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October 2019

Microwave Journal

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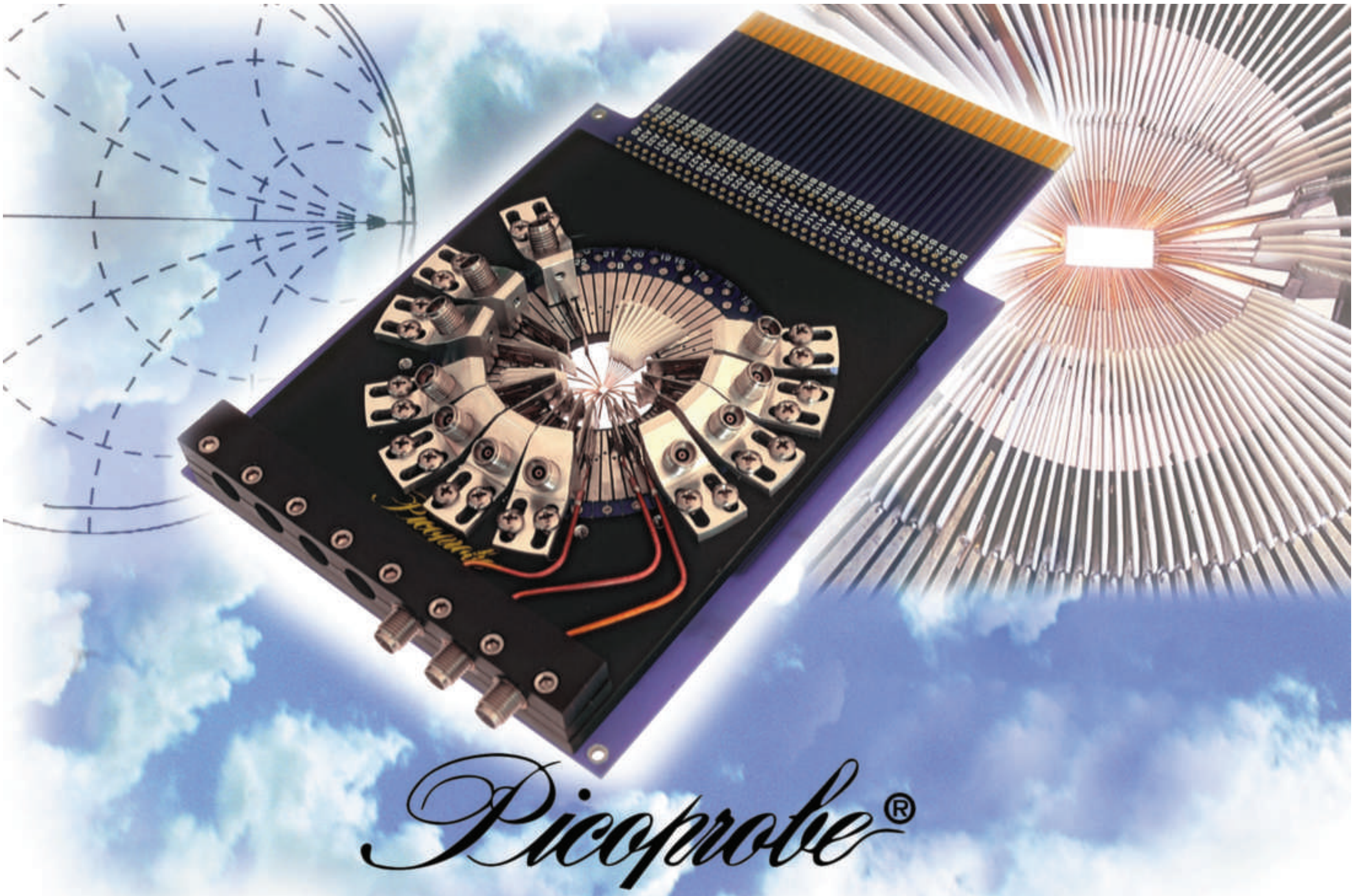

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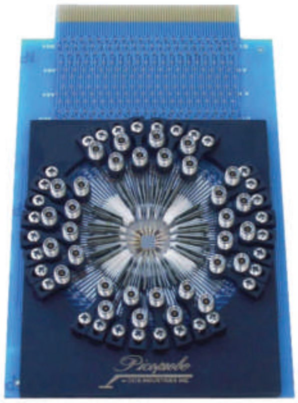

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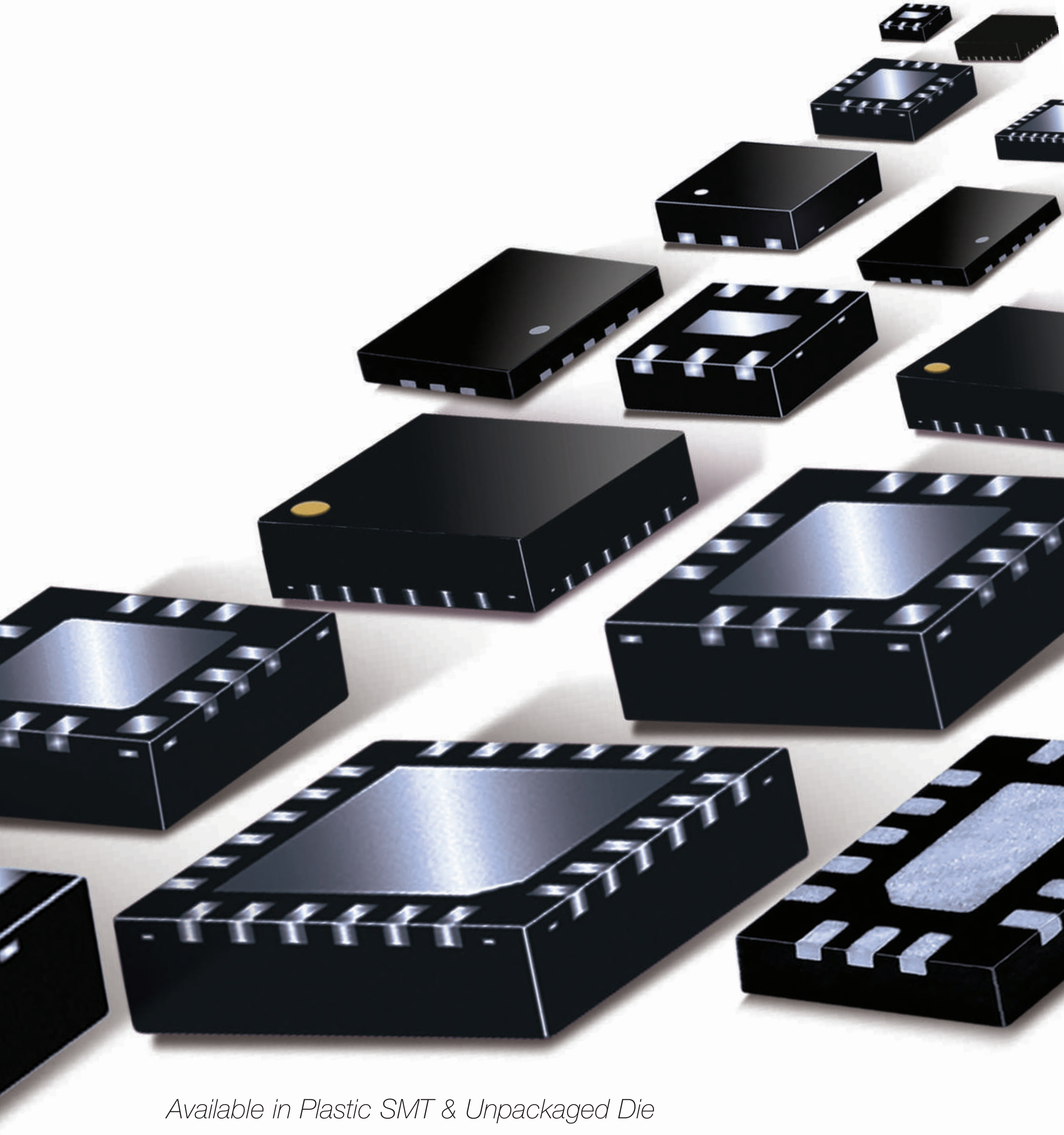

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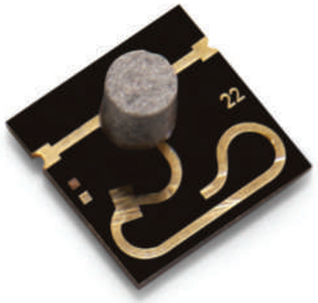

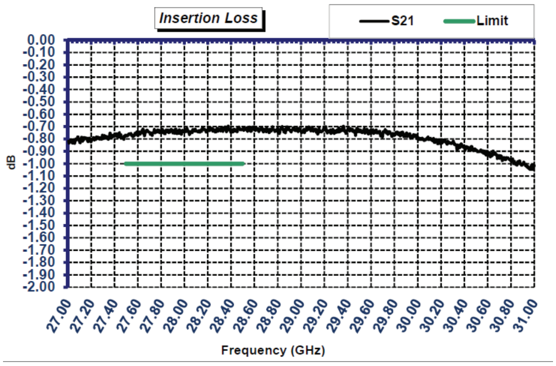

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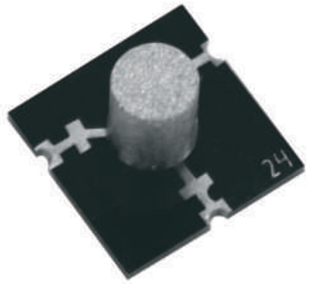

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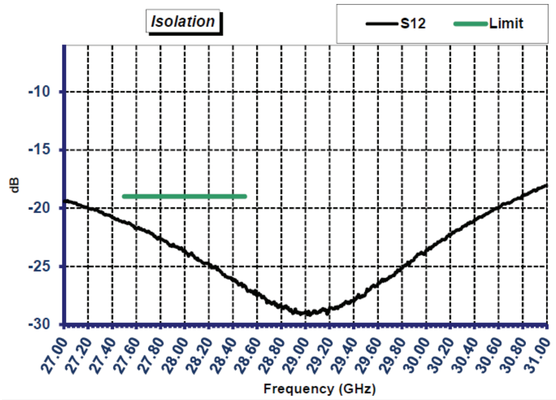


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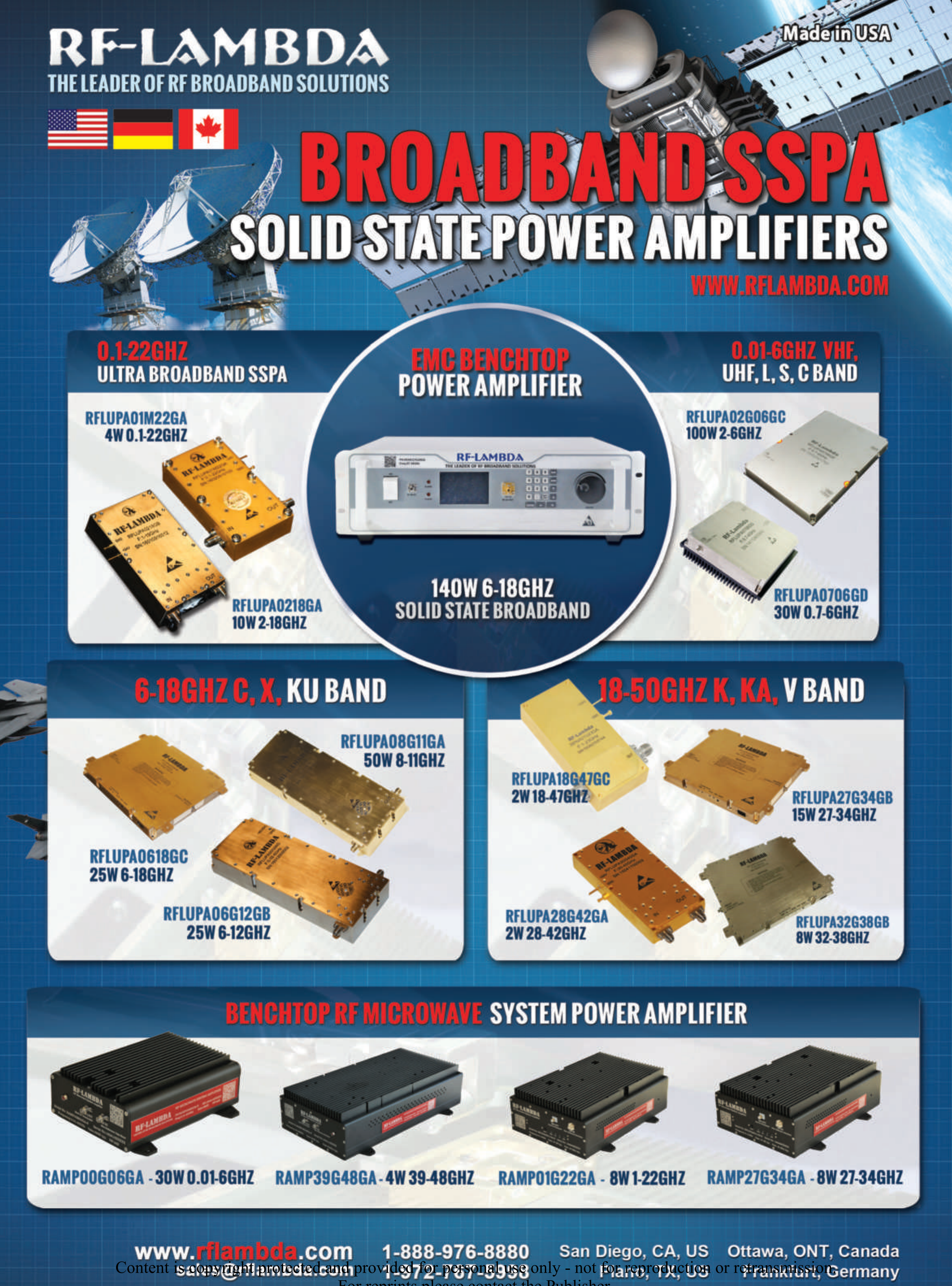
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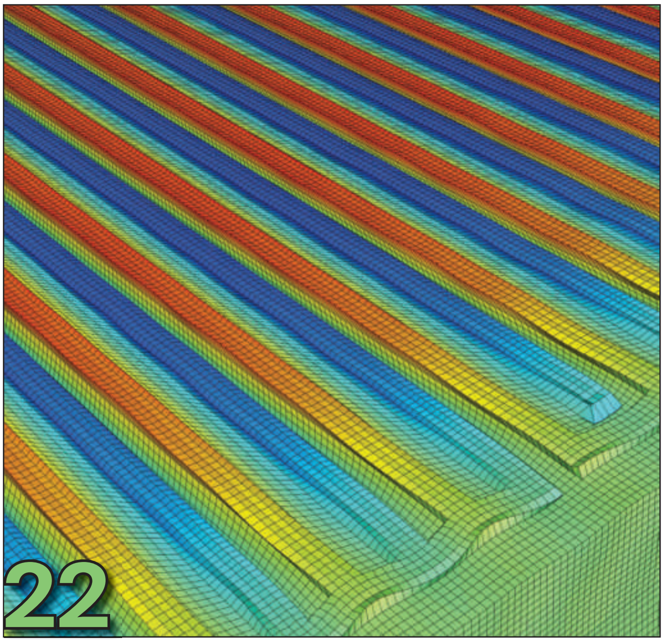

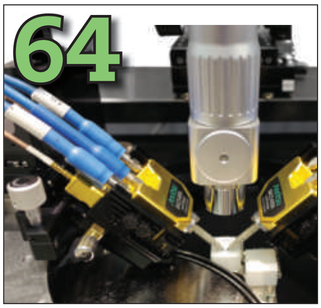

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Legacy Standards and Test Methods Limit the Use of Modern Spectrum & Signal Analyzers

Darren Tipton, Rohde & Schwarz

Cover image: 3D FEM simulation of a full SAW resonator with out-of-plane velocity shown at the series resonance, highlighting the surface motion of the interdigital transducers to highlight areas where energy is leaking. Image was made using OnScale cloud engineering simulation software and provided courtesy of OnScale.

Cover Feature

Application Note

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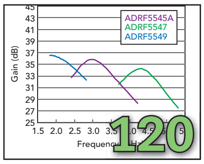

Tech Briefs

Departments

ERRATUM

In the article "Digital Code Modulation MIMO Radar Improves Automotive Safety," published in the August 2019 issue, equation 3 for calculating the phase shift between each of the received signals should have been

$$\phi = \frac{2x \cdot \pi \cdot \sin(\theta)}{\lambda} = \pi \cdot \sin(\theta) \text{ if } x = \frac{\lambda}{2}$$

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Executive Interviews

George Holmes, CEO of filter start-up **Resonant**, discusses how its Infinite Synthesized Networks® design capability is reducing development time for the complex, high performance acoustic filters so critical to 4G and 5G smartphones.

Chinh Doan and **Jean-Marc Laurent**, cofounders of **Milliwave Silicon Solutions**, discuss their preference for silicon for mmWave ICs and how IC development led to the unique MilliBox chamber for over-the-air testing.

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4-6

IEEE COMCAS 2019

Tel Aviv, Israel

IEEE COMCAS 2019 continues the tradition of providing a multidisciplinary forum for the exchange of ideas, research results and industry experience in areas such as communications, antennas, radar, RF and microwave circuits and systems and bio-medical engineering. The COMCAS 2019 scientific program will comprise 230 technical presentations, talks and tutorials, arranged in 60 sessions over three days with up to nine parallel sessions.

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5-7

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12-14

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19-21

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21-23

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October 22–24 • Los Angeles, Calif.
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https://bcicts.org

IEEE COMCAS 2019
November 4–6 • Tel Aviv, Israel
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Global MilSatCom 2019
November 5–7 • London, U.K.
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November 12–14 • Norfolk, Va.
https://events.afcea.org/MILCOM19/Public/enter.aspx

Space Tech Expo Europe 2019
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www.spacetechexpo.eu/

IEEE WiE Forum USA East 2019
November 21–23 • Arlington, Va.
https://attend.ieee.org/wie-forum-usa-east-2019/

DECEMBER

IEEE IMaRC 2019
December 5–7 • Mumbai, India
https://imarc-ieee.org/

65th Annual IEEE International Electron Devices Meeting (IEDM)
December 7–11 • San Francisco, Calif.
https://ieee-iedm.org/

Asia Pacific Microwave Conference 2019
December 10–13 • Singapore
https://apmc2019.miceapps.com/client/sites/view/SP8f993

JANUARY

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www.ces.tech/

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www.arftg.org

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FEBRUARY

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March 17–18, 2020 • San Diego, Calif.
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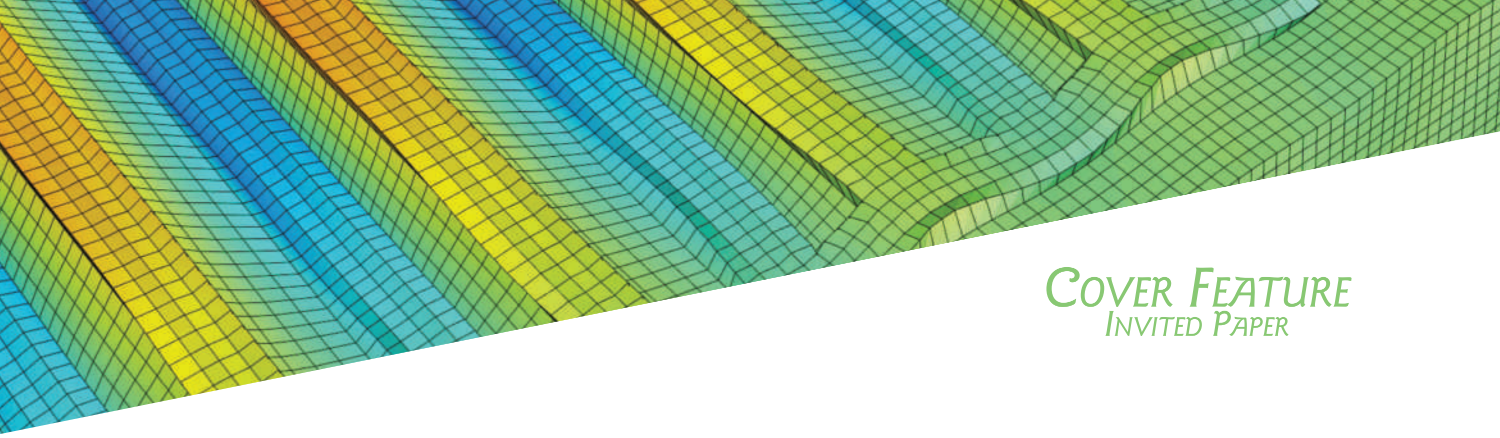

Piezo-On-Insulator Engineered Substrates for 4G/5G RF Front-End Filters

Christophe Didier, Eric Butaud and Sylvain Ballandras
Soitec, France

The deployment of advanced 4G and 5G sub-6 GHz networks requires the introduction of new features and technologies by operators and phone makers. In order to provide access to the larger data bandwidth that the new network promises to deliver, the RF communication between the base station and user equipment must rely on a more complicated band setup. The complexity of the RF front-end module therefore increases dramatically and will have to integrate more than 100 filters to support all communication modes.

