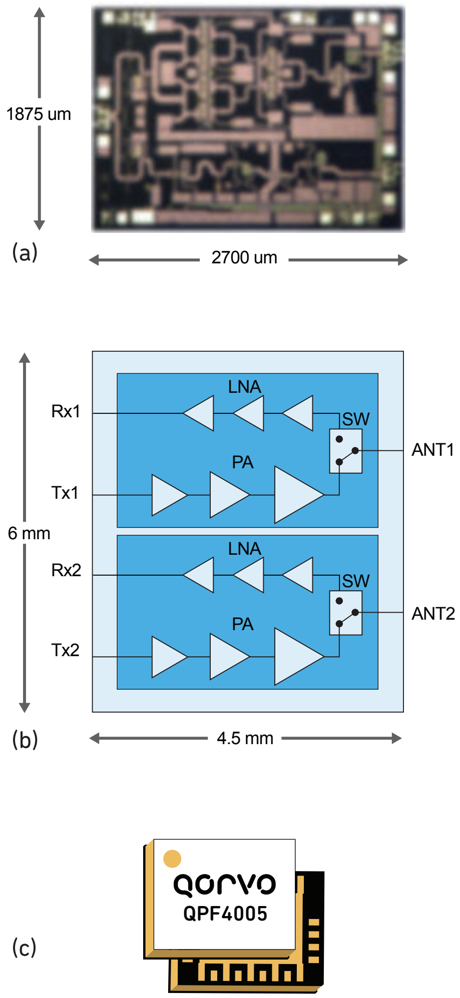


Figure 17 Integrated 39 GHz GaN front-end MMIC - intentionally blurred (a), dual-channel FEM (b) and package (c).

Summary

FWA is rapidly approaching commercialization. This is due to the abundance of low-cost spectrum, early regulatory and standards work and the opportunity for operators to quickly tap a new market. The remaining challenge is the availability of equipment capable of closing the link at a reasonable cost. Both hybrid beamforming and all-digital beamforming architectures are being explored. These architectures capitalize on the respective strengths of commercial semiconductor processes. The use of GaN front-ends in either approach provides operators and manufacturers a pathway to achieving high EIRP targets while minimizing cost, complexity, size and power dissipation. To prove the feasibility, Qorvo has developed a 39 GHz FEM based on a highly integrated GaN-on-SiC T/R MMIC and is developing similar FEMs for other millimeter wave frequency bands proposed for 5G systems.

What's Best? Wi-Fi 6 (802.11ax) or 5G?

Every time a new cellular phone standard comes out, we see new claims about the "end of Wi-Fi." When 3G was announced, the promise was that it would make Wi-Fi (802.11b) redundant, which clearly turned out to be incorrect. With 4G (LTE), this story repeated itself and claimed it would put Wi-Fi (802.11ac) in the shredder. And now the 5G message is that it will cover both the inside and outside of homes and buildings. It's almost as though Wi-Fi will soon no longer be needed.

This begs the question: What will be the impact of the next generation of Wi-Fi, Wi-Fi 6 (802.11ax)? Do we even need it in the 5G/wireless landscape? We need better questions.

Beyond the Hype

Of course, some of the messaging around 5G is just typical marketing hype, showcasing the favorable points and ignoring the less favorable ones. For example, 5G with 4 Gbps will be faster than Wi-Fi (.11ac) with 1.3 Gbps. The immediate counter argument is that Wi-Fi (.11ax) with 9.6 Gbps will be faster than 5G. But will these speeds be achieved in real life? We've seen this before, these glossy promises of high-speed access being wiped away by the hard truth of "no connection in the basement," or something similar. Cue the collective consumer yawn.

(And by the way, how good will 9.6 Gbps Wi-Fi be in the basement, if the connection to the home is 300 Mbps, or even less? What problem is this solving?)

If we want a real sense of where the developments are heading, it's probably a good idea to go a little deeper than marketing headlines. What are the real facts that can guide us? For starters, laws of physics tell us that radio waves (both Wi-Fi and 5G) have difficulties penetrating objects such as walls and foliage, and their data rates decrease with distance. Radiating more power helps a little, but it also causes unwanted noise, making equipment more expensive. In addition, there are legal maximum output power ratings to adhere to.

There are also economic laws. Cellular (3G/4G/5G) uses licensed bands. Mobile operators (service providers) pay money to use this spectrum and need to roll out a network of (connected) base stations to cover a large area. They then need to recover this money with subscription fees. In such a service area, many users need to be served, sharing the same frequency band over multiple channels.

In contrast, Wi-Fi uses unlicensed spectrum, which is available to all for free. However, the output power is very low, so the radio signal (more or less) stays in your own house or building and has a favorable (so-called) spectral reuse. The same frequency band can be used in every house. However, to get the internet at your front door, you need to pay an internet service provider a subscription fee, including a simple router that is part of that fee. If you want, you can buy a more expensive router as well.