Different technologies are available to address the growing filter market but most struggle to meet the more stringent requirements demanded by the 5G networks. New Piezo-On-Insulator (POI) substrates, however, allow the manufacturing of high performance, integrated surface acoustic wave (SAW) filter components that can meet the requirements of 5G networks. These filters can be used in smartphone front-end modules along with the power amplifiers, switches and antenna tuners devices that are already manufactured using RF-SOI substrates or others.

5G CHALLENGES OF FRONT-END MODULES

With 5G, larger RF spectrum provides access to data rates twenty times higher than 4G data rates. Devices connected simultaneously will multiply, resulting in a connection density of a thousand times higher than what is available today. All devices using the mobile network will be impacted by the arrival of this new standard.

To provide data rate in excess of 20 Gb/s, acoustic filters need to adapt to the complex challenges related to 5G networks: more bands, bands with larger bandwidths, higher frequency bands, many band combinations to support the different carrier aggregation (CA) modes and MIMO antenna design.

In order to achieve these new requirements, the signal selectivity needs to be more precise. For this, it is important to enable resonators that have an extremely low temperature coefficient factor (TCF), typically lower than 10 ppm/K, while providing a high Q-factor, Bode Q typically greater than 2000. Also, out of band rejection must be considered much more carefully in order to support the different carrier aggregation and MIMO features.

The optimization of energy consumption in the front-end module remains a key concern. The components must also limit insertion losses so that at equal power levels, the signal travel as far as possible and at the same time the device must dissipate the power very efficiently.

A proliferation of components inside the smartphone front-end modules are greatly constraining the available space. There are already more than 60 filters in the current high-end phones, and we should expect to see more than a hundred in the next generation of high-end phones. Each filter addresses a specific RF band and requires unique design and performance characteristics. Integrating such a high number of different components in a very limited space causes many challenges for design and manufacturing teams. For these reasons, form factor, thermal dissipation and improved performance are becoming critical characteristics of the filters inside the front-end modules.

MARKET NEEDS

Until recently, there were two main filter technologies to select the signal in smartphones. The piezoelectric material would generate acous-

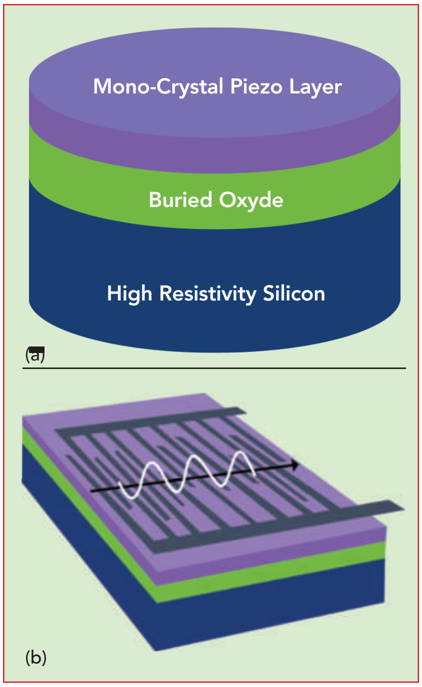

Fig. 1 **Structure of the POI engineered substrate (a) and resulting SAW propagation (b).**

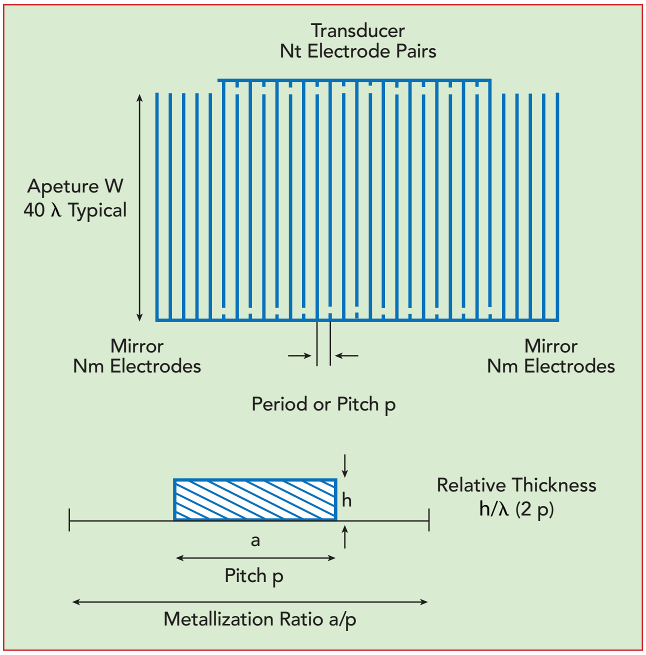

Fig. 2 **SAW resonator design.**

tic waves that could propagate freely on the surface of the material (SAW), or through the bulk of the active layers (BAW: bulk acoustic wave).

Current SAW filters are very well suited for low and medium 4G frequency bands but are limited when addressing the more difficult 5G requirements (high TCF, low Q, low coupling factor) and higher frequencies. The SAW filter frequency response is sensitive to temperature variations due to the high thermal expansion of the substrate (usually lithium tantalate or lithium niobate). This issue of temperature sensitivity can be compensated partially by adding a layer on top of the metal layer at the end of the device fabrication process, but this layer affects the coupling efficiency and the final performance of the filter.

The BAW filter technology allows filters to operate at higher frequencies with good performance but cannot be thinned down as much as SAW filters, creating module integration challenges. In addition, it requires more complicated manufacturing processes and offers limited integration of a filter multiplexer or filter duplexer on the same die.

THIN FILM PIEZO-ON-INSULATOR

Because it is no longer possible to compromise on some of the performance criteria and in response to the more stringent requirements demanded by the new 5G network features, Soitec has developed a new engineered substrate that enables operators and phone makers to respond to these challenges. POI engineered substrates consist of a thin layer of single-crystal piezo material (today single-crystal lithium tantalate) on top of a SiO_2 layer and a high resistivity silicon substrate as shown in ***Figure 1a***. The top lithium tantalate thickness typically ranges from 0.3 to 1 µm. This thin film POI engineered substrate is built using Soitec Smart-Cut™ technology which allows for high uniformity layers and high-quality volume manufacturing.

This structure guides the acoustic wave at the surface of the substrate and confines its energy in the top thin lithium tantalate layer with very low losses (see ***Figure 1b***). With this engineered substrate, filter designers have access to a substrate material with a better coupling factor (k^2) and a lower thermal expansion coefficient. This enables them to design resonators with a high-quality factor at higher frequencies and target larger bandwidth filters with low temperature sensitivity. It also provides the capability to integrate multiple filters on the same die.

The POI substrate is composed of three layers, a piezoelectric material, a buried oxide and a silicon layer. The thin and highly uniform piezoelectric layer confines the energy of the guided wave, enabling high performance acoustic characteristics. The buried oxide selects and guides only high velocity waves and constrains the piezo material, reducing thermal expansion and in-turn temperature sensitivity. This structure allows for high signal se-

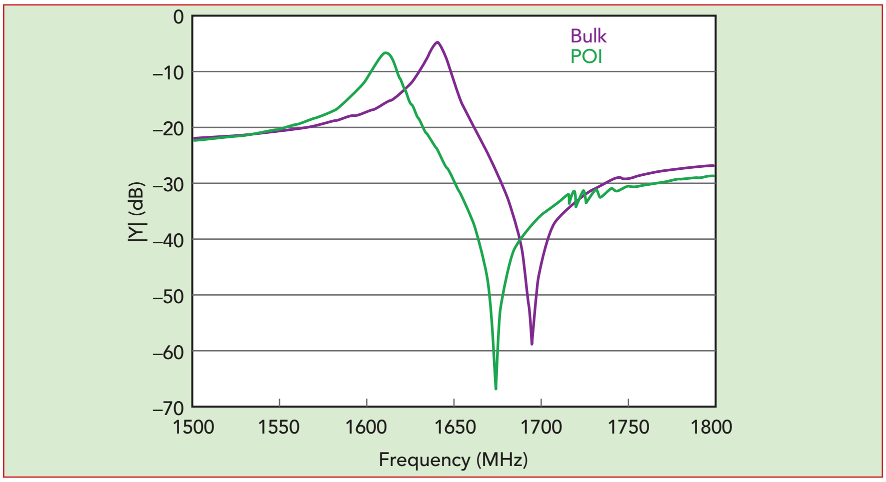

Fig. 3 **Resonator k^2 measurement of bulk and POI substrates.**

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TABLE 1
POI FILTER CAPABILITY

	POI	TC-SAW	BAW
High Quality Factor	✓	✗	✓
High Temperature Stability	✓	✓	=
Low Loss Filters	✓	✗	✓
High Frequency	=	✗	✓
Efficient Same Die Integration	✓	=	✗
Cost	=	✓	✗

✓ Best
✗ Limitation
= Best Achievable in Cases

lectivity, as well as frequency stability when temperature changes. Therefore, it also simplifies the manufacturing process compared to TC-SAW since filter device manufacturers do not need to add a thick layer on top to constrain the piezo material, thus improving the coupling efficiency.

The very low insertion losses achievable by a SAW filter designed on a POI substrate allows device manufacturers to efficiently manage energy consumption. Compared to existing solutions, SAW filters on POI have a high Q-factor, high coupling for large bandwidth filters, extremely low TCF and efficient integration of filters on the same die (see ***Table 1***).

In addition, it should be noted that designing filters on POI substrates requires very similar skills to those required for designing SAW filters on bulk piezo wafers and manufacturing devices on POI substrates is straightforward (standard metal layer deposition for the main part) using a small number of manufacturing process steps.

SAW RESONATOR AND FILTER DESIGNS ON POI

Measured performance of SAW resonators built on lithium tantalate wafers and SAW resonators built on thin film POI were prepared and characterized. The results demonstrate the performance improvement of the POI substrate. For this experiment, a single port resonator of dipoles using 120 finger pairs and 20 electrodes on each side acting as mirrors was manufactured. The acoustic aperture was set at 40 λ and the distance between fingers and electrodes set at 1.2 μm with a ratio metal/spacing of 0.5 (see ***Figure 2***).

A 1.6 GHz central frequency was targeted for those resonators and used tip probing to measure their characteristics. The POI substrates used had the following characteristics: 600 nm thick (YX)/42° $LiTaO_3$ on a 500 nm thick SiO_2 on a high resistivity Si (100 crystal).

Coupling k^2

The coupling k^2 of the POI reached 8.13 percent when the bulk $LiTaO_3$ wafers used for conventional TC-SAW devices was limited to 5.98 percent (see ***Figure 3***). k^2 is calculated as $1\text{-}fr^2/fa^2$ (fr is the resonance frequency and fa is the anti-resonance frequency). The benefits of the higher k^2 provided by the POI substrate enable design of larger bandwidth filters to address some of the new 5G bands (up to 6 percent bandwidth of the center frequency).

Q-factor

Another significant performance improvement of the POI substrate appears on the Bode Q factor at anti-resonance. Under the same conditions, the Q-factor of the bulk $LiTaO_3$ reached 935 compared to 2200 on the POI substrate (see ***Figure 4***). This value should enable SAW filters to compete against BAW filters in the L- and C-Bands.

Temperature Compensated Factor (TCF)

The TCF factor (cubic polynomial fit) on the POI substrate is also significantly reduced. We are able to achieve much less than 20 ppm/K (typically below 10 ppm/K) while the bulk $LiTaO_3$ would be around 40 ppm/K. ***Figure 5*** shows the quasi-compensation of temperature effect on a 1.4 GHz resonator—second order effect is notable (TCF1 = −1.93 ppm/K, TCF2 = 403.5 ppb/K)

Based on our characterization work on the resonators, a ladder

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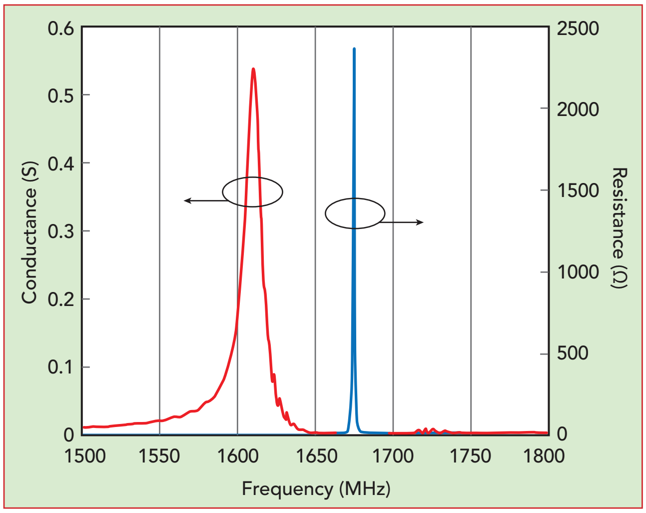

Fig. 4 **POI-based resonator response—max. Q at anti-resonance.**

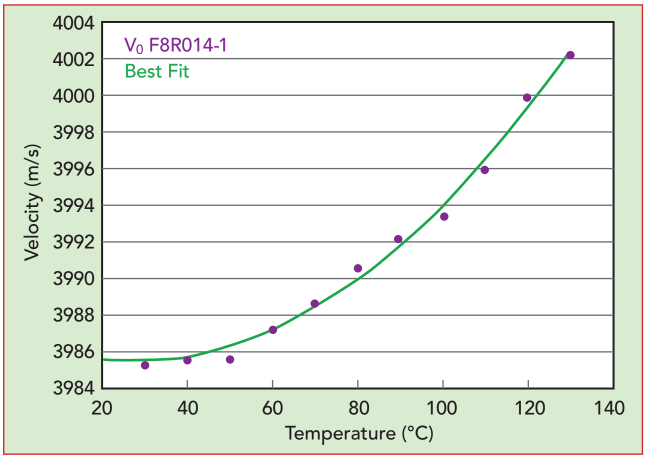

Fig. 5 **Sensitivity of velocity vs. temperature.**

architecture was designed and simulated for a SAW filter at 2 GHz. The filter resonantors were implemented on POI wafers and performance measured. There was no target frequency band, but rather the filter was designed to take advantage of the modes of propagation that the POI substrate can enable.

The resulting extrapolated filter had 80 MHz bandwidth (1 dB band), less than 2 dB insertion loss, rejection greater than 40 dB and a group delay variation of about 50 ns or better. The absolute TCF was under 10 ppm/K over the entire operating range. Bandpass characteristics could be further optimized with filter design, but these results illustrate what can be achieved on this new platform (see ***Figure 6***).

SUMMARY

The 5G roll-out is bringing a set of new challenges to front-end module devices, including form factor, thermal dissipation and performance. Improved performance is needed in order to achieve a successful roll-out. Filters are playing a key role since their numbers are increasing dramatically to support the new bands

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Waveguide Band (GHz)	**WR28** 26-40	**WR15** 50-75	**WR12** 60-90	**WR10** 75-110	**WR8** 90-140	**WR6.5** 110-170	**WR5.1** 140-220	**WR4.3** 170-260	**WR3.4** 220-330	**WR2.8** 260-400	**WR2.2** 325-500	**WR1.5** 500-750	**WR1.0** 750-1,100
Dynamic Range (BW=10Hz, dB, typ)	120	120	120	120	120	120	120	115	115	100	110	100	65
(BW=10Hz, dB, min)	110	110	110	110	110	110	110	110	105	80	100	80	45
Magnitude Stability (±dB)	0.15	0.15	0.15	0.15	0.15	0.25	0.25	0.3	0.3	0.5	0.5	0.4	0.5
Phase Stability (±deg)	2	2	2	2	2	4	4	4	6	6	6	4	6
Test Port Power (dBm)	13	13	13	18	6	13	-1	-2	1	-10	-8	-25	-30

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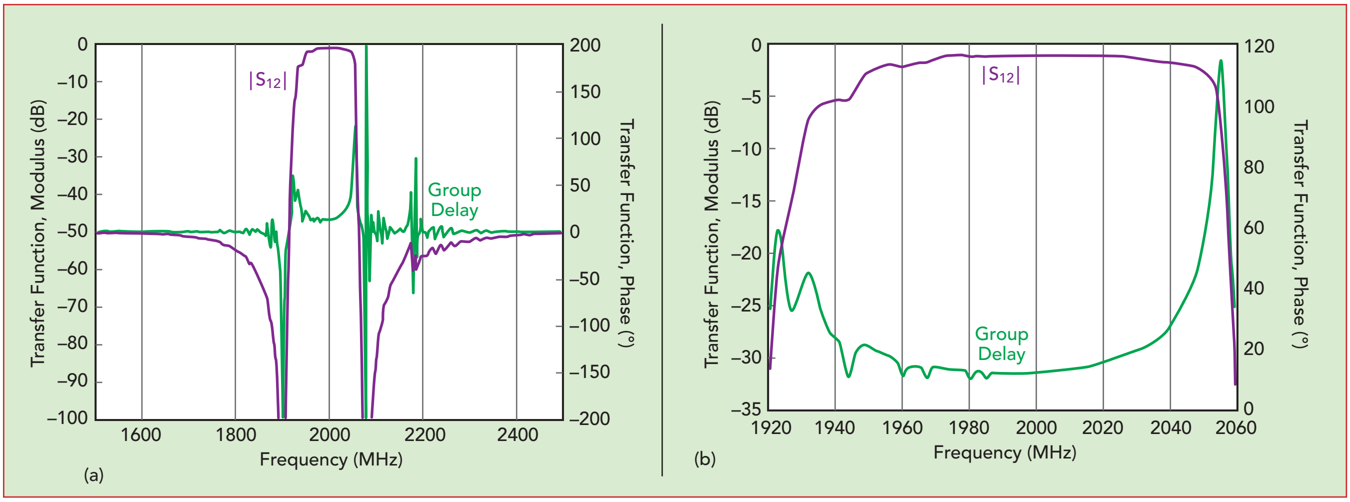

Fig. 6 **Transmission and group delay of the 2 GHz SAW filter fabricated on POI: wideband (a) and passband (b) performance.**

requirements in front-end modules.

Soitec has developed a new type of engineered substrate consisting of a very thin and uniform single-crystal lithium tantalate layer on a thin silicon oxide layer on high resistivity handle substrate using its Smart Cut™ technology. The proposed solution provides resonators and filters with figures of merit in line with 5G filter requirements, particularly regarding the quality and coupling factors that are both greatly improved compared to standard SAWs on bulk piezoelectric material.

Designing, integrating and manufacturing filters on POI wafers remains straightforward as it relies on similar techniques used for SAW devices fabrication. SAW filters on POI can also compete with BAW filters for required frequencies in L- and S-Bands as they also bring the required performance.

The piezoelectric material expertise associated with Smart Cut™ technology allows Soitec to manufacture large volumes of uniform engineered substrates in their dedicated production line and is available to support the stringent filter requirements of 5G.■

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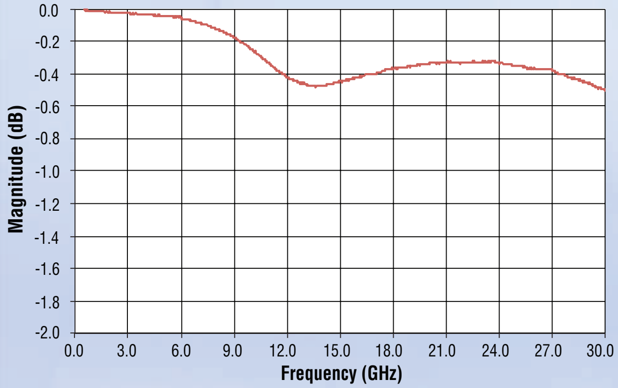
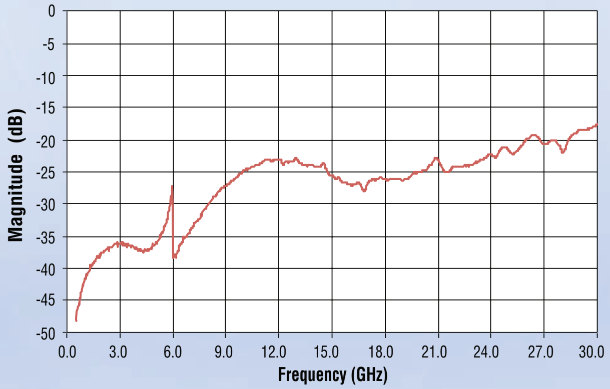


531Z Return Loss (S11)



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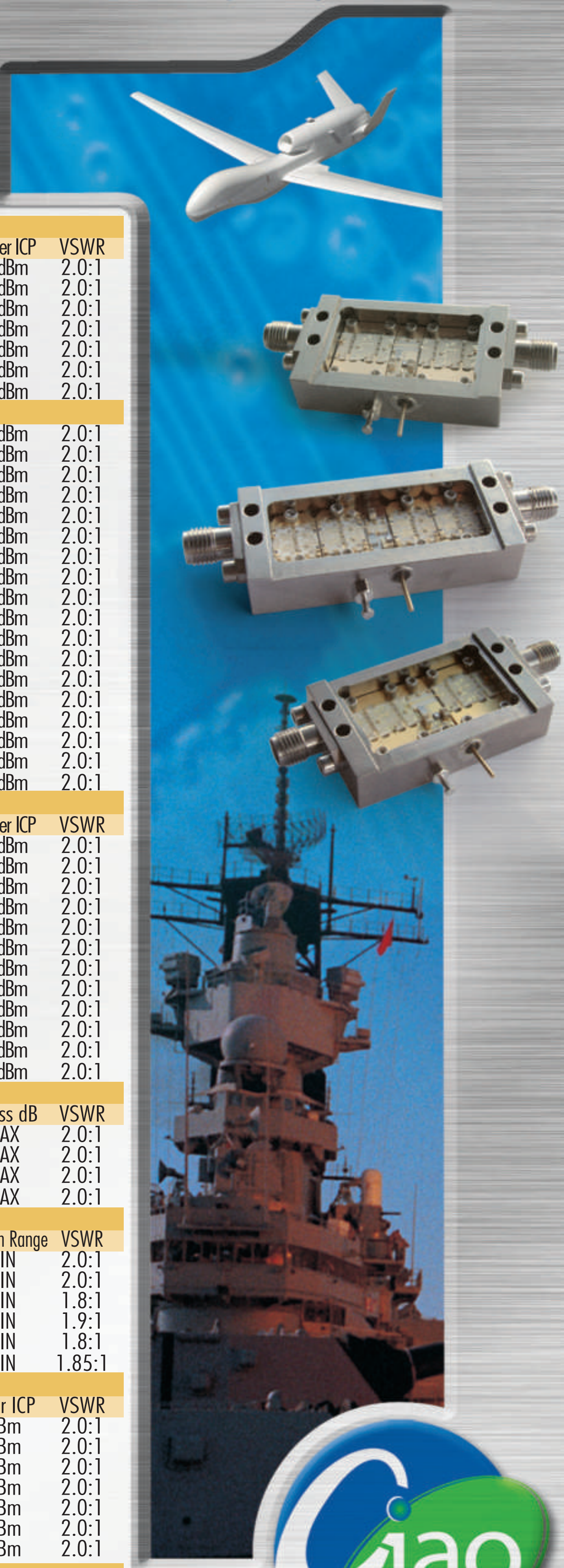

OCTAVE BAND LOW NOISE AMPLIFIERS

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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US Navy Littoral Combat Ships Operate HENSOLDT's TRS-4D Naval Radars

Sensor solutions provider HENSOLDT Inc. has successfully installed the first two of its TRS-4D naval radars aboard the U.S. Navy's "Freedom" Variant Littoral Combat Ships (LCS). After passing acceptance trials on Lake Michigan without issue, the radar on-board LCS 17 (Indianapolis) was delivered by Freedom Variant LCS prime contractor, Lockheed Martin, to the U.S. Navy. The second radar has been installed aboard LCS 19 (St. Louis) and is preparing for acceptance trials.

"System characteristics of the TRS-4D are an excellent match for the environment LCS faces," says Ken Loy, managing director of HENSOLDT Inc. "The radar's AESA technology delivers increased sensitivity to detect smaller targets with greater accuracy, as well as faster track generation to give LCS more time to react to advanced threats."

The TRS-4D (recently designated by U.S. Navy as AN/SPS-80) radar for LCS is a rotating version of the active electronically scanned array (AESA) fixed panel TRS-4D radar currently going aboard the German F-125 frigates. The TRS 4D will be the first AESA rotating radar aboard a U.S. Navy ship. Currently, eight TRS-4D are under contract for the Freedom Variant LCS. Six of them have passed factory acceptance. The new radar combines mechanical and electronic azimuth scanning to achieve fast generation of target tracks. This software-defined radar is programmable by the customer, enabling changes to radar characteristics to match future threats that evolve over the life of the ship. The ability to customize the characteristics of the TRS-4D radar enables designers to maximize the inherent modularity of LCS variants to best suit a specific LCS configuration.

Littoral combat ships are fast, agile surface combatants optimized for operating in the highly trafficked near-shore regions of the world. Through its innovative modular design, LCS can be reconfigured for surface warfare, anti-submarine warfare and mine countermeasures in the near term, and adapt its capabilities for changing threats and scenarios that will occur over its service life.

LCS (Source: HENSOLDT)

Hypersonic Missiles Blur the Line Between Conventional & Nuclear Warfare

"As hypersonic weapons fly at extremely high speeds and some are maneuverable, they are more likely to disrupt the international offense-defense balance of technology, increasingly blurring the line between nuclear and conventional weapons," said Rahul Udoshi, analyst at Jane's by IHS Markit. "Striking virtually anywhere in the world within an hour means these weapons affect the perceptions of strategic stability and further risk crisis escalation over ambiguity of warhead types." China, Russia and the U.S. are all currently investing heavily in hypersonics, while a few other countries are also exploring the technology to a much lesser degree.

To date, Jane's estimates the U.S. to have spent over $3.3 billion for the research and development of hypersonic technologies and weapons, with a further 2020 budget request of $2.6 billion.

> **Ongoing research and development will disrupt the defense market as we know it.**

"Currently, we see Russia and China both leading research and developmental work with considerable funding, suggesting that the U.S. has somehow fallen behind these countries. However, this may change in the near term, given the existing U.S. programs' priority and commitment," said Udoshi.

Russia is estimated to have spent over $1.1 billion covering the Avangard, 3M22 Tsirkon and Kinzhal programs. Russian spending on hypersonic weapons is not expected to rise significantly as the Kinzhal is already in service while the Tsirkon and Avangard are close to entering service.

Chinese funding for hypersonic weapons is estimated to be more than Russia with over $1.5 billion spent on programs such as the DF-ZF and the Starry Sky-2. DF-ZF is expected to be operational by 2020, while Starry Sky would be operational by around 2025. China is expected to sustain its funding for hypersonic technologies as it takes the current programs to their conclusions.

India is estimated to have spent over $500 million on the research and development of hypersonic weapons. Programs include Shourya, Brahmos II and Hypersonic Technology Demonstrating Vehicle (HSTDV). India has

For More Information — Visit mwjournal.com for more defense news.

collaborated with Russia for the development of Bramhos II. Funding for the Indian hypersonic weapons programs is expected to grow as they are still at the development and testing stage.

LM's Expertise in Hypersonic Flight Wins New Army Work

The U.S. Army recently awarded Lockheed Martin (LM) a contract at an estimated value of $347 million as part of a multi-year hypersonic weapons development in support of the Army's focus in long-range precision strike missiles.

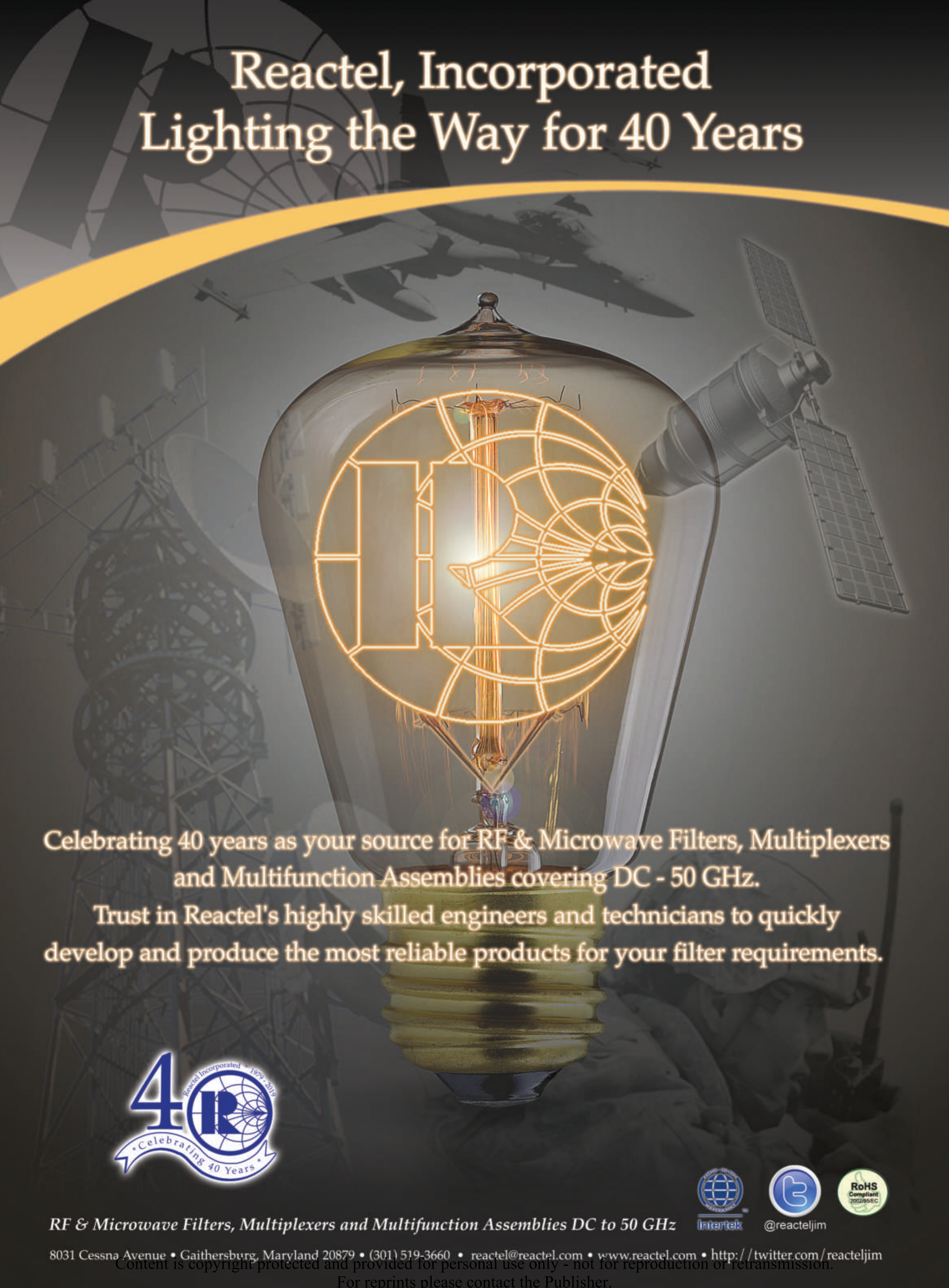
As the prime contractor for the long-range hypersonic weapon (LRHW) systems integration project, the LM team will develop and integrate a land-based hypersonic strike prototype in partnership with the Army Hypersonic Project Office, part of the Army Rapid Capabilities and Critical Technologies Office. The team includes: Dynetics Technical Solutions (DTS), Integration Innovation Inc. (i3), Verity Integrated Systems, Martinez & Turek and Penta Research.

The Army also awarded a contract to DTS at an estimated value of $352 million to produce the first commercially manufactured set of Common-Hypersonic Glide Body (C-HGB) systems. DTS selected LM to support integration and prototyping of this new C-HGB. The C-HGB will be available across military services to provide commonality to air, land and sea platform needs and requirements.

The Army LRHW prototype will leverage the C-HGB and introduce a new class of ultrafast and maneuverable long-range missiles with the ability to launch from ground mobile platforms. The LRHW system prototype will provide residual combat capability to soldiers by 2023.

Hypersonic strike weapons, capable of flying speeds in excess of Mach 5, are a key aspect of the long-range precision fire modernization effort for the Army and the national security strategy to compete with and outpace potential threats.

HGB (Source: Lockheed Martin)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FCC Chair Recommends No Change to RF Safety Standards

Federal Communications Commission (FCC) Chairman Ajit Pai has proposed the FCC maintain the existing health standards for exposure to RF radiation, which are among the most stringent limits for RF exposure in the world. He said the recommendation is based on more than six years of public input and review.

Jeffrey Shuren, director of the Food and Drug Administration's Center for Devices and Radiological Health, supports keeping the current limits, writing that the "available scientific evidence to date does not support adverse health effects in humans due to exposures at or under the current limits."

While extending the existing standards, Pai is also proposing to establish a uniform set of guidelines, regardless of service or technology, to ensure compliance. This will replace the FCC's "inconsistent patchwork of service-specific rules," according to a release describing Pai's recommendations.

Pai's proposal, which needs to be voted on by the commission, includes the following elements:

- Maintain the existing RF exposure limits. This would close the the FCC's 2013 Notice of Inquiry seeking public input on whether to change the RF exposure limits.
- Establish a uniform set of guidelines for determining compliance with the standards, using frequency, distance and power and independent of the service or technology.
- Seek comments on establishing a rule to formalize the existing standard for devices operating at high frequencies.

"The FCC sets RF limits in close consultation with the FDA and other health agencies. After a thorough review of the record and consultation with these agencies, we find it appropriate to maintain the existing RF limits, which are among the most stringent in the world for cell phones," said Julius Knapp, chief of the FCC's Office of Engineering and Technology.

> Seeks uniform guideline to ensure compliance.

In 1996, the FCC adopted maximum permissible exposure limits for field strength and power density for transmitters operating from 300 kHz to 100 GHz, which were developed by the National Council on Radiation Protection and Measurements (NCRP). The FCC has also adopted the specific absorption rate (SAR) limits for devices operating close to the body, as specified by the American National Standards Institute (ANSI) and the IEEE.

3G and 4G Will Drive M2M Service Revenues on Cellular Public Networks

The global cellular M2M market will nearly quintuple from over 620 million connections in 2019 to 3 billion connections in 2024 according to ABI Research. While connection revenues will double to $32 billion, these revenues will account for just 14 percent of all cellular M2M value-added services revenues in 2024. To capture greater share of the M2M revenue opportunity, global operators must expand their horizontal capabilities, partner with vertical specialists and move up the value stack.

"While many operators are hedging their bets on the emergence of new 5G and LPWA networks to expand their M2M endeavors, the reality is that in 2024 3G and 4G connections will account for 72 percent of total M2M value-added services revenues," says Dan Shey, VP, ABI Research. "This result is partly due to the influence of connected vehicle markets which will rely heavily on 3G and 4G technologies; but it also reflects supplier focus on bringing full stack solutions to well serve very specific vertical markets. Regardless of network technology, operators can gain greater share of value-added services revenues by formulating the right set of services and partnerships to create high-value end-to-end M2M solutions."

> Top 10 mobile operators cellular M2M connection share to grow over the next 5 years.

Additionally, network operators need to realize how M2M revenue growth will change by type of M2M service and how fierce the competition is among network operators. Only a handful of operators have been able to generate annual revenues close to $1 billion from their M2M activities, and they have done so by focusing beyond the device and its connectivity to the value that these connections generate through analytics and other platform services. Within this competitive and growing market, dominant players such as Vodafone, AT&T and China Mobile have already emerged and established dominant footholds in their respective regional markets which will continue to expand throughout the forecast period. In 2019, the top 10 operators will account for about three out of five cellular M2M connections; in 2024, these operators will account for more than two out every three cellular M2M connections.

"In order for cellular network operators to fully leverage M2M opportunities, they must undertake a critical assessment of their own internal capabilities and implement strategies that enable them to meet the demands of M2M end-users," Shey advises. "To move up the value-chain, operators need to move past the underlying connectivity technology and establish dedicated M2M

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teams, partner with vertical specialists along the value chain and deploy solution-based business models. By moving beyond simple connectivity, network operators can maximize the value of their networks and fully leverage solution opportunities that will eventually transition to LPWA and 5G technologies."

Embedded Security Semiconductor Shipments to Exceed 4B By 2023

Accelerating demand for embedded security in industrial and automotive segments is driving the market for technologies such as secure microcontrollers (MCU) and trusted platform modules (TPM). ABI Research forecasts that total global shipments of secure embedded hardware will double by 2023, surpassing the 4 billion mark.

TPMs are finally gaining momentum, notably in new industrial markets, after more than a decade since its standardization. It had largely become static in the PC space, with almost 100 percent adoption for machines running Windows 10. "The renewed interest is coming from the industrial and automotive sectors, in large part boosted by the release of TPM 2.0 in 2016, which adapted the technology to IoT scenarios. Infineon and STMicroelectronics are set to gain significantly in this reinvigorated market, with both offering dedicated TPM 2.0 solutions for embedded applications," says Michela Menting, research director of digital security at ABI Research.

In parallel, emergence of secure varieties of microcontrollers for the IoT market is gaining traction, and is seeing demand in smart cities, homes and buildings, as well as in utilities and the industrial IoT. Improved processing and performance capabilities for MCUs has allowed the inclusion of security features that work well with embedded and deterministic imperatives. NXP and Renesas are both offering secure MCU platforms, Kinetis and Synergy, respectively, that have proven hugely successful since their release.

Other strong contenders in the market for secure embedded hardware include Microchip, Cypress (soon to be part of Infineon), RedPine, Nuvoton, Maxim Integrated, Goodix, TI and MediaTek.

With declining ASPs and growing demand for secure silicon-to-cloud solutions, secure connectivity will have to be anchored in secure hardware for embedded systems. As such, strong growth is projected for the global hardware security market going forward. "As the semiconductor industry moves toward integrating ever more security features on smaller form-factors, competition in the space will increasingly focus on those hardware elements that can provide the best performance for tailored IoT applications," Menting concludes.

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

COLLABORATIONS

Raytheon Co.'s Missile Systems business has signed a new strategic supplier agreement with **Ducommun**. The new initiative gives Ducommun the ability to engage in more opportunities on virtually every program within the RMS portfolio. Raytheon Missile Systems spends approximately $4 billion annually with suppliers around the globe. Ducommun currently provides RMS with electronics, circuit card assemblies, harnessing cables and more for both core and emerging programs. Raytheon selected Ducommun Performance Center in Monrovia, Calif. as a 2019 Raytheon Supplier Excellence Program Premier Award winner in the partnership category.

Rohde & Schwarz in collaboration with **Vector, Savari and Quectel** successfully presented an application layer test solution for 3GPP C-V2X Release 14, specifically aimed at the growing Chinese market. This integrated test platform was presented at the MWC Shanghai 2019 and is a complete solution for simulation development and testing of all V2X-based applications. The presented C-V2X test solution consists of a device under test C-V2X module AG15 provided by Quectel, running Savari's MobiWAVE® V2X Software Stack and receiving the ITS messages provided by the R&S CMW500 wideband radio communication tester and the GPS signal by R&S SMBV100B vector signal generator.

Richardson RFPD announced that it has become a sponsoring member of the **Chicago Connectory**. Founded in 2017, the Chicago Connectory is the first Midwest innovation space dedicated completely to IoT. It is a 20,000 sq. ft. co-creation space and IoT incubator developed by Bosch and 1871 that fosters collaboration, networking, problem solving and cutting-edge technology. As a sponsoring member, Richardson RFPD brings its strong level of IoT and wireless design expertise to the Chicago Connectory and its members. One of Richardson RFPD's first contributions to the Chicago Connectory will be the development and installation of an interactive, multi-radio tracking demo with 24/7 cloud-based monitoring.

Modelithics announced that **TDK** is now a Sponsoring Modelithics Vendor Partner (MVP). Under the MVP program, Modelithics and TDK are working together to develop and support the highest accuracy device simulation models for TDK components, and promote their availability to designers on the latest electronic design automation (EDA) simulation tools. There are currently nine Microwave Global Models™ available for TDK RF inductor components, with each highly scalable model representing a full series of parts, covering their available range of values. Microwave Global Models feature substrate scaling, pad scaling and part value scaling, all within one schematic element for a part series.

COMSOL announced that the **Manufacturing Technology Centre (MTC)** has officially joined the ranks of its global list of Certified Consultants. The MTC provides technologies and tools that advance the adoption of innovative manufacturing processes in the U.K. and beyond. The use of COMSOL Multiphysics® software allows them to create highly-accurate virtual models to predict the performance of and optimize processes for their clients. As a COMSOL Certified Consultant, MTC can expand into industries such as automotive, aerospace, food, electronics and construction that need to incorporate multiphysics simulation in their R&D, manufacturing and production to boost their competitiveness, reduce costs and time to market.

SWISSto12 and **Tyvak Nano-Satellite Systems** have established a partnership to offer mini-GEO satellites. The two companies aim to provide customized satellites at competitive cost, with telecom payloads in X-, Ka-, Q- and V-Band. Swissto12 will contribute the telecom payload and 3D printed RF products, while Tyvak brings mission operations, platform and payload expertise. The two companies will leverage their engineering teams in Europe and the U.S. to expedite the delivery of mini-GEO fleets. Mini-GEO satellites weigh 100 to 500 kg, fly in geostationary orbits and typically provide regional telecommunications coverage.

ACHIEVEMENTS

Launched at 20:30 GMT on August 6, 2019 from the **Guiana Space Centre** in French Guiana, **HYLAS 3** is **Avanti Communications Group**'s latest satellite deployment, and one of its most ambitious to date. With over 4 GHz capacity of steerable beam technology in a unique steerable user and gateway beam combination—which allows coverage to be quickly allocated where it is needed—HYLAS 3 extends Avanti's satellite connectivity across EMEA creating a comprehensive and flexible communications network in that region. HYLAS 3 has been carefully constructed in partnership with the European Space Agency (ESA), MDA, Airbus and OHB.