So, in this frequency band perspective, there's an interesting technology split between Wi-Fi and 5G, but do customers really care? Customers care about fast internet access — anywhere — at a decent price. In contrast, operators/providers care about providing good internet service everywhere (at home and around the home) and keeping costs under control. Interestingly enough, with so-called Wi-Fi off-load (where a cellular network off-loads traffic to Wi-Fi connections), the border between the two different technologies is already blurring.

A Bit of History Can Be Helpful

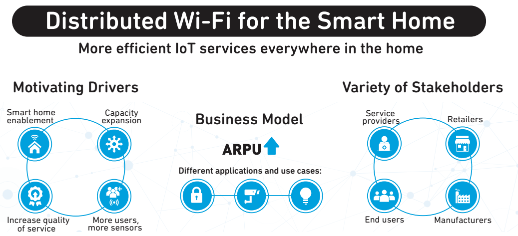
It's interesting to note that the Wi-Fi world is rooted in the commercial computer industry, while 5G is rooted in the more legislated telephone industry. So, telephone operators (now service providers) have more affinity with 5G than with Wi-Fi. When most telephone operators started to deliver internet to consumers, it was delivery to the front door. What happened inside the house was the consumer's responsibility.

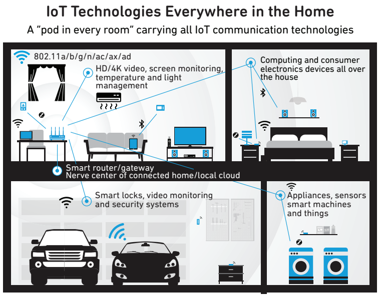
There's another distinction between cellular and Wi-Fi: a mobile phone uses a service subscription that requires a SIM card. This SIM card ensures that phones are connected to subscriptions and don't use the network illegally. But Wi-Fi doesn't need a SIM card; the frequency band is license-free. Not surprisingly, the mobile world is looking for ways to make the SIM card redundant, but initiatives like soft SIM and eSIM aren't making the desired progress because they're too cumbersome and/or are not sufficiently secure.

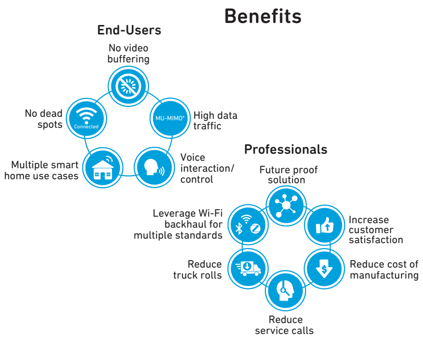
The consequence of these histories is that the consumer's internet connectivity world is split into two parts: mobile (with a subscription and SIM) and stationary (with a router at home). This scenario is now well-established. Of course, wireless internet connectivity can be troublesome, and initially telephone operators used this hassle as an opportunity to promote cellular as an alternative for Wi-Fi. The good news is this mentality is changing.

Cable operators have also entered the picture. They've found that, for many consumers, Wi-Fi coverage in the home was a major concern. Cable operators responded by extending their service to include good coverage inside the home. This is forcing cellular operators to do the same, as well as to develop a better quality of wireless indoor internet service.

Wi-Fi 6 (IEEE 802.11ax)







Better coverage inside the home is one of the key characteristics of the new generation of Wi-Fi, now called Wi-Fi 6 (based on the IEEE 802.11ax standard). The distributed concept behind this new version of the Wi-Fi standard (also called Wi-Fi mesh) helps to distribute internet to every room in the home, with the main router at the front door, and small satellite routers (also known as repeaters) on every floor and in every room. This enables internet service providers to sell and support solid internet connectivity everywhere in the home — all good news!

There are also interesting crossover products, though, and a nice example is the FRITZ!Box 6890 from German supplier AVM. This box is a traditional router, providing Wi-Fi everywhere in the home. But it doesn't use DSL, fiber or cable — it uses LTE. So, this box has a SIM card and operates the same way as if you use your mobile phone as a hotspot to connect your tablet to the internet, for example. The difference is the FRITZ!Box makes this configuration permanent in your house. The trick is to make sure you have the right subscription service (preferably unlimited data) to avoid high mobile charges for your private wireless hotspot.

A Better Way Of Looking At Things

Despite these crossovers, when talking about cellular and Wi-Fi, it still feels like two separate worlds and that we're switching back and forth between them, like a car shifting gears. Fortunately, most phones are somewhat smart, and when the Wi-Fi connection isn't working, the phone automatically switches to the cellular network. But there's a real problem if you're "on the edge of Wi-Fi" and Wi-Fi attempts to take back the connection, leaving you in limbo with a nonworking Wi-Fi and a nonworking cellular connection. In those moments, the solution is to turn off Wi-Fi to end the battle and avoid poor response times.