Lockheed Martin (LM) recognized 27 small business suppliers that made exemplary contributions to its Missiles and Fire Control business area's products and services in 2018. **Custom MMIC** received an award for their exemplary work in helping LM deliver crucial missions to their customers. For more than 20 years, LM has celebrated small business suppliers' successful efforts in providing quality goods and services and outstanding support.

German radar company **HENSOLDT** has successfully passed certification of its Monopulse Secondary Surveillance Radar (MSSR) 2000 I identification system by the AIMS Program Office of the **U.S. DoD**. This makes HENSOLDT the first company outside of the U.S. to fulfill this critical pre-requisite for delivering identification, friend or foe (IFF) devices for the upcoming conversion of all NATO identification systems to the future "Mode 5" standard without any discrepancies. AIMS certification

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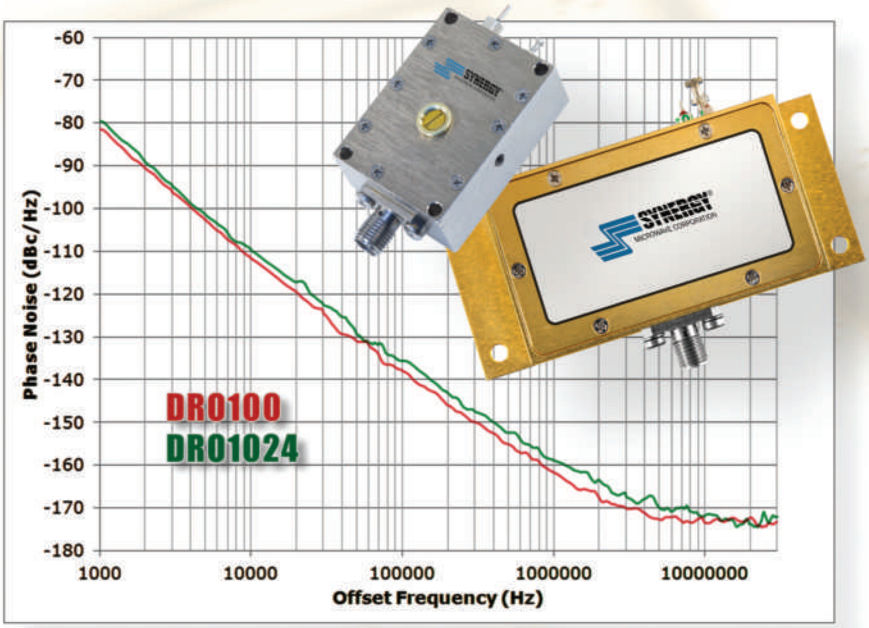

Model	Frequency (GHz)	Tuning Voltage (VDC)	DC Bias (VDC)	Typical Phase Noise @ 10 kHz (dBc/Hz)
Surface Mount Models				
SDRO800-8	8.000	1 - 10	+8.0 @ 25 mA	-114
SDRO900-8	9.000	1 - 10	+8.0 @ 25 mA	-114
SDRO1000-8	10.000	1 - 15	+8.0 @ 25 mA	-107
SDRO1024-8	10.240	1 - 15	+8.0 @ 25 mA	-105
SDRO1118-7	11.180	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1121-7	11.217	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1130-7	11.303	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1134-7	11.340	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1250-8	12.500	1 - 15	+8.0 @ 25 mA	-105
Connectorized Models				
DRO80	8.000	1 - 15	+7.0 - +10 @ 70 mA	-114
DRO8R95	8.950	1 - 10	+7.0 - +10 @ 38 mA	-109
DRO100	10.000	1 - 15	+7.0 - +10 @ 70 mA	-111
DRO1024	10.240	1 - 15	+7.0 - +10 @ 70 mA	-109
DRO1024H	10.240	1 - 15	+7.0 - +10 @ 70 mA	-115
KDRO145-15-411M	14.500	*	+7.5 @ 60 mA	-100

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is mandatory for non-NATO countries whose forces are deployed together with NATO nations in joint missions.

Telit has announced that its LE910C1-NF and LE910C4-NF modules are certified for use on the three largest U.S. mobile network operators. The certifications enable original equipment manufacturers (OEM) to develop solutions for many verticals and use cases that can be immediately deployed across the three largest U.S. mobile networks using a single SKU. The Telit LE910C1-NF provides 10 Mbps download and 5 Mbps upload LTE Category 1 speeds, ideal for trackers, telematics, navigation solutions, digital signage, ATMs, kiosks and video capture devices to name a few.

Radio Frequency Systems (RFS) has announced that two of its high-power broadcast transmission antennas are deployed at the Nanyue TV and FM transmission station on Mount Heng, one of the Five Great Mountains of China. The Nanyue TV and FM transmission station is operated by the Hunan Broadcasting System and is one of the most well-known broadcast transmission stations in China. The antennas' unique, multi-sided designs enable near-perfect horizontal field coverage for FM radio and digital TV transmissions.

Quectel Wireless Solutions has announced that Telstra has certified its EG06-E, EM06-E, EP06-E 4G/3G and EG06-AUTL modules for operation on the carrier's commercial network in Australia. The new LTE-Advanced (LTE-A) module approvals can accelerate time to market for customers deploying high speed wireless connectivity in mobile and fixed IoT applications. Based on Qualcomm's 9x40 chipset and in compliance with 3GPP R.11 standard, the modules support 256QAM and 2xCA and have been certified as LTE Cat.13 (DL) and Cat.6 (UL), achieving speeds of 390 Mbps DL and 50 Mbps UL, respectively. The modules offer high speed USB3.0/USB2.0 connectivity, 4G voice (VoLTE and E000 Call) and integrate multi-constellation GNSS receiver.

A team of researchers from the **Institute of Science and Technology Austria** demonstrated a quantum radar that relies on using entangled photons and operates at such low power levels that it can hide behind background noise, making it useful for biomedical and security applications. One of the advantages of the quantum revolution is the ability to sense the world in a new way. The general idea is to use the special properties of quantum mechanics to make measurements or produce images that are otherwise impossible.

CONTRACTS

Mercury Systems Inc. announced it won a $22 million order from a major defense prime contractor for high performance airborne radar processing subsystems, another demonstration of the company's leading capability in providing the most secure, innovative technology solutions for defense applications. Quickly developed, these processors were designed using Mercury's sen-

sor open system architecture (SOSA)-compatible building blocks that feature the latest data center processing power and scalability required by next-generation radars. This multi-year order was received in the company's fiscal 2019 fourth quarter and is expected to be shipped over the next few years.

Comtech Telecommunications Corp. announced that during its fourth quarter of fiscal 2019, its New York-based subsidiary, **Comtech PST Corp.**, which is part of Comtech's Government Solutions segment, received multiple orders totaling approximately $3.6 million for solid-state high-power RF amplifiers from a major domestic prime contractor. These amplifiers are key elements in complex data communication systems and these orders supplement an installed base of Comtech solid-state high-power RF amplifiers previously delivered to this major domestic prime contractor.

EM Solutions has been awarded two contracts from the **Australian Department of Defence Innovation Hub** to develop next-generation satellite ground terminal capability. The first is a AUD$1.9 million contract to develop a low-profile, flat panel antenna SATCOM terminal. Based on a novel low-cost "leaky-wave" antenna developed in concert with researchers at the University of Queensland, this system is intended to provide improved communications capability from land, air or sea platforms to any satellite. In the same announcement from the Australian Minister for Defence Industry, the company was also awarded a AUD$5.8 million contract to continue its development of a ruggedised SATCOM terminal for potential deployment on current and future Royal Australian Navy vessels.

Echodyne announced that its surveillance radar, EchoGuard, has been selected by a top tier defense supplier for mission-critical ground and airspace perimeter security deployments in the U.S. and overseas. Echodyne has completed delivery of the first 100 EchoGuard radars under the contract which includes an option for additional radars in 2019 and subsequent years. Echodyne's breakthrough EchoGuard radar was chosen for its industry-leading combination of performance and price. The innovative sensor accurately detects and tracks ground and airspace security threats using patent-protected MESA™ technology combined with powerful control software.

BAE Systems has completed the first full rate production delivery of the CV90 Mjölner Mortar System to the **Swedish FMV (Defence Materiel Administration)**, introducing a new capability to the fleet of CV90s by adding indirect firepower. The first four vehicles will be handed over to the Swedish Army following the recent delivery that met schedule, budget and quality requirements. The CV90 Mjölner has now become the 16th variant in the family of combat proven CV90 vehicles, demonstrating the ability of the platform to cost effectively adapt to a large range of mission sets to meet the needs of our customers.


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Around the **Circuit**

PEOPLE

▲ *Dr. Ulrich Rohde*

The Institute of Electronics and Telecommunication (IETE) has given its highest honor, the Honorary Fellowship, to **Dr. Ulrich Rohde**. The Honorary Fellowship of the Institution is accorded to an eminent person in the field of science, technology, education and industry.

▲ *Mike Ryan*

TMD USA has appointed **Mike Ryan** to the new position of senior account executive. With his in-depth knowledge of selling direct into prime contractors and the U.S. government, Ryan will be playing a major role in TMD USA's ongoing market and customer base expansion program into the defense, homeland security and scientific fields. Ryan's broad-based experience also covers engineering, designing, patenting, marketing and selling new products and custom solutions to OEMs, government organizations and consumer markets.

▲ *Mark McLaughlin*

Qualcomm Inc. announced the appointment of **Mark McLaughlin** as its chairman of the board, effective immediately, replacing Jeff Henderson, who had served in that capacity since March 2018. Henderson, the former CFP of Cardinal Health, will remain on the board and continue to chair its Audit Committee.

PLACES

The Elevator & Escalator Division of Mitsubishi Electric US Inc., headquartered in Cypress, Calif., has announced the expansion of its branch office in the Dallas-Fort Worth, Texas area. Since the opening of the Dallas-Fort Worth office in 2017, Mitsubishi Electric US's Elevator & Escalator Division has worked with building owners, architects and general contractors in Texas on everything from elevator and escalator design and installation to maintenance. Steady business growth has prompted the need for the branch office to relocate to an expanded facility with additional warehouse space and office space.

Isola Group has completed a 118,000 sq. ft. lease to remain in Chandler, and relocate its headquarters, R&D and manufacturing operations. The company will be moving into a newly constructed industrial building at the Lotus Project. The new state-of-the-art facility will be optimized for the quick-turn PCB market that drives much of the product innovation in North America.

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Uni-Guide™ Waveguide Connector

The waveguide, along with the coaxial line, is one of the most important transmission media in any modern RF, microwave and millimeter-wave component, and sub-assembly and system. Due to its metal tubing configuration, the waveguide tends to be heavy and bulky, especially in low microwave frequencies. However, it is always a preferred transmission means when performance and high power are priorities.

On the other hand, the coaxial transmission line offers the alternative approach. It delivers moderate RF performance, but its light and flexible features are attractive for many component and system applications.

Figure 1. The Coaxial Connectorized Components

Figure 2. Dedicated Package with the Built-in Waveguide Transitions

However, waveguide interfaced components are required from time to time, due to the requirements of high performance, high power handling and system integrations. Because of that, the industry is using either the coax to waveguide adapters or the dedicated package with built-in waveguide transitions to create the waveguide interface. A waveguide connector was never invented nor introduced to the industry since the waveguide was born 120 years ago.

The waveguide to coax adapter approach is bulky and expensive. It also introduces additional circuit loss which could degrade system performance and increase system manufacturing cost. On the other hand, the dedicated package with built-in waveguide transition option requires special or custom designs and manufacturing process, which is costly and time consuming. Furthermore, this option is not flexible and creates additional parts to manage, which is not welcome in any manufacturing organization.

It would be desirable if the waveguide connector, like the coaxial connector, existed so that the direct waveguide interface can be realized without additional engineering efforts, extended development cycle time, and massive inventory management. In addition, hermetically sealing the waveguide involves a special and costly process. SAGE Millimeter has invented the waveguide connector to overcome these difficulties. Currently, SAGE Millimeter has released WR-28, WR-22 and WR-19 waveguide connectors to accept the most commonly used 12-mil diameter glass bead with 0.48" mounting hole separation in the industry. Other bands and configurations are still under development.

Figure 3-A. WR-28 Waveguide

Figure 3-B. WR-22 Waveguide

Figure 3-C. WR-19 Waveguide

Figure 4. Waveguide Connector, Offering Direct Replacement of the Coax Connector

From Figure 4, one can see how the direct replacement of the coaxial connector to form the waveguide interface is accomplished. In addition, the newly invented waveguide connector offers flexible installation to form various waveguide orientations. While Figure 5 shows that the input and output waveguide ports are vertically aligned, Figure 6 shows they can be horizontally aligned just by rotating the connectors 90-degrees.

As mentioned earlier, the waveguide connector solves the hermeticity challenges with no efforts and no additional cost. This is simply because it is a connector just like the coax connector. Once the package is sealed, there is no need to seal the waveguide window.

Furthermore, the waveguide connector can reduce product development cycle time, eliminate additional design cost and minimize additional inventory management. Instead of developing various custom waveguide interfaced packages to satisfy different frequency bands and waveguide orientation requirements, only a few standard housings and waveguide connectors are needed to accommodate many package variations.

The trademark for the waveguide connectors is Uni-Guide™, which can play equal and more extended roles in any microwave and millimeter-wave components and sub-assembly interconnections as coaxial connectors.

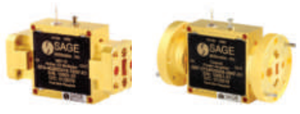

Figure 5. Housing with Waveguide Connector Vertically Aligned

Figure 6. Housing with Waveguide Connector Horizontally Aligned

Currently, SAGE Millimeter is focusing on developing the WR-42, WR-15, WR-12 and WR-10 Uni-Guide™. SAGE Millimeter also accepts custom inquires to develop custom waveguide connectors to satisfy various waveguide interface requirements.

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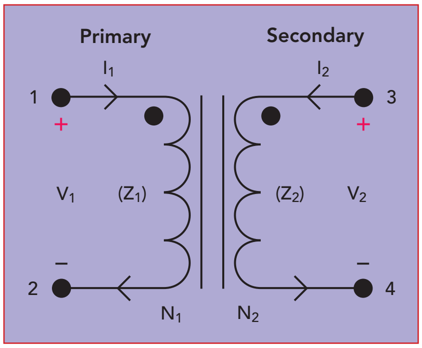
Demystifying RF Transformers: A Primer on the Theory, Technologies and Applications

William Yu and Urvashi Sengal
Mini-Circuits, Brooklyn, N.Y.

This article is the first in a series on demystifying RF transformers. It focuses on introducing RF transformer theory and discusses common RF transformer technologies and applications.

In essence, a transformer is merely two or more conductive paths linked by a mutual magnetic field. When a varying magnetic flux is developed within a core, by alternating current passing through one conductive path, a current is induced in the other conductive paths. This induced current is proportional to the ratio of the magnetic coupling between the two conductive paths. The ratio of the magnetic coupling of the conductive paths with the core determines the induced voltage in the additional conductive paths, providing both an impedance transformation and a voltage step-up or step-down. Additional conductive paths, potentially all with different coupling ratios, may be added to realize various functions, which is why RF transformers are such varied and versatile devices and used widely throughout the RF/microwave industry.



▲ Fig. 1 Schematic of an ideal transformer.

A common implementation of an RF transformer consists of two or more distinct wires wrapped around a magnetic core—or an air core at higher frequencies—which is why RF transformers are often described as the ratio of the number of windings or turns. RF transformers are used for a variety of applications, as the nature of the device allows for various configurations serving different functions, including

- Providing an impedance transformation for impedance matching.
- Stepping up or down a voltage or current.
- Efficiently coupling between balanced and unbalanced circuits.
- Enhancing common mode rejection.
- Providing DC isolation between circuits.
- Injecting DC current.

Several common technologies are used to build transformers, including core-and-wire, transmission line, low temperature co-fired ceramic (LTCC) and MMIC. Each is available in a variety of packages with a range of performance characteristics.

TRANSFORMER THEORY

Though not realistic for actual applications, a model of the ideal transformer illustrates the fundamental behavior of transformers (see ***Figure 1***). Ports 1 and 2 are the input of the primary winding, and ports 3 and 4 are the output of the secondary winding. From Faraday's Law, the current through the primary winding creates a magnetic flux through the mutual magnetic field of the

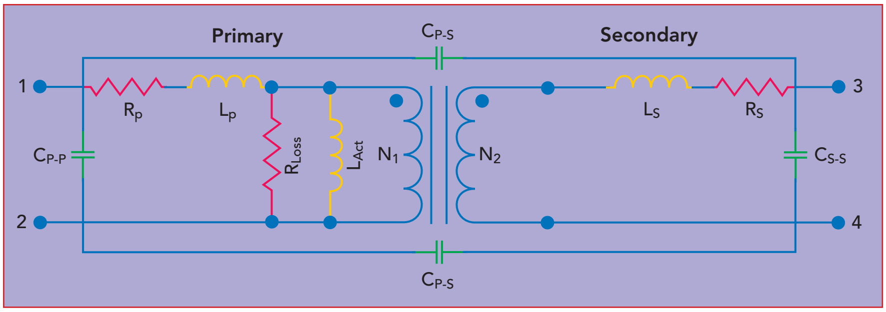


Fig. 2 Transformer model with parasitic elements.

core, inducing a proportional current and voltage in the secondary winding. Both the current and voltage developed are proportional to the ratio of the windings or the magnetic coupling between the windings and the core. Hence, the secondary impedance is a function of the square of the windings ratio multiplied by the impedance of the primary. The operation is described by the following:

$$n = \frac{N_2}{N_1}, V_2 = nV_1, I_2 = \frac{I_1}{n},$$
$$Z_1 = \frac{V_1}{I_1}, Z_2 = \frac{V_2}{I_2}, Z_2 = n^2 Z_1 \qquad (1)$$

where I_1, V_1 and Z_1 are the current, voltage and impedance through the primary winding; I_2, V_2 and Z_2 are the current, voltage and impedance through the secondary winding; N_1 is the number of turns in the primary winding; and N_2 is the number of turns in the secondary winding.

A real transformer includes several parasitic resistances, inductances and capacitances, both mutual and self-parasitic capacitances. ***Figure 2*** shows a lumped-element model of a non-ideal RF transformer, which depicts the parasitic resistances and inductances of the two windings, as well as the core resistive losses and the windings' active inductance. The parasitics cause an actual transformer to operate over a limited bandwidth, with insertion loss and limited power handling (see ***Figure 3***). The performance also depends on frequency, temperature and power.

An actual RF transformer's lower cutoff frequency is dictated by the winding's active inductance, and the high frequency cutoff is dominated by the inter-winding and intra-winding capacitance. The insertion loss in the operating bandwidth is a product of the ohmic losses in the primary and secondary windings, as well as the dissipation within the core. As the ohmic losses tend to be a function of frequency and temperature, the transformer's effective operating bandwidth is limited by these factors. Several RF transformer types introduce leakage inductances due to incomplete magnetic coupling between the windings. As the reactance of the leakage inductance is proportional to frequency, these parasitics reduce the return loss at high frequency and increase the insertion loss at lower frequency.

More complex RF transformer topologies, such as transformers with several windings, taps and additional elements, present varying performance dynamics based on the topology and transformer construction. For example, an RF device known as a balun is used to efficiently interconnect balanced (i.e., differential signal) circuits to unbalanced (i.e., single-ended signal) circuits using impedance transformation; it can be realized with an RF transformer. Another device similar to a balun, known as an unun, is used to interconnect unbalanced to unbalanced RF circuits, and it can be realized with an RF transformer. A common balun fashioned from a transformer is a flux coupled balun transformer, constructed by winding separate wires around a magnetic core and grounding one side of the primary winding. The single-ended RF signals entering the primary unbalanced winding undergo an impedance transformation to a differential (i.e., balanced) output through the secondary winding.

RF transformers that include a magnetic core—typically ferromagnets—have several undesirable factors that degrade performance. The magnetizing inductance of the

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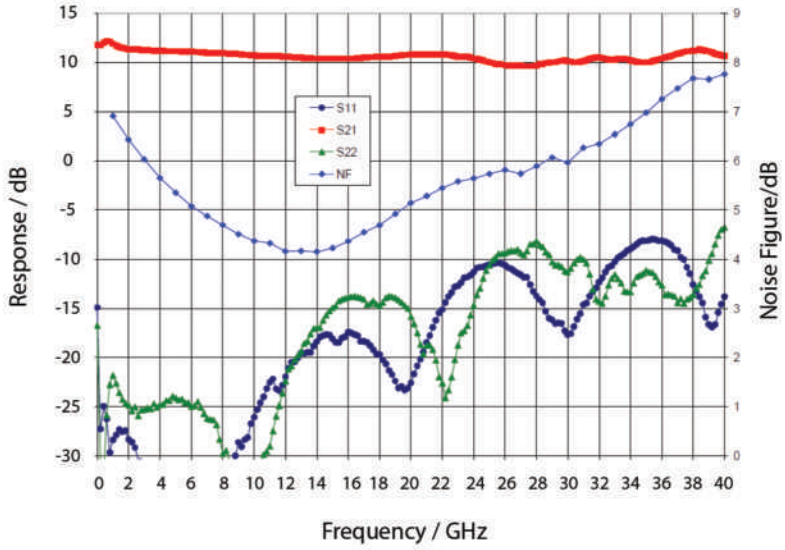

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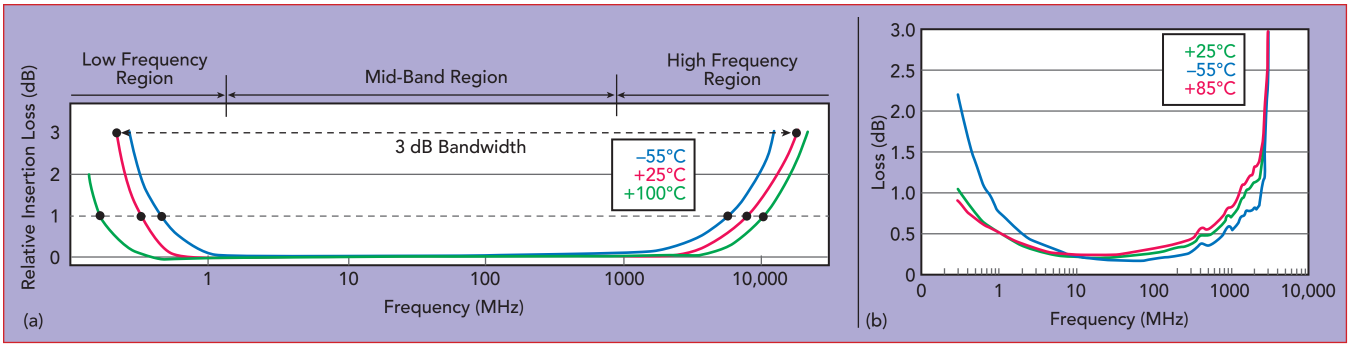

Fig. 3 Theoretically, a transformer has a bandpass frequency response (a) which measurements confirm (b).

Fig. 4 Construction of a wire-wound transformer with magnetic core.

core limits the low frequency performance of the transformer. This inductance is a function of the core permeability, cross sectional area and number of windings around the core. The magnetizing inductance increases the insertion loss at low frequencies and degrades the return loss. The permeability of the core is also a function of temperature; permeability increasing with temperature increases the low frequency insertion loss.

RF TRANSFORMER TECHNOLOGIES

The two main types of discrete RF transformers are core-and-wire and transmission line. Additionally, two common types of low profile and compact transformer designs are LTCC and MMIC.

Core-and-Wire RF Transformers

Core-and-wire transformers are fabricated by wrapping conductive wires, typically insulated copper wires, around a magnetic core such as a toroid. There may be one or more secondary windings, which may also be center tapped to enable additional functions. ***Figure 4*** shows an RF transformer made from a toroidal magnetic core and insulated copper windings. Due to the nature of the inductive coupling between the wires and the core, smaller core-and-wire dimensions tend to yield core-and-wire transformers that operate at much higher

frequencies than those with larger core-and-wire transformers. However, the smaller size of the compact transformers increases the resistive losses of the windings and the core, resulting in greater insertion loss at lower frequencies.

Transmission Line RF Transformers

Transmission line transformer topologies may include precisely designed transmission lines placed between two mismatched loads or a complex arrangement of several transmission lines. For instance, a length of transmission line can be used to implement an impedance transformation between two mismatched loads. Some transmission line transformers use insulated wires wrapped around ferrite cores, closely resembling typical core-and-wire transformers—often considered core-and-wire transformers. Nonetheless, the following discussion is provided less for categorization than to describe transformer behavior and enhance understanding.

A basic transmission line transformer consists of a two conductor transmission line. The first conductor is connected from the generator to the load, and the other conductor is connected at the output of the first transmission line and the load to ground (see ***Figure 5***). With this configuration, the current flowing through the load is twice the current flowing through the generator, and V_0 is half the voltage V_1. Hence, the load resistance is only a quarter of the resistance seen at the generator side, yielding a 1:4 transformer, as described by

$$V_0 = \frac{V_1}{2}, R_G = \frac{V_1}{I_1},$$

$$R_L = \frac{V_0}{2I_1} = \frac{V_1/2}{2I_1} = \frac{R_G}{4} \qquad (2)$$

A common version of the transmission line transformer is the quarter-wave transmission line. This topology uses a transmission line with a characteristic impedance that enables impedance matching between the input impedance and the load. The length of a quarter-wave transformer is dictated by the operating frequency, with the bandwidth limited to one octave around the center frequency. Consider a lossless transmission line with characteristic impedance Z_0 and length L, connected between an input impedance Z_{in} and load impedance, Z_L (see ***Figure 6***). To match Z_{in} with

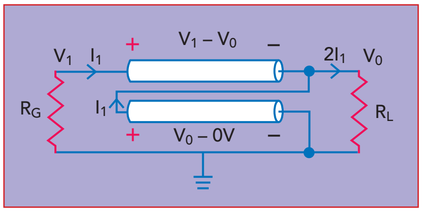

Fig. 5 Schematic of an ideal transmission line transformer.

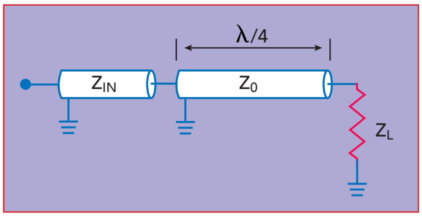

Fig. 6 Quarter-wave transmission line transformer.

Z_L, the characteristic impedance of the quarter-wave transmission line, Z_0, is determined by

$$\beta = \frac{2\pi}{\lambda}, \; Z_{IN} = Z_0 \frac{Z_L + jZ_0 \tan\beta L}{Z_0 + jZ_L \tan\beta L}$$

$$@L \sim \frac{\lambda}{4} Z_{IN} = \frac{Z_0^2}{Z_L}, \; Z_0 = \sqrt{Z_{IN} Z_L} \qquad (3)$$

One advantage of a transmission line transformer is that a significant portion of the interwinding capacitance, along with the leakage inductance, is assumed by the transmission line, which results in a wider operating bandwidth compared to core-and-wire transformers.

LTCC Transformers

LTCC transformers are multilayer components fabricated using a ceramic-based substrate. LTCC transformers use coupled lines acting as transmission lines to achieve impedance transformation and signal conversion from single-ended to balanced. LTCC transformers rely on capacitive coupling, enabling LTCC transformers to operate at higher frequencies compared to ferromagnetic transformers. However, this may lead to performance degradation at low frequencies. One benefit of LTCC technology is the ability to fabricate small and rugged transformers, ideal for high-reliability applications (see ***Figure 7***).

MMIC Transformers

Like LTCC transformers, MMIC transformers are made using 2D substrates with precision layered planar metallization. Typically, MMIC transformers are fabricated using spiral inductors printed on a substrate in a two transmission line configuration, with the lines parallel. A MMIC transformer can be fabricated using a GaAs integrated passive device process (see ***Figure 8***). The precision lithography helps achieve outstanding repeatability, high frequency performance and excellent thermal efficiency.

TRANSFORMER FUNCTIONS & APPLICATIONS

Depending upon topology, RF transformers serve a variety of functions:

Matching—A transformer can match two circuits with different

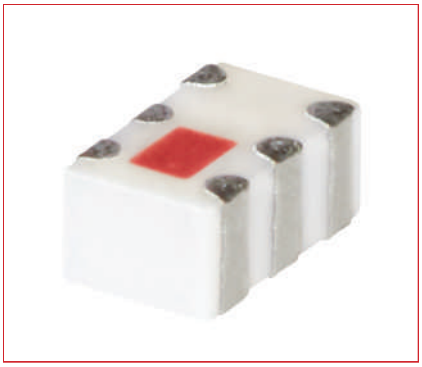

Fig. 7 Transformer fabricated with LTCC technology.

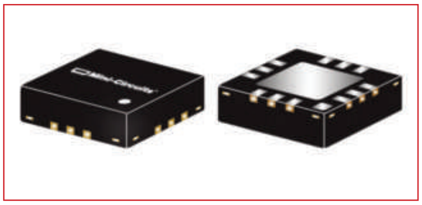

Fig. 8 Transformer fabricated with MMIC technology.

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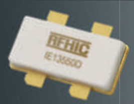

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impedances or provide voltage step-up or step-down of the source voltage. In RF circuits, an impedance mismatch between two nodes causes reduced power transfer and troublesome reflections. The impedance matching transformer effectively eliminates the reflections and provides maximum power transfer between the two circuit nodes (see ***Figure 9***).

Baluns and ununs—Baluns are used to connect balanced and unbalanced circuit sections. For unbalanced lines, an auto-transformer configuration can be used for impedance matching, i.e., an unun.

Bias injection and isolation—An RF transformer can be designed to provide DC isolation between the primary and secondary windings, which is useful for separating RF circuits requiring a DC bias from circuits negatively impacted by a DC voltage. If a DC current is required for a portion of the circuit, a specialized RF transformer can be used to inject current into the signal path. For example, two center-tapped transformers can inject a DC bias and replace two bias tees (see ***Figure 10***).

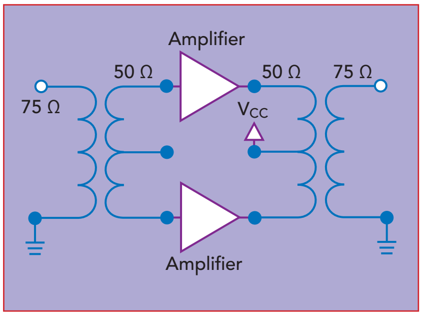

Fig. 9 50 Ω balanced amplifier using transformers for impedance matching to 75 Ω.

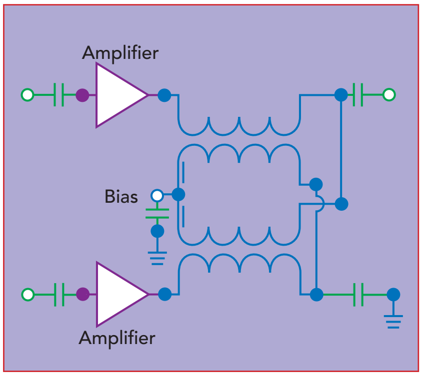

Fig. 10 Using a center-tapped transformer to replace bias tees.

Other functions—RF transformer designs can be used to provide enhanced common mode rejection for balanced (i.e., differential) circuits. Other topologies can function as a choke, filtering high frequency components from a signal line.

SUMMARY

RF transformers are fabricated using a wide variety of manufacturing methods and diverse materials. They are configured in a myriad of topologies to perform many functions in RF circuits. Depending on the materials, construction and design, RF transformers can be narrowband or wideband, operating at low or high frequencies. Understanding the nuances of RF transformers can help designers optimize a design by choosing the best transformer. Additional articles discussing RF transformers will be published online at www.mwjournal.com.■

INVITED PAPER

Design of an Integrated VNA Covering 70 kHz to 220 GHz

Jon Martens and Tom Roberts
Anritsu Co., Morgan Hill, Calif.

Andrej Rumiantzev and Kooho Jung
MPI Corp., Hsinchu, Taiwan

As markets tap higher mmWave frequencies, device and subsystem modeling will follow. These efforts require even higher frequency measurements and equipment limitations that can hinder the development. In addition to standard S-parameters, other measurements such as gain compression, intermodulation distortion and frequency conversion may be needed across wide frequency ranges. Concatenating banded instrument data can work, yet the setup and calibration times become long and, since the uncertainty differs by band, stitching together data sets results in discontinuities.

A broadband vector network analyzer (VNA) covering low frequencies through 220 GHz, with accompanying probes, can resolve many of these measurement complications. Developing such a VNA requires multiplier arrays with adequate output power and control, down-converters with good noise performance and adequate linearity, source and receiver multiplexing that handles wide frequency ranges and a broadband connection enabling a single on-wafer measurement covering the entire frequency range. This article discusses these challenges and the technology options to create a broadband VNA with the required stability, noise, linearity and power performance.

MEASUREMENT REQUIREMENTS

Broadband S-parameters and other microwave measurements are central to many model extraction procedures.[1–6] In others, microwave data serves to generate the parasitic elements in the device models. In either case, the quality of the underlying measurement data is important to overall model performance and any descriptive analysis. Further stressing the need for measurement quality, de-embedding is typically necessary to get from the probe tips to the device or subsystem boundaries. Measurements are often required beyond purely small-signal and linear to include compression (AM/AM and AM/PM), harmonics, intermodulation distortion, adjacent channel power rejection and other parameters. Those quasi-linear or nonlinear quantities may be part of a complete nonlinear modeling effort or may be used for basic characterization. Some of these parameters may only be invoked at the subsystem level, with other measurements used at that stage, such as frequency conversion (gain and phase) and modulation distortion. What is common to all is the need to perform the analysis over a very broad frequency range, using an instrument whose own linearity does not dominate the measurement.


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MEASUREMENT CHALLENGES

Measurements above F-Band (90 to 140 GHz) face several challenges. A typical setup may consist of a broadband system operating to 110 or 125 GHz with banded waveguide modules for the higher frequencies (e.g., 110 to 170 and 170 to 260 GHz or 90 to 140 and 140 to 220 GHz). Mounting and demounting the modules and probes from the probe station—unless one is fortunate enough to have two or three equivalent probe stations—can yield measurement errors.

For broadband device model parameter extraction and IC performance verification, product and process design kit specifications require the same device under test (DUT) to be measured at multiple temperature points (usually five or more), meaning multiple touchdown cycles to the DUT contacts. DUT contact pads suitable for sub-mmWave probing are very small, since parasitic pad reactance increases with frequency. As small pads support only a few RF probe touchdown cycles, measuring the same DUT over the multiple bands covering the whole frequency range and all temperature points may be impossible. This limitation requires engineers to choose different DUTs for different temperatures or frequency bands, which increases uncertainty in the measured parameters and resulting models. A measurement system that reduces the number of touchdowns or enables one touchdown measurements over a wide frequency range will help.

Conventional VNA frequency extenders are sensitive to the measurement laboratory environment. Without multiple feedback control loops, the broadband measurement system characteristics of the remote module can drift faster than those of the base VNA. This leads to more frequent system recalibration, increasing the cumulative measurement cycle time. Frequent system reconfiguration and changeover, required for wide frequency range measurements, increase test cell downtime and risk damaging expensive system components, such as the wafer probes and VNA extenders. This increases the already expensive cost of test.

Data Integrity

Data integrity is also an issue. With several probes used for the different bands—each with unique touchdown characteristics, loss and matching—and several measurement modules used—with different matching, efficiency, spectral purity, stability and noise performance—the data in each band will be measured under different circumstances. While calibration corrects for some of these differences—however, not linearity, noise, spectral purity, drift or repeatability—the uncertainties and distributions in the bands will likely differ. This raises the question of how to handle the inevitable data steps (see ***Figure 1***). The figure shows an example where the uncertainty ranges in two bands overlap; while nothing is fundamentally wrong with either measurement process, the discontinuity complicates the measurement and analysis. If the individual modules and probes have higher uncertainties at the band edges, the analysis becomes even more nuanced.[7]

Once the measurement data is collected, de-embedding to the desired reference plane can be an adventure. Particularly with BiCMOS and CMOS processes with five to nine metal layers, the desired transistor reference plane may be at the bottom layer and the probe pads

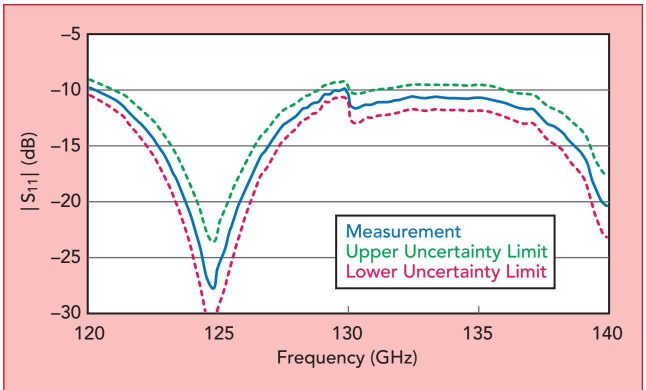

Fig. 1 Data stitching anomalies occur at measurement transitions between equipment setups.

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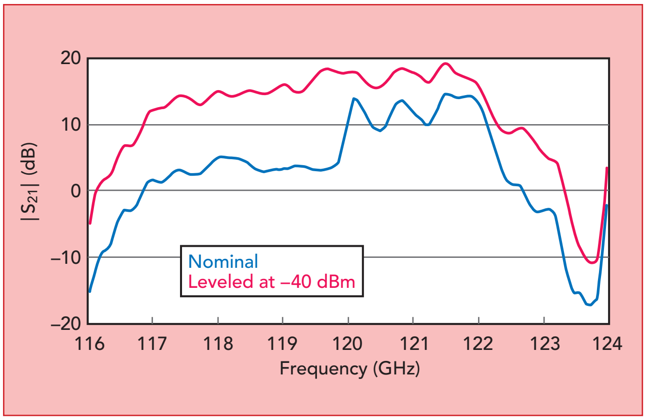

Fig. 2 120 GHz LNA measured at two drive levels, where the nominal level compresses the amplifiers.

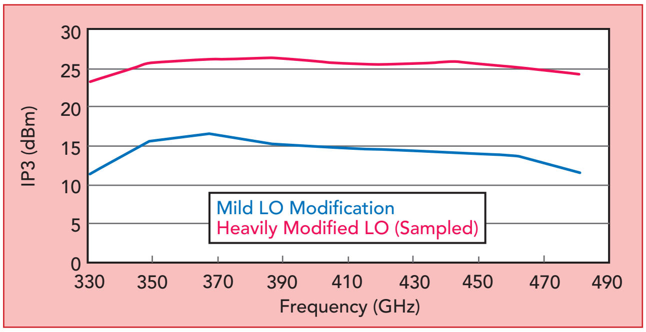

Fig. 3 Third-order intercept point for two mmWave receivers with the same harmonic number but different LO designs.

at the top. This leads to a "network to de-embed" consisting of many vias and transitions, with significant insertion loss and mismatch.[7–9] The increased loss and mismatch complicates the de-embedding process and increases potential error in the measurement results, particularly with drift.[10–11] Since such semiconductor fabrication processes are increasingly used at mmWave frequencies, the stability and accuracy of the S-parameter data is critical, which emphasizes the challenges in stitching data and controlling uncertainties in all bands, including touchdown repeatability.

Ensuring Linearity

The RF drive level is important for transistors and amplifiers at these frequencies, as their input compression points may be low. The drive power may need to be −40 dBm or lower and accurate control of the power may be important to avoid inadvertent compression. For quasi-linear measurements, accurate power control is more important.[12] The historic solution using a mechanical variable attenuator will not provide sufficient power flatness for this class of measurements. ***Figure 2*** illustrates this, showing the measurement of a 120 GHz LNA where the drive level was not considered (the "nominal" curve). The input power to the LNA was not flat, reaching −15 dBm in places. A second measurement leveled the input power at −40 dBm. The nominal gain measurement shows the amplifier highly compressed, varying significantly with frequency because the drive was not flat versus frequency. While this example may be extreme, at higher mmWave frequencies—particularly with bare transistors—early onset compression is not unusual.

Even if the drive power is accurate, another challenge is the linearity of the instrument receiver; correcting for receiver distortion is difficult. Since many mmWave receivers use relatively high order harmonic mixing, the design of the internal local oscillator (LO) system is important to maintain linearity at the test port. A comparison of the intermodulation performance of two receivers is shown in ***Figure 3***, using free space combining of two tones with 100 MHz separation. The two receivers have the same harmonic number but use different LO systems: one with mild clipping, the other more heavily clipped with active edge sharpening. The residual linearity, expressed as the third-order intercept point of the receiver referenced to the measurement plane, differed by close to 10 dB. As the converter designs have different breakdown voltages, broad conclusions are not possible; nonetheless, a wide variance in receiver linearity can occur in this frequency range.