But wouldn't it be better if there were a good hand-off between the Wi-Fi connection and the cellular connection, so that the user always gets the best performance against the lowest cost?

Some consumers won't care if they are connected via Wi-Fi or, in the future, 5G. The system should just provide the best connectivity, whether at home indoors, outside, or on the road. Maintaining one subscription for both home internet and cellular service — we're talking about a different way of thinking. In this scenario, a service provider (whether it's a mobile operator or a cable operator) provides the highest quality wireless internet access service, both at home and on the road. There are many initiatives underway in this area, all in the category of "Wi-Fi off-load," and in principle the technology is there. But it isn't mainstream yet, due to multiple competing and legacy interests.

The "Right" Choice

It may be clearer that the customer genuinely isn't interested in next-generation Wi-Fi or in the "next G." The consumer simply wants the best internet connection — anywhere, at any time and at the most affordable price. This is the way everyone — whether cellular providers, hotspot providers or internet service providers — can think about how to deliver the best service most efficiently to their vast subscription base.

The key is to envision 5G and Wi-Fi 6 working together to implement this, instead of playing one against the other. There should be no "right" technology choice or choosing the one best technology for a given application.

Hopefully this different way of thinking will also help to concentrate on today's real bottleneck — how to get high-speed internet to the home.

Is 5G Already a Reality?

It should come as no surprise that the pending arrival of 5G was THE big story from Mobile World Congress 2019 in Barcelona. Qorvo's Brent Dietz covered his top five takeaways from MWC19, including foldable phones and Sophia the robot — but here's a recap of Qorvo's highlights from the show.

Qorvo's 5G Mobile Portfolio Enters High-Volume Production

Most people in the industry didn't think 5G would be a reality before 2020, but one overriding message from Barcelona is that 5G is coming faster than anyone actually expected — and we could see 5G handsets in the second half of 2019.

In support of that transition, we announced at MWC 2019 that our portfolio of mobile 5G products has moved into high-volume production, helping leading smartphone manufacturers accelerate the rollout of 5G around the world. Featured products include the highly integrated front-end modules (FEMs) shown below, which support all major baseband chipsets and incorporate all the RF front-end (RFFE) functions required to support new and "refarmed" 5G bands targeted in early deployments.

Part Number	Description	5G NR Band Support
QM78203	5G Switched Power Amplifier plus Duplexer (S-PAD) Module with LNA Receive	Bands n77, n78 and n79
QM75041	5G Power Amplifier Duplexer Module (PAMiD)	Bands n41
QM77038	Multi-Mode Mid/High Band Switched Power Amplifier plus Duplexer (S-PAD) Module	Bands n41, n3

Enabling 5G Wireless Infrastructure With 100+ Million Shipped RF Devices

5G handsets won't work unless cellular infrastructure is set up to support 5G. Not only have Qorvo infrastructure products been used in dozens of 5G field trials, including the Samsung 5G multiple-input/multiple-output (MIMO) demo at the 2018 Winter Olympics, but we also announced at MWC19 that we've shipped more than 100 million 5G wireless infrastructure components since January 2018.

Our 5G infrastructure portfolio includes solutions for both the receive and transmit RF front end, enabling customers to use beamforming with massive MIMO base stations to achieve higher data capacity, wider coverage, and indoor penetration using sub-6 GHz and millimeter wave frequencies.

We were also featured in MWC press announcements from silicon-on-insulator (SOI) partner GlobalFoundries and 5G GaN partner Gapwaves. Gapwaves' 28 GHz 5G active antenna features a Qorvo integrated FEM and our GaN-on-SiC technology.

Integration Will Be Critical For 5G Handsets

One mobile industry trend showing no sign of stopping: integration of components amid tight space constraints. Indeed, integration will be even more critical for 5G handsets, as the number of RF components in the phone only continues to grow.

Qorvo's RF Fusion™ products integrate the power amplifier, switch and filter content into a single RFFE module, and we announced at MWC that our newest generation of RF Fusion products had multiple design wins from leading smartphone manufacturers.

The newest generation of RF Fusion leverages Qorvo's advanced BAW and SAW filter technologies to deliver complete coverage in low-band and mid/high-band placements, with our QM77033 and QM77031 modules. The latest design wins also include the QM17001 mid/high-band diplexer and RF8129 envelope-tracking (ET) power management module.

RF Fusion continues to evolve and add functions and features in preparation for the rollout of 5G. The latest generations add support for new and refarmed 5G bands and EN-DC operation, in a range of scalable options. You can view our full catalog of RF Fusion solutions for 4G/5G in our latest brochure on qorvo.com/brochures.