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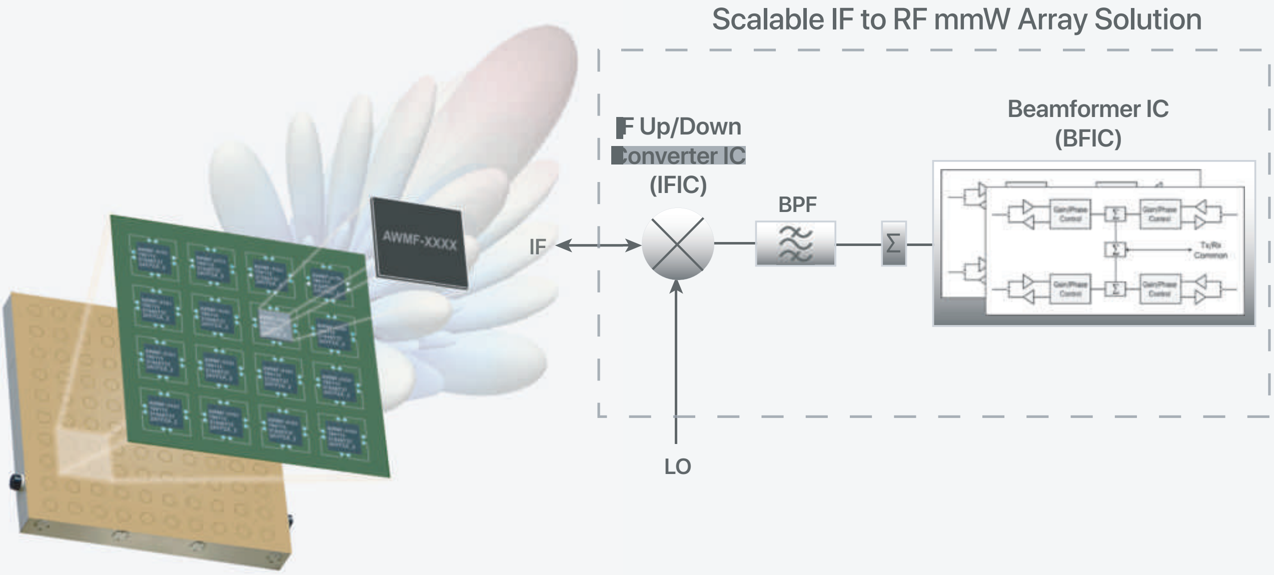

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Broadband VNA Design

One way to address these challenges is using a broadband VNA designed with high linearity receivers and sufficient integration and system control to ensure stability. The block diagram of one such system is shown in ***Figure 4a***, comprising a base VNA and mmWave modules. The module receivers cover 30 to 226 GHz using broadband forward couplers and a high LO sampling system based on III-V nonlinear transmission lines.[13] The port referred third-order intermodulation product of these downconverters exceeds 30 dBm, which helps meet the linearity requirements. The modules provide source multiplication above 54 GHz and use a series of four multiplexers, before the measurement couplers, to inject energy from the respective multipliers. Since progressively less power is available at the higher mmWave frequencies, the highest frequency multiplexer is last and has the tightest coupling. Leveling loops for both RF and LO extend to the modules to improve measurement stability.

The integration of the receivers, couplers and multipliers in a small space helps ensure thermal uniformity and stability, as does the close location of the couplers to the probe tip (see ***Figure 4b***). The test port is a novel structure supporting a coaxial mode, using a 0.6 mm outer conductor and a precision UG-387 flange, instead of a threaded body, to form the outer

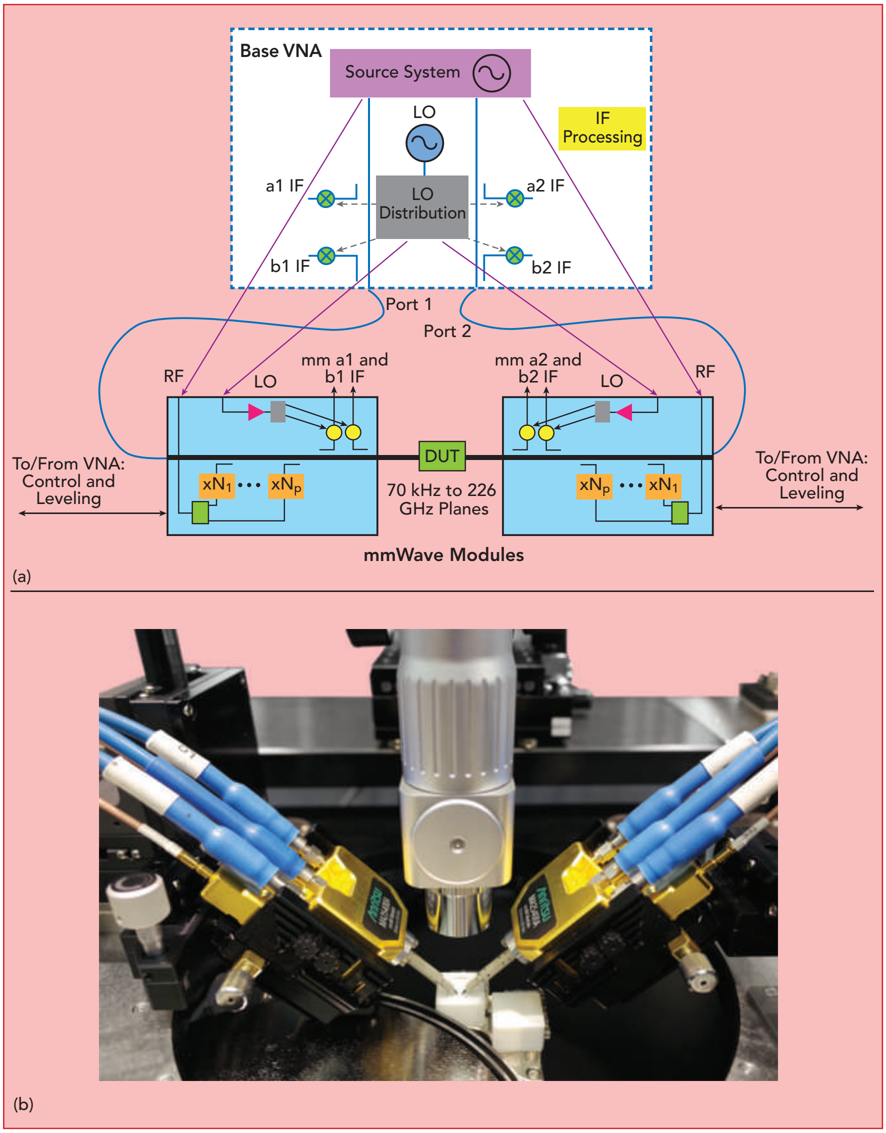

Fig. 4 70 kHz to 226 GHz VNA block diagram (a), showing one measurement setup where the two mmWave modules are connected to on-wafer probes (b).


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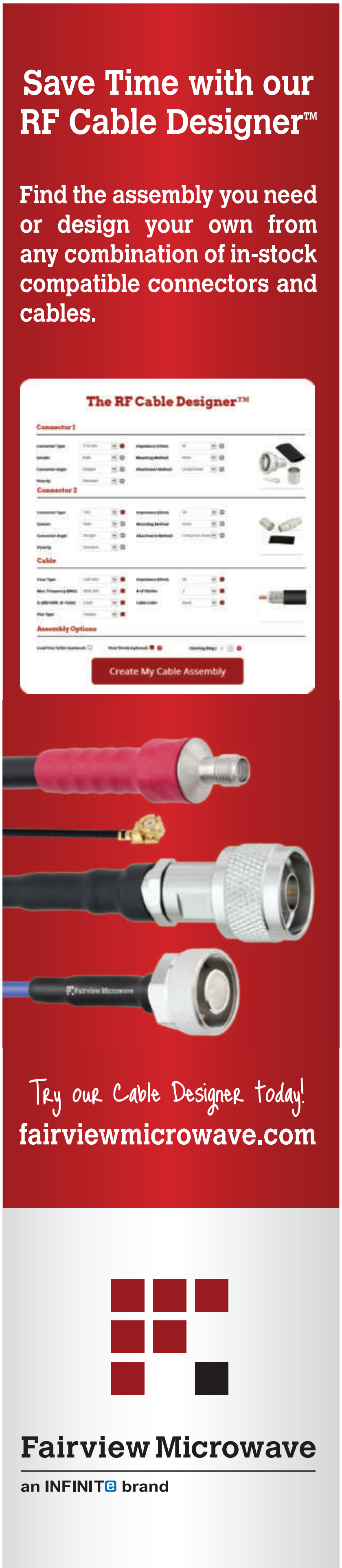

mate. The increased mating area of the flange interface improves durability and significantly reduces the axial forces and bending moments of the connecting device. Repeatability with and without rotation is improved using a precision pin-guided UG-387 flange and limited angular connection orientations, 0 and 180 degrees. Such an interconnect system enables using a single on-wafer probe for measurements from 70 kHz to 226 GHz.

RF wafer probes convert the electromagnetic energy traveling along the three-dimensional media—a coaxial cable or rectangular waveguide—to the on-wafer DUT and its contact pads. This transition is designed to achieve minimal mismatch in the fields and impedance. This is particularly hard to achieve at sub-mmWave wavelengths, so precision wafer probe manufacturing processes are crucial to the overall system performance. Precision probes contribute to well-matched probes for improved calibration and measurement results over a wide frequency range. The 220 GHz MPI TITAN™ Probes incorporate 50 Ω MEMS contact tips to achieve the frequency coverage. Another important aspect of the probe design is maintaining visibility of the tip contacts during touchdowns to minimize potential inaccurate placement. Consistent positioning of the probes on calibration standards and small DUT pads achieves better repeatability and reproducibility, even when used by inexperienced operators. An often-overlooked aspect of probe technology is wear. After multiple probe cycles, the length of the probe tip typically shrinks. However, the unique design of the TITAN probe maintains the RF characteristics after hundreds of thousands of cycles; the lifetime of the probe outperforms the lifetime of comparable probe technologies—even on Al DUT pad metallization—reducing the cost of test and ROI of the test cell.

Using an external stimulus, ***Figure 5*** shows the relative receiver compression at +5 dBm input power relative to a −20 dBm input. This performance is achieved through careful control of the LO waveforms used to drive the sampling downconverters.[14] As discussed, power control is an important attribute for accurate measurements. One way to achieve it is with a heterodyne detection circuit feeding a leveling loop with widely adjustable time constants and gain. In this system, a wide control range of approximately 35 dB at 225 GHz (see ***Figure 6***) and generally greater than 40 dB below 220 GHz is achieved with reasonable control linearity.

Stability is important to maximize

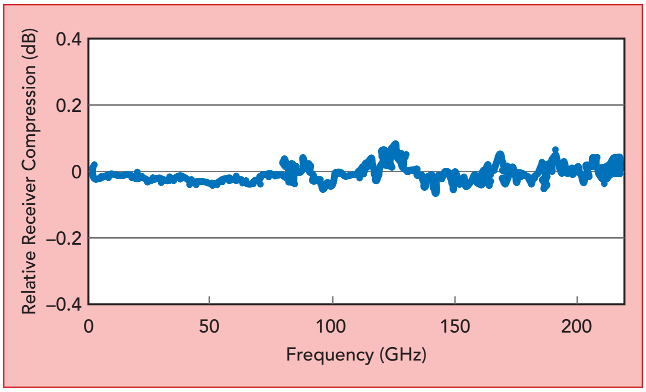

Fig. 5 Relative compression of the VNA receiver, showing the difference between +5 and −20 dBm at the VNA port.

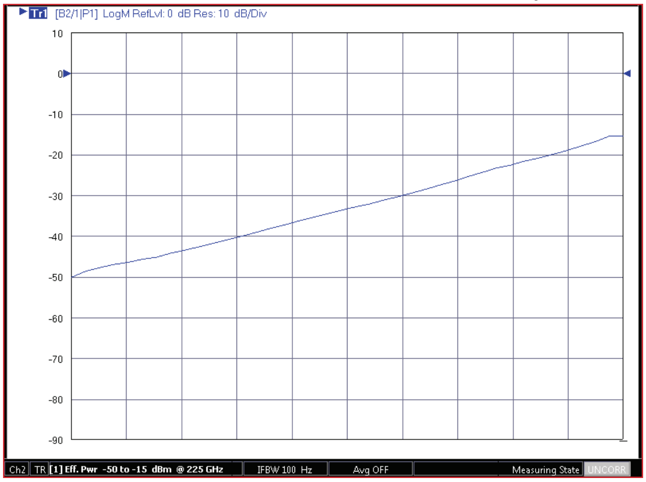

Fig. 6 VNA power control range at 225 GHz.

the time between probe tip calibrations and avoid adding data distortion that complicates model fitting and analysis. ***Figure 7*** shows the transmission measurement of a thru line in the port interface's coaxial structure over 18 hours at 25°C ±3°C. As expected with temperature variation affecting LO cables, the drift increases with frequency since the LO multiplication factor increases with frequency. As the VNA receivers are used below 30 GHz, the RF cable to the modules (see Figure 4) contributes more at the lower frequency.

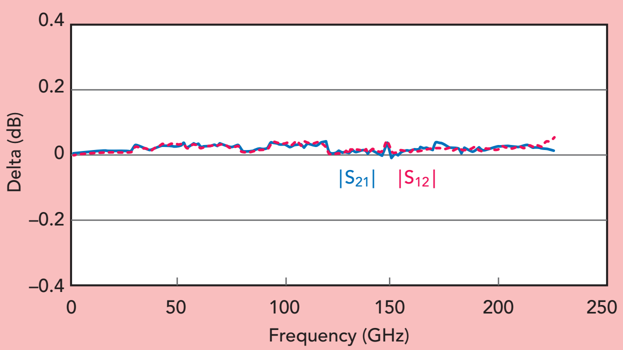

Fig. 7 VNA stability over 24 hours at room temperature, measured using a thru-line.

SUMMARY

Increasingly, broadband mmWave VNA measurements are needed at higher frequencies, creating measurement challenges: stitching data from multiple bands, controlling power levels and ensuring linearity and stability. An integrated, broadband 220 GHz system with a single connection to the DUT is a simple and elegant approach to address these challenges. The linearity, power control, noise performance and stability of such a system improves measurement accuracy and repeatability.■

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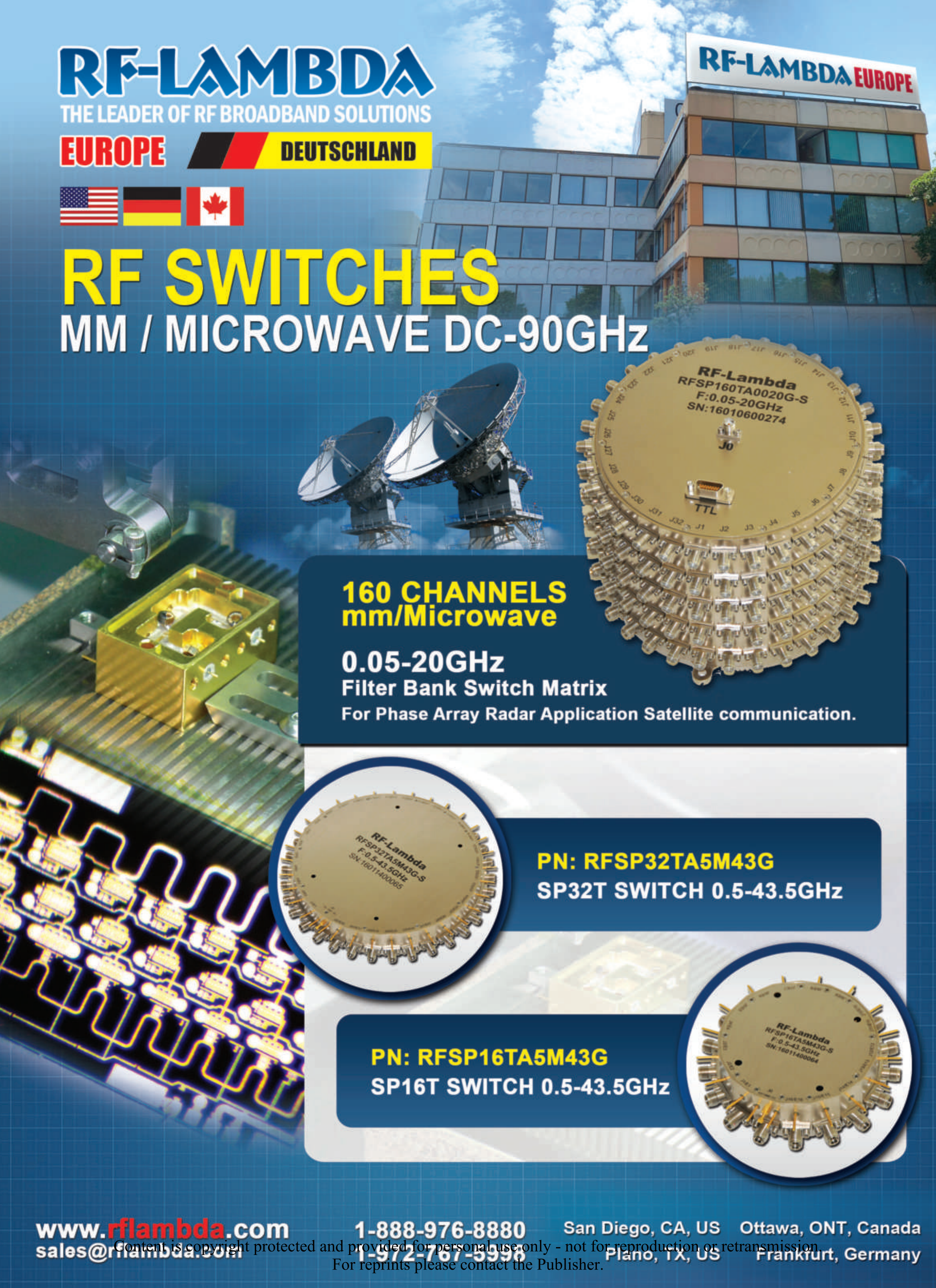

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INVITED PAPER

1.35 mm Precision Coaxial Connector Enables High Performance E-Band Cable Assemblies

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The 1.35 mm connector was created in response to the need for a robust mechanical connector for commercial opportunities up to E-Band, such as satellite and mobile communications and automotive.

Moore's Law was named after Gordon Moore, cofounder of Intel. In 1965, Moore observed that the number of transistors in a dense integrated circuit doubled about every year. By 1975, the industry unofficially dubbed this Moore's Law, and Moore modified his prediction to state the doubling would occur every two years.

A similar, less formalized axiom in the world of connectors is a relationship to frequency. In the early 1960s, the 14 mm precision connector was developed to operate to 8.5 GHz, followed by a succession of connector designs to reach higher frequencies: 7 mm, precision Type N, 3.50 mm, 2.92 mm, 2.40 mm, 1.85 mm and 1.00 mm. A loose corollary to Moore's Law was a 20 to 30 percent increase in frequency with each new connector design. The final leap between the 1.85 mm connector, with a maximum frequency of 65 GHz, to the 1.00 mm connector, with a maximum frequency of 110 GHz and encompassing both E- and W-Bands, is a 70 percent increase in frequency. This double band jump left an opening for a connector for E-Band. Twenty years later when the 1.00 mm connector was commercialized and some deficiencies were realized, the characteristics and design of the 1.35 mm connector was conceived.

Technological innovations are typically driven by research or a commercial application and a corresponding industry supplier. For 1.00 mm connectors, the supplier was Hewlett-Packard, and the connector was formally proposed as a standard (IEEE Std 287-2007) in 1989. However, the first commercial quantities of 1.00 mm connectors were not available until 2010. At higher frequencies, physics constrains the implementation of features such as captivation and connector thread pitch, and the size associated with these higher frequencies results in the 1.00 mm connector being less rugged. Initially, this was not a problem, since the users comprised mostly research facilities that understood how to handle sensitive connectors and cable assemblies.

With deregulation of these frequency bands and applications becoming more cost effective, the commercial world has begun to realize the potential. A group of commercial applications, namely automotive and satellite/mobile communications, reside below 90 GHz in E-Band, and they require large numbers of assemblies that must also be rugged and cost effective. In 2014, SPINNER GmbH decided these applications would benefit from a rugged connector with some but not all of the W-Band connector attributes. Leveraging V- and W-Band connector design fea-

TABLE 1
CONNECTOR REQUIREMENT AND CONFORMITY

Requirement	1.85 mm (V Connector)	1.35 mm (E Connector)	1.00 mm (W Connector)
Pin and Socket Design with Air Dielectric Interface			
Two Different Connector Quality Levels (Like the IEEE "Metrology Grade" and "Instrument Grade")			
Upper Operating Frequency of ≥ 90 GHz	65 (70) GHz	90 (92) GHz	110 (120) GHz
Robust Design: Not Over-Miniaturized, Big Centering Cylinder & Large Contact Surface			
Fine Threaded Coupling Nut Prevents Loosening	M7 x 0.75	M5.5 x 0.5	M4 x 0.7
Socket Connector Equipped with Locking Groove to Allow for Push-On Pin Connector			
"Thru Male" Capability with a Standard Semi-Rigid Cable	0.086 in.	0.047 in.	
Applicable Locking Torque of 1.6 Nm without Plastic Deformation of Outer Conductor			
Coupling Nut with Flat Size of 8 mm		7 or 6.35 mm Option	6 mm
Accepts Same Wrench as the 3.50, 2.92 and 2.40 mm Connectors (Equal Size and Torque)			

(GREEN = CONFORM, RED = NOT CONFORM)

TABLE 2
1.35 MM CONNECTOR ELECTRICAL SPECIFICATIONS

Description	Instrument Grade	Metrology Grade
Characteristic Impedance	50 ± 0.25 Ω	50 ± 0.15 Ω
Guaranteed Upper Operating Frequency	90 GHz	
Unsupported Air Line H_{11} Cutoff Frequency	98.5 GHz	
$\|S_{11}\|$	–20 dB	–24 dB
$\|S_{11}\|$ Repeatability	–43 dB	–48 dB
Insertion Loss	0.05 dB	
Insertion Loss Repeatability	0.03 dB at 90 GHz	
Transmission Phase Repeatability	1° at 90 GHz	
Electrical Length Tolerance	±75 μm	
Shielding Effectiveness	–90 dB	

TABLE 3
1.35 MM CONNECTOR MECHANICAL SPECIFICATIONS

Description	Specification
Outer Conductor Inside Diameter	1.35 mm (0.053 in)
Inner Conductor Outside Diameter	0.586 mm (0.023 in)
Connect/Disconnect Life	3000 cycles
Coupling Torque	0.9 Nm (8.0 in-lb)
Maximum Safety Torque	1.65 Nm (14.6 in-lb)
Coupling Thread	M5.5 x 0.5
Coupling Nut Wrench Size	8 mm (7 or 6.35 mm for Special Applications)

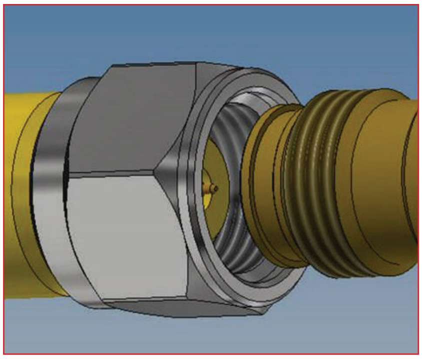

Fig. 1 1.35 mm connector pin and socket.

tures, SPINNER began developing a 1.35 mm E-Band connector with the more rugged construction of the V connector and broadband performance to at least 90 GHz. SPINNER teamed with Physikalisch-Technische Bundesanstalt, the national metrological institute of Germany; Rosenberger; and Rohde & Schwarz to define and develop the 1.35 mm interface. The resulting design was proposed to the IEEE P287 committee, a group revising the IEEE Std 287-2007 for precision coaxial connectors, which decided to include the 1.35 mm connector in the next edition of the standard. In parallel, the interface design was also submitted to IEC, which will publish it as IEC 61169-65.

1.35 MM CONNECTOR DESIGN

For the 1.35 mm connector interface, several development requirements were defined and realized (see ***Table 1***). The table shows the requirements, comparing them with the other two existing connectors (1.85 mm and 1.00 mm) covering the adjacent frequency bands. ***Tables 2*** and ***3*** are extracts from the 1.35 mm connector's electrical and mechanical interface specifications, respectively. The complete specifications and all drawings will be published in the next edition of the IEEE Standard.

A 3D view of the 1.35 mm interface is shown in ***Figures 1*** and ***2***. The overall design avoids any unnecessary over-miniaturization, making it strong and robust, even for a frequently used front panel connector on a test instrument. The pin connector features a relatively large centering sleeve (3.5 mm × 2.6 mm). When the pin and socket connectors win SEMICONDUCTORS | Compound Semiconductor Solutions from RF to Lightwave™

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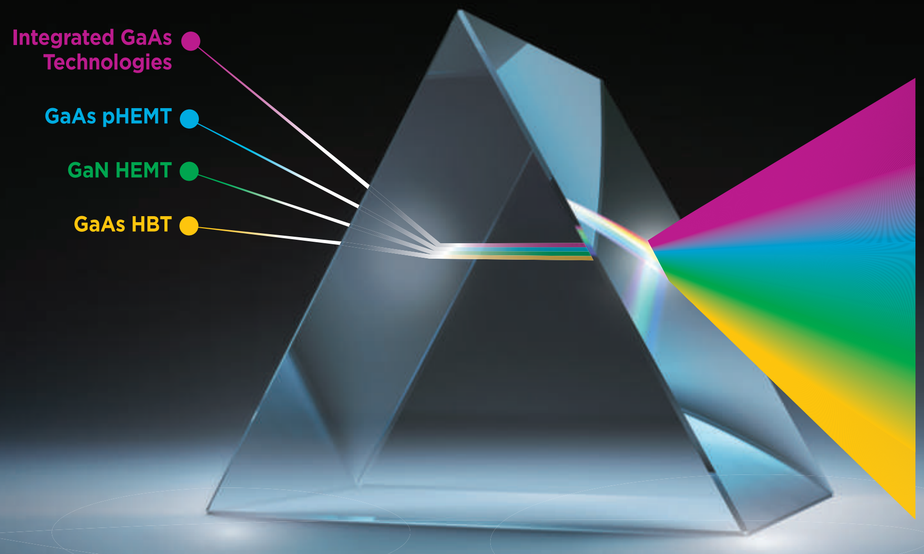

APPLICATIONS

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E-Band Backhaul	70-90GHz
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mmWave Active Antenna	28-45GHz
mmWave Front-Ends	28-45GHz

5G Sub-6GHz

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eMBB UE	3-6GHz
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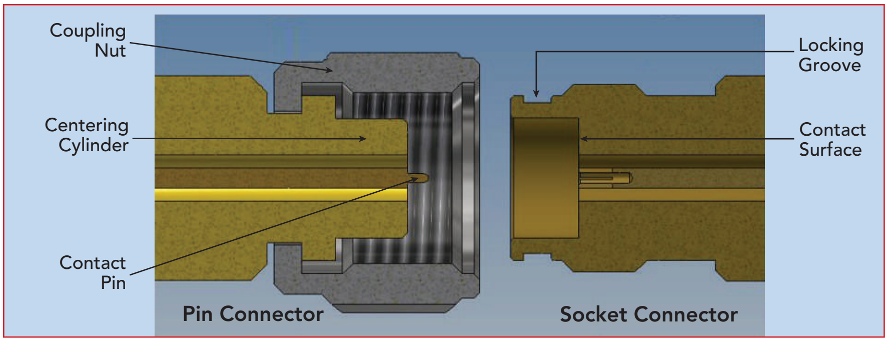

Fig. 2 Longitudinal cross-section of the 1.35 mm pin and socket.

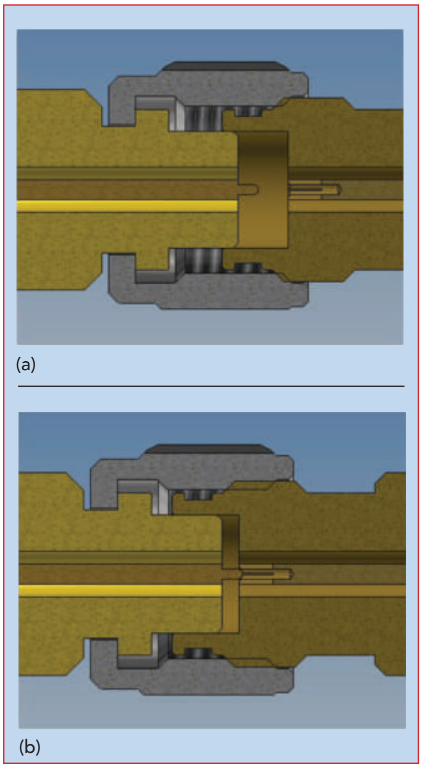

Fig. 3 1.35 mm connector mating, showing engagement of the outer conductor centering cylinder (a) and engagement of the inner conductor pin (b).

are mated, the outer conductor is guided precisely before the center conductors make contact (see ***Figure 3***). The large size of the centering sleeve together with the fine thread (M5.5 × 0.5) of the coupling nut ensures the robustness of the interface. The interface has a large contact surface to avoid plastic deformation of the contact area, even when operated with a maximum locking torque of 1.6 Nm (14.6 in-lb). This is the precondition for the operational coupling torque of 0.9 Nm (8.0 in-lb), which is the same as for the lower frequency 3.50, 2.92, 2.40 and 1.85 mm connectors. The diameter of the contact pin is equal to the nominal center conductor diameter of a standard 0.047 in. semirigid cable (MIL-DTL-17/151). This feature enables the design of high quality, low budget "thru male" pin connectors. The 1.35 mm socket connector is equipped with a standard locking groove, which allows mating with an optional push-on type pin connector.

CABLE ASSEMBLY CHALLENGES AND CHOICES

In the world of mmWave connectors, the three cornerstones of

design are tolerances, tolerances and tolerances. From the previous connector design discussion, dimensional integrity was enforced with various design choices, such as a centering sleeve on the pin side and a locking groove on the socket side. The connector is created from several machined parts whose dimensional integrity is limited by the sophistication and precision of the machining process. For a cable assembly there are additional factors, including cable construction, cable preparation (i.e., stripping three layers: the inner conductor, outer conductor and outer braid) and soldering the layers. The machined connector parts are metal (e.g., stainless steel and beryllium copper) and harder plastics (e.g., Ultem) that are manufactured to defined tolerances.

Applying tolerances to a cable that consists of multiple layers and materials that move in relation to one another, as well as applying heat to a solder joint, requires art as well as science. There are multiple, established cable designs; for this application, the combination of an extruded PTFE core for strength and robustness, a helical wrap outer conductor for superior electrical performance and stability and an outer braid for strength were chosen. Initial testing revealed electrical performance instabilities at E-Band that were not apparent at V-Band and below. Adding a layer between the outer conductor and the outer braid reinforced the rotational integrity of the helical wrap, providing extra dimensional support and eliminating the instabilities.

The solution to this problem underscores the known difficulty of the preparation and termination of a cable with a tape layer to the cable entry portion of the connector. This involves consideration of the tolerances for each of the strip lengths of the individual cable layers, i.e., the inner conductor, outer conductor and outer braid. In addition, each individual layer consists of a different base material, which necessitates a tailored stripping approach. While the intellectual understanding of soldering a two-stage ferrule is well understood, at mmWave wavelengths an iterative termination process was required—each time improving, learning and discovering. While the science of thoroughly documenting each step is important, equally important is the art of the skilled, experienced and intuitive technician.

The confluence of art and science is even more crucial in the soldering process. There is no concept of a precise application of heat in a non-automated soldering process, which is how the 1.35 mm cable assemblies are manufactured. Also, there are many dissimilar materials in the cable construction (e.g., PTFE, steel and copper) with individual coefficients of thermal expansion and minutely non-symmetrical construction (e.g., a helical wrap that creates an internal spiral to mimic a smooth cylinder). L- through Q-Band cable constructions are more forgiving to the application of heat and the imprecision of the

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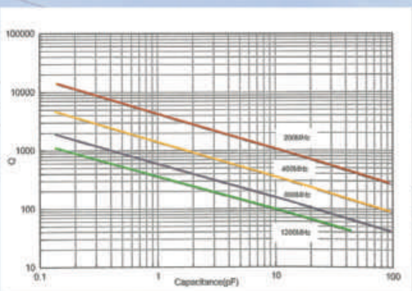

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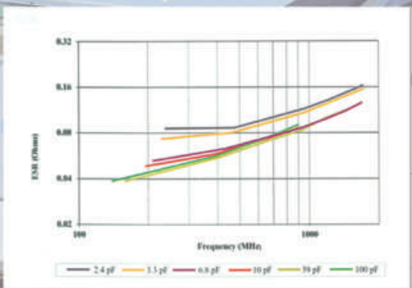

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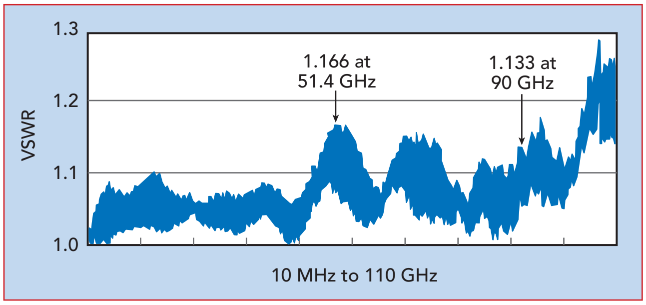


▲ Fig. 4 **1.35 mm cable assembly VSWR measured with 1.35 to 1.00 mm adapters gated out of the measurement.**

mechanical connections. Starting with V-Band and quite dramatically at E- and W-Band, small mechanical variations translate to electrical performance degradation.

There are effectively a series of micro-environments in the cable to connector interface, starting with the soldering of the outer braid portion of the ferrule, proceeding to the outer conductor portion of the ferrule and transitioning to the rear portion of the connector. The goal is to keep each of these sections as close to 50 Ω as possible. If there must be an impedance difference in the connector, the transition should be gradual. When soldering the cable to the connector, the heat expands the PTFE dielectric. For this size cable (0.055 in. diameter) a 1 mil change in the diameter of the extruded dielectric results in a change of 1 Ω. In practice, analyzing and compensating each micro-environment of impedance is not possible. What is possible is honing the manufacturing process by minimizing heat and creating tooling that enables precise trimming and measurement during cable preparation. Then the manufacturing technicians use their accumulated skills and experience to manufacture the cable.

PERFORMANCE

The following data represents the performance of connector in pre-production. ***Figure 4*** shows the broadband VSWR response; the highest VSWR is 1.16:1 at 51 GHz, dropping slightly to 1.13:1 at the upper frequency of 90 GHz. When these measurements were made, the 1.35 mm calibration kit was still being developed (it has since been finished), so the VNA was calibrated to 110 GHz using 1.35 to 1.00 mm adapters over the full bandwidth. To eliminate the contribution of the adapters, the calibration comprised 11,000 points to use the VNA's gating function. The VSWR readings are gated to the end of the pair of adapters. The insertion loss of the cable assembly is plotted in ***Figure 5***. Table 2 specifies the upper frequency to be 90 GHz and the theoretical cut-off to be 98.5 GHz. From the data, the connector modes close to 98 GHz.

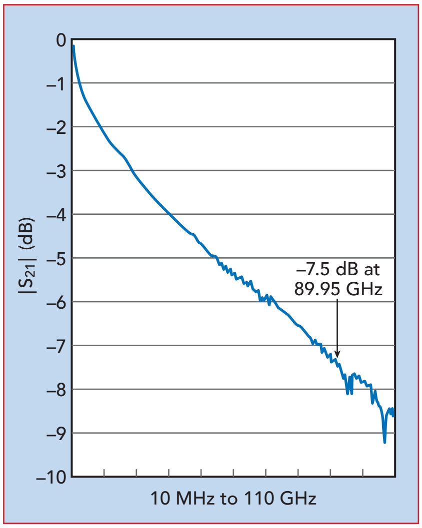
Figure 6 shows the time domain performance of the cable, which quantifies impedance mismatches at different sections of the assembly out to 800 ps, which includes the end of the VNA test port, the adapters, the connector and a por-

tion of the cable. The Y axis shows the impedance deviation from 50 Ω. The calibration point at 0 ps is at 50 Ω. Between markers 1 and 2 is the 1.00 mm to 1.35 mm adapter, which is matched to the network analyzer and connector. Before marker 3, which is at the end of the ferrule section of the connector, there is a 2 Ω mismatch caused by dielectric expansion, which occurred when the ferrule was heated for soldering. Fine tuning this pre-production connector design included changing the inner diameter of the ferrule, with a 1 mil change lowering the inductive reflection and improving the VSWR.

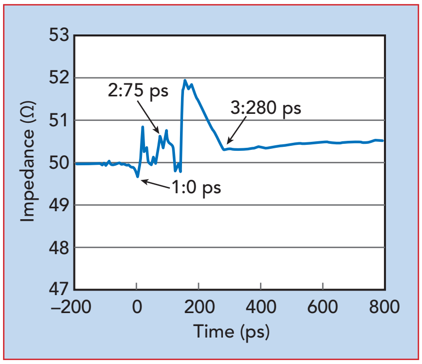
LAUNCHING THE 1.35 MM FAMILY

With the connector and cable development complete, the cable assembly and manufacturing processes are being fine-tuned to support an early October product launch. The 1.35 mm connector system—comprising the calibration kit, rotary joint, inter-series adapter, printed circuit board connectors and cable assemblies—are available. Near-term development plans include a waveguide to 1.35 mm adapter for hybrid applications.

The 1.35 mm connector was created to fill the need for a robust mechanical connector "up to E-Band," to support the satellite and mobile communications and automotive sectors. The commercial release follows a five-year gestation from the definition of standards to the availability of products. The evolution of connector technology will continue, with 5G and future generations anticipating systems operating to 140 GHz—driving the exploration of a commercial 0.8 mm connector.■



▲ Fig. 5 Measured $|S_{21}|$ including the 1.35 to 1.00 mm adapters.



▲ Fig. 6 Time domain measurement of the connector showing a 2 Ω mismatch, caused by dielectric expansion when the ferrule was heated for soldering.

INVITED PAPER

Characterizing Uncertainty in S-Parameter Measurements

Tekamul Buber, Pragti Narang, Giampiero Esposito and Sathya Padmanabhan
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Markus Zeier
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One might ask why engineers should expand their S-parameter measurement practices to include uncertainties, since they have been largely ignored until now. The answer lies mainly in the advancement of technology: as new technologies emerge and are introduced as standards, the specifications and requirements for products get tighter, especially with increasing frequency. This trend can be seen not only with systems, but also at the component level, including amplifiers, filters and directional couplers. Therefore, engineers responsible for the design and production of these components need to increase the confidence in their measurements and product characterization.

Imagine the following: an engineer designs an amplifier requiring a minimum gain over a frequency bandwidth. The amplifier is measured and meets the specification. A few hours later, the amplifier is remeasured and no longer meets the specifications at the high end of the frequency band (see ***Figure 1***). Why is the amplifier not meeting the specification? There could be many reasons: the measurement system drifted, someone in the lab moved or damaged one of the cables in the measurement setup or one of many other possibilities, including doubts about the design, fabrication or stability of the product.

If it is that easy to take two measurements and obtain different results, how can one know which measurement is correct? The confusion arises from not characterizing and including the uncertainties in the measurement, which ultimately leads to an overall lack of confidence in the results. Careful engineers use methods to validate a setup before taking measurements. More careful users test "golden devices"—those with similar characteristics to the actual device under test (DUT)—as a validation step and reference internal guidelines to decide whether the data is good enough. While this is a step in the right direction, how are these guidelines defined? Are the guidelines truly objective, or is subjectivity built in? How close is close enough? Uncertainty evaluation is a powerful tool allowing users to both validate vector network analyzer (VNA) calibration and properly define metrics for golden devices before taking measurements. ***Figure 2*** illustrates this, showing the same amplifier gain measurement with the uncertainties of the system.

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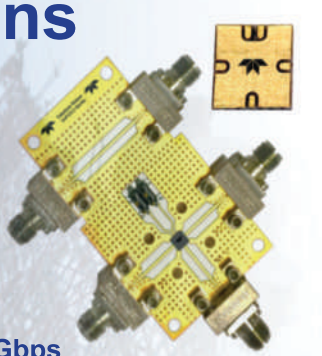

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UNCERTAINTIES

Every measurement, no matter how carefully performed, inherently involves errors. These arise from imperfections in the instruments, in the measurement process, or both. The "true value of a measured quantity" (a_{true}) can never be known and exists only as a theoretical concept. The value that is measured is referred to as "indication" or (a_{ind}), and the difference between the true value and the measurement indication is the error:

$$e = a_{true} - a_{ind} \quad (1)$$

Since the true value is unknown, the exact error e in the measurement is also unknown. There are two types of errors:

Systematic errors: In replicate measurements, this component remains constant or varies in a systematic manner and can be modeled, measured, estimated and, if possible, corrected to some degree.[1] Remaining systematic errors are unknown and need to be accounted for by the uncertainties.

Random errors: This component varies in an unpredictable manner in replicate measurements.[2] Some examples are fluctuations in the measurement setup from temperature change, noise or random effects of the operator. While it might be possible to reduce random errors—with better control of the measurement conditions, for example—they cannot be corrected for. However, their size can be estimated by statistical analysis of repetitive measurements. Uncertainties can be assigned from the results of the statistical analysis.

In general, a measurement is affected by a combination of random and systematic errors; for a proper uncertainty evaluation, the different contributions need to be characterized. A measurement model is needed to put the individual influencing factors in relation with the measurement result.[3] Coming up with a measurement model that approximates reality sufficiently well is usually the hardest part in uncertainty evaluation. Propagating the uncertainties through the measurement model to obtain a result is merely a technical task, although sometimes quite elaborate. Finally, the measurement result is generally expressed as a single quantity or estimate of a measurand (i.e., a numerical value with a unit) and an associated measurement uncertainty u. This procedure, described here, is promoted by the "Guide to the expression of uncertainty in measurement" (GUM),[4] which is the authoritative guideline to evaluate measurement uncertainties.