Honored For Helping To Drive The Global Adoption for 5G

Among the many highlights during MWC, Qorvo's Paul Cooper was recognized by the Global TD-LTE Initiative (GTI) as a 2019 Honorary Award recipient at its GTI Night celebration.

Paul, who is the director of carrier liaison and standards at Qorvo, has worked for several years to further the cause of the GTI 2.0 mission to establish a 5G RF front-end sub-6 GHz ecosystem, supporting member carriers in the U.S., China and Europe. The Qorvo Carrier Program team coordinated test and marketing staff to provide data in support of 3GPP new radio (NR) standards that will drive global adoption of 5G. This award was the culmination of the hard work put in by Qorvo's 3GPP RAN4 standards team and engineering teams providing lab test data.

We're proud to be among a team of experts from multiple companies, including Qorvo, Skyworks, Sprint, Qualcomm and LG, that are helping our customers' customers — the wireless carriers — address the RF challenges of 5G.

Qorvo's Paul Cooper and a cross-company collaborative team accept a GTI Honorary Award at MWC19.

Getting Ready For 5G: Antenna Tuning Is Essential

The transition to 5G will drive a significant increase in the typical number of antennas in each handset, from 4-6 in today's LTE handsets to 6-10 in 5G smartphones. At the same time, the space for those antennas is decreasing, creating problems for antenna efficiency and bandwidth.

To counteract these challenges, 5G handset designers will need to use antenna tuning to optimize the antenna. Aperture tuning is one method used today, but implementing it requires in-depth knowledge.

Visit qorvo.com to download our new **How to Implement Aperture Tuning**: **Best Practices for 4G/5G Smartphones** e-guide to learn more.

What's Next: How Do We Make 5G Happen Right Now?

Learn how 5G will change how we live and operate in Qorvo's series, "5G in 60" on www.qorvo.com/videos.

Eric Creviston, president of Qorvo Mobile Products, sums it up best: "We heard over and over during MWC that 5G handsets are being pulled in sooner than planned. Consumer awareness of 5G is very high and consumers want to 'future-proof' the phones they buy this year by having 5G capability, even if the network coverage is not yet in place."

We may be in the earliest stages of the 5G rollout, but it's exciting to see all the hard work and collaboration from the 3GPP standards, bodies and the industry starting to come to fruition!

News and Awards

Qorvo RF Fusion™ Wins Multiple Marquee Smartphone Designs (2/25/19)

Utilizing the newest generation of its RF Fusion RF front-end modules, Qorvo now supports marquee product releases across leading smartphone manufacturers with highly integrated mid-high band module solutions. In addition, Qorvo can now leverage their unique capabilities to deliver enhanced performance in a small solution size and reduced footprint.

As the industry begins its transition to 5G, manufacturers can accommodate complex RF content in handsets and accelerate delivery of next-generation LTE, LTE-A, 5G and IoT products. This helps smartphone manufacturers reduce time to market, optimize their handset portfolio and improve manufacturing yields.

The latest design wins also include the QM17001 mid-high band diplexer and RF8129 envelope-tracking (ET) power management module.

Qorvo and National Instruments Demonstrate First 5G RF Front-end Module (2/27/18)

In early 2018, Qorvo partnered with National Instruments to test the first commercially available 5G RF front-end module. Testing demonstrations were held during the 20th GTI Workshop in London.

Qorvo's QM19000 5G FEM, which combines a power amplifier and low noise amplifier into a single package, is targeted for mobile devices operating in the 3.4 GHz spectrum.

The FEM was tested with the advanced NI PXI system, as part of an ongoing effort to help customers design and test 5G technology for early deployments of 5G in mobile devices.

Paul Cooper, director of Carrier Liaison and Standards, Qorvo Mobile Products, stated "The wide bandwidth, excellent RF performance, and flexibility of NI's PXI test system were critical in helping us introduce the industry's first commercially available 5G FEM. Qorvo's focus on innovation was clearly demonstrated at the 20th GTI Workshop in London."

To learn more about Qorvo's news, visit

www.qorvo.com/news

Qorvo Wins Prestigious GTI Award for 5G RF Front End Module

Qorvo's QM19000, the world's first 5G front-end and recipient of the GTI 2017 Award for "Innovative Breakthrough in Mobile Technology" offers a robust and reliable platform to accelerate 5G testing and deployment.

The award-winning front-end has been a key element of 5G tests and demonstrations by operators and ecosystem partners across the world.

The QM19000 meets the challenging requirements of 5G non-standalone (NSA) and standalone (SA) deployments for advanced applications such as high-definition mobile video and virtual reality.

To learn more about Qorvo's awards, visit

www.qorvo.com/awards