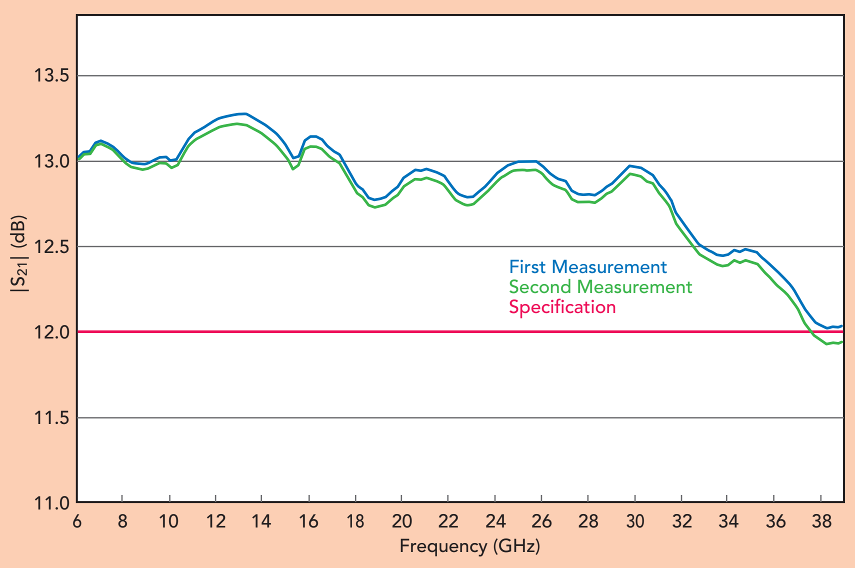
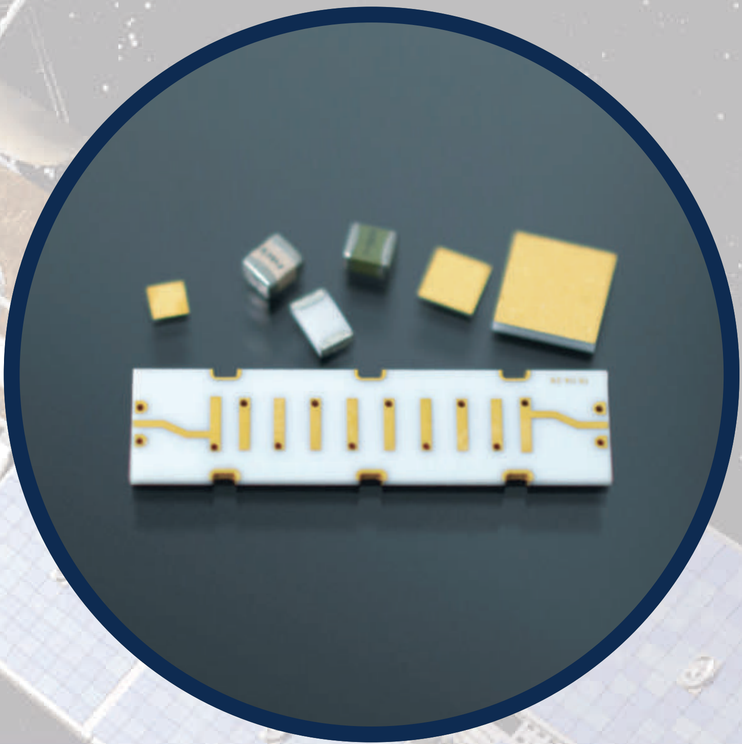
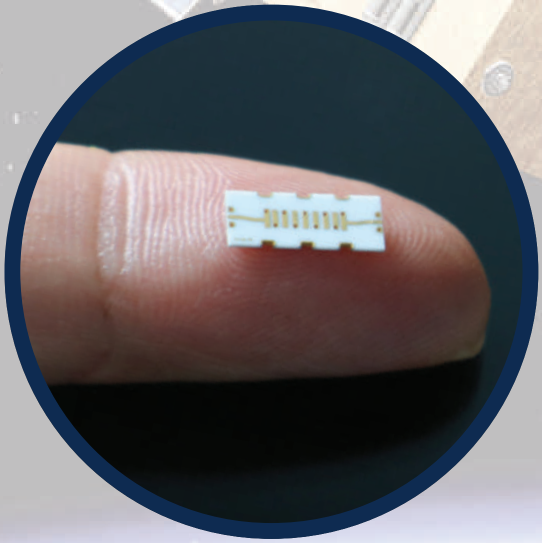
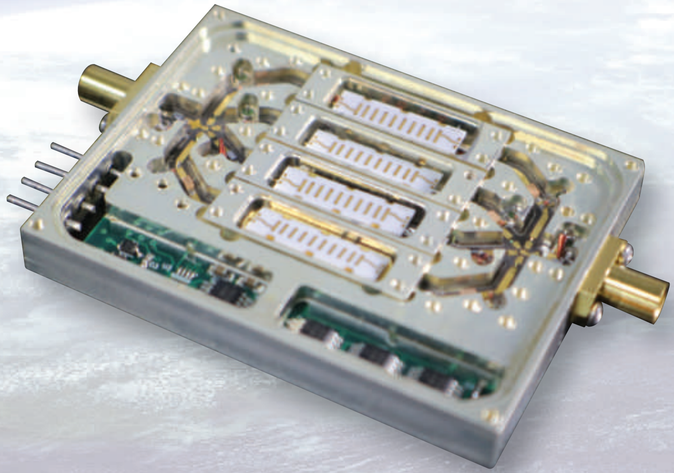


Fig. 1 **Amplifier gain measurements at two times: the first in spec, the second out of spec at the upper band edge.**







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S-PARAMETERS AND VNA CALIBRATION

How do these concepts apply to S-parameter measurements? Recall that S-parameters are ratios of the incident (pseudo) waves, denoted by a, and reflected (pseudo) waves, denoted by b:

$$S_{11} = \frac{b_1}{a_1}, S_{21} = \frac{b_2}{a_1} \quad (2)$$

The definition of S-parameters implies a definition of reference impedance.[5-6] The most common measurement tool used to measure S-parameters is a VNA. While different VNA architectures exist, the most common versions for two-port measurements use either three or four receivers.[5-7]

To simplify the understanding of the subject, consider a one-port VNA measurement (see ***Figure 3***). The case for two-port or more general N-port measurements can be obtained through generalizations, as shown in the literature.[7] Figure 3a shows a typical setup, where a VNA, cable and connectors are used as a measurement system to measure a DUT. To evaluate uncertainties in the S-parameter measurements, a measurement model first needs to be established, to describe the relation between the output variables, the incident and reflected waves at a well-defined port (i.e., the reference plane), and the indications at the VNA display (i.e., the raw voltage readings of the VNA receivers). These models should include systematic as well as random er-

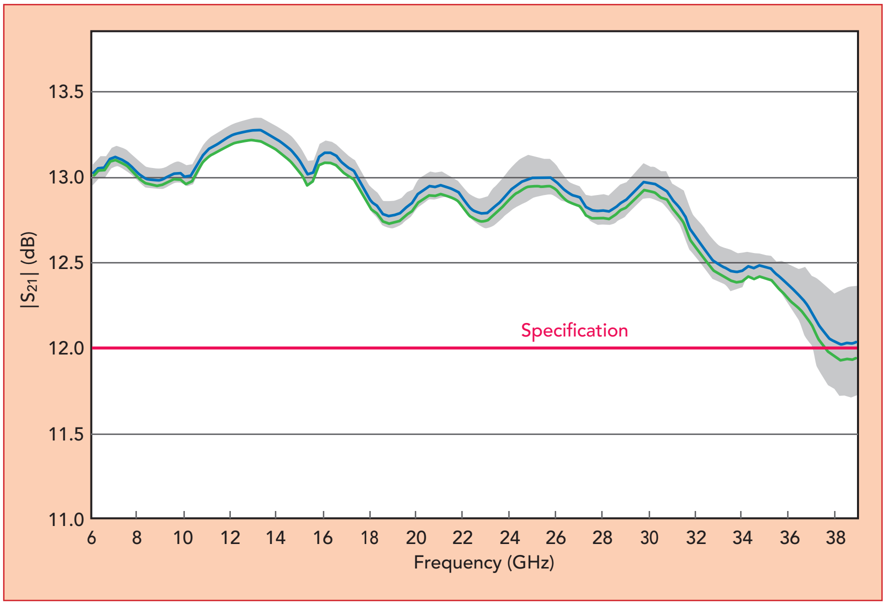

Fig. 2 Amplifier gain measurement showing measurement uncertainty, calculated using Maury MW Insight software.

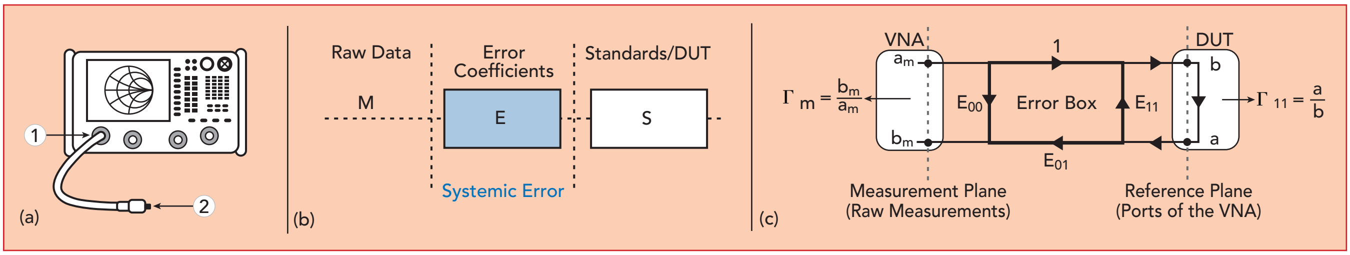

Fig. 3 One-port measurement hardware setup (a), systemic error model (b) and signal flow graph (c).

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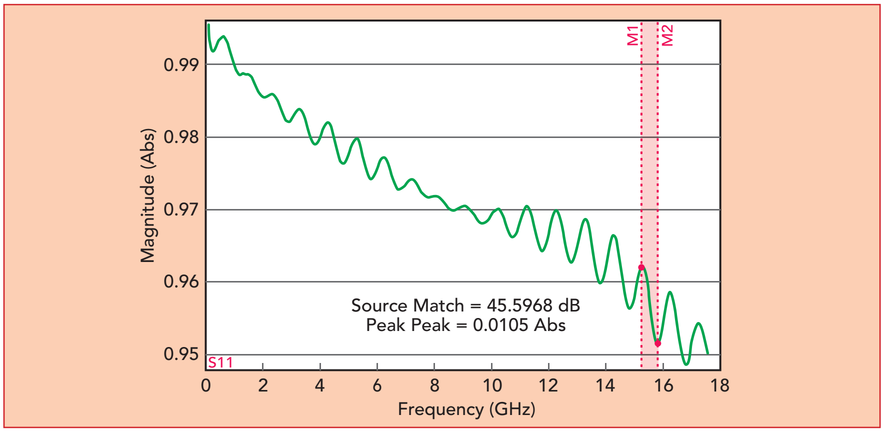

Fig. 4 Source match after one-port calibration using Maury MW Insight software.

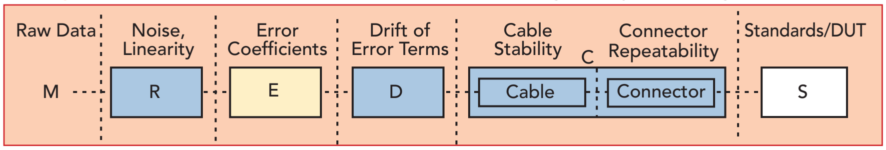

Fig. 5 VNA measurement model.

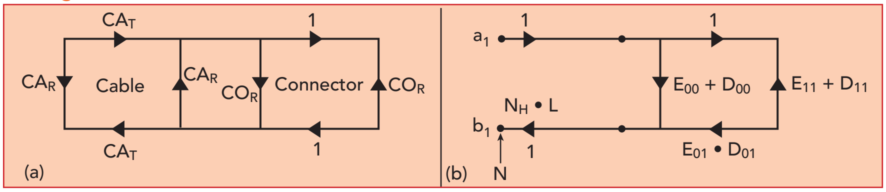

Fig. 6 Models for the cable and connector (a) and VNA noise, linearity and drift (b).

rors to increase confidence in the results. Not estimating systematic errors correctly leads to inaccurate measurements. On the other hand, wrong estimates of the random errors can either degrade the precision of the result or indicate the results are precise when they are not.

CLASSICAL VNA ERROR MODEL

VNA measurements are affected by large systematic errors which are unavoidable and inherent to the measurement technique, related to signal loss and leakage. They establish a relation between the indication (measured)

$$\Gamma_m = \frac{b_m}{a_m}$$

and the S-parameter at the reference plane

$$\Gamma_{11} = \frac{b}{a}$$

shown by the signal flow graph of Figure 3c. The error box consists of three error coefficients: directivity (E00), source match (E11) and reflection tracking (E01). The graphical representation in Figure 3b can be transformed into a bilinear function between the indications and S-parameters at the reference plane through the three unknown error coefficients. To estimate the unknown error coefficients of the model, three known calibration standards must be measured for the one-port case, more if multiple ports are involved. After estimating the error coefficients, any subsequent measurement of raw data (i.e., indications) can be corrected. This technique is commonly referred to as VNA calibration and VNA error correction.

Different calibration techniques have been developed to estimate the error coefficients. Some require full characterization of the calibration standards, such as short-open-load (SOL) or short-open-load-thru (SOLT), while others require only partial characterization, such as thru-line-reflect (TRL), short-open-load-reciprocal thru (SOLR) and line-reflect-match (LRM) for two-port calibrations.[8] Even if the calibration standards are characterized, they are not perfectly characterized, and the error associated with the characterization will increase the inac-


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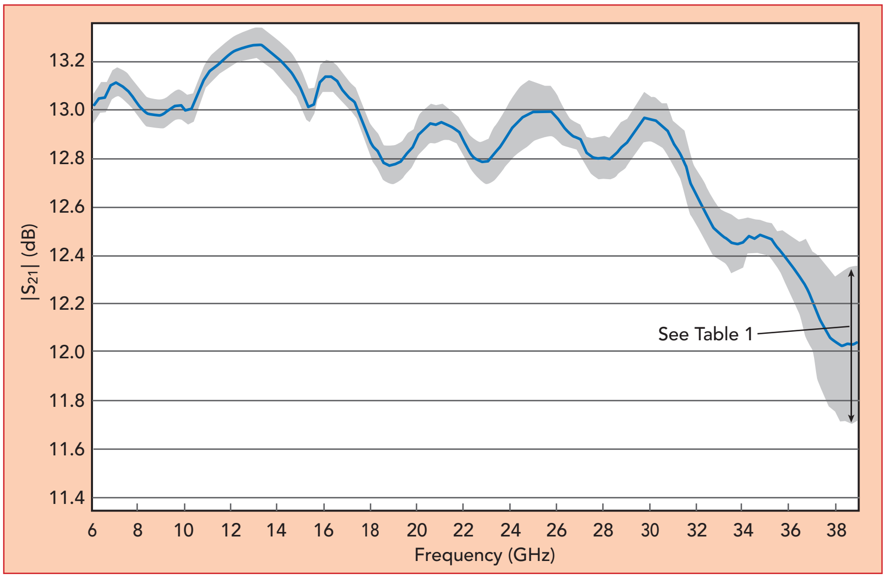

Fig. 7 **Total amplifier gain measurement uncertainty, calculated using Maury MW Insight software.**

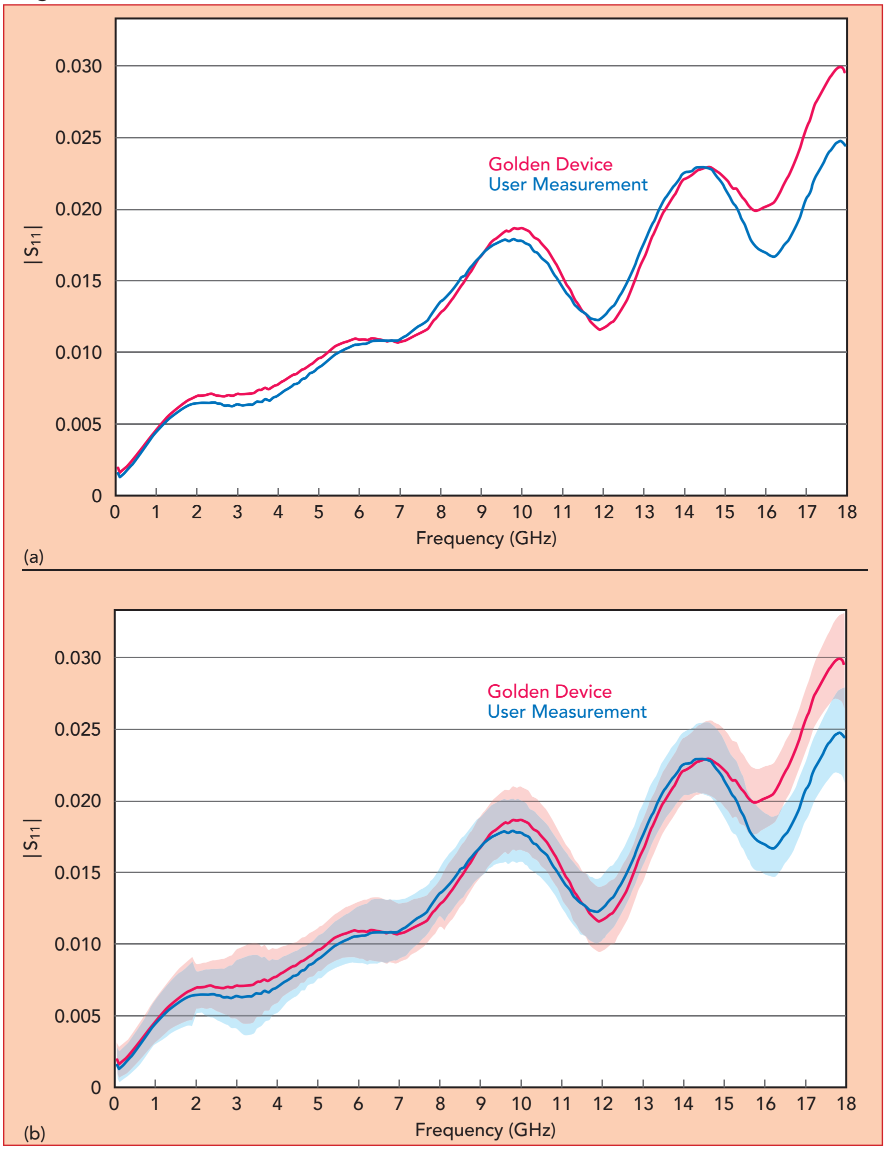

Fig. 8 **Comparison of "golden" device and user measurements (a); same data showing measurement uncertainty (b).**

curacy of the estimated error coefficients: directivity, source match and reflection tracking.

Engineers have developed experimental techniques to estimate these residual errors (i.e., residual directivity, residual source match and residual reflection tracking). Connecting a beadless airline terminated with a reflection standard to the calibrated port enables the residual errors to be observed as a superposition of reflections versus frequency. In the frequency domain, this implies ripples in the reflection coefficient (see ***Figure 4***). Due to the characteristic pattern in the frequency response, the method is referred to as the "ripple method," where the magnitude of the ripples is used to estimate the residual errors and uncertainties related to directivity and source match. This method has various shortcomings: it is unable to determine the residual error in tracking and requires handling air-dielectric lines, which becomes impractical as frequency increases.[7]

Residual errors have been used to gain confidence in the measurement based on experience. The challenge is to understand what a residual directivity of 45 dB means if a DUT with 36 dB return loss is measured. However, the uncertainties of the error coefficients are not reliable when estimated with the ripple method, and they are insufficient to gain confidence in the measurement results. The classical VNA error model is thus incomplete to perform VNA calibration and VNA error correction with uncertainty evaluation.

ADDING UNCERTAINTIES TO THE CLASSICAL VNA ERROR MODEL

This section explains how to expand the classical VNA error model into a full measurement model by adding the other factors influencing the measurement. Using such a full model, the uncertainties can be evaluated in a direct and conceptually clear method. The measurement setup leading from the calibration reference plane to the receiver indications contains several sources of error and influence factors that contribute to the total uncertainty. The classical VNA error model can


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be expanded to include these factors, becoming a full measurement model. Typical components include the VNA (e.g., linearity, noise and drift), cables, connectors and the calibration standards. The European Association of National Metrology (EURAMET) recommends the model shown in ***Figure 5***, where the traditional error coefficients are identified by the E block and the other influence factors represented by the R, D and C blocks.[7,9] The full model in the figure contains just the building blocks, which are further refined using signal flow graphs. Without going into the details of these models, the main errors and related signal flow graphs are described.

Cable and Connector

Cables are used between the reference plane and the receiver indications, making them part of the calibration. They are subject to environmental variations, as well as movement and bending. When cables are moved or bent during calibration or DUT measurement, the error coefficients are expected to change. The cable model uses two parameters: cable transmission (CA_T) and cable reflection (CA_R), shown in ***Figure 6a***. While cable suppliers typically specify these values in cable assembly datasheets, the cables should be characterized for the typical range of flexure or movement during calibration and measurement.[7]

Similarly, the connectors used for connecting and disconnecting the calibration standards and DUT affect the reference plane, based on how repeatable the pins and fingers are designed and built. The S-parameter response of a device differs each time it is connected, disconnected and reconnected, which is modeled by one parameter, the connector repeatability (CO_R).

VNA

The receivers in the VNA tend to deviate from linear behavior at high input power levels. Nonlinearity is essentially a systematic error that can be corrected using an appropriate nonlinear model. Since the nonlinear behavior may be different for each receiver and modeling each is impractical, the non-linearity is approximated with a linear model, denoted as L in ***Figure 6b***.

Noise is a random error and encompasses unpredictable fluctuations in the indications of the VNA. The noise influence is divided into the noise floor (N_L) and trace noise (N_H), where the noise floor is observed without any source signal, and the trace noise scales with the applied source signal level.

Drift accounts for changes in the performance of the entire measurement system over time, due to thermal and other environmental effects. A simple model associates a drift value (D_{00}, D_{11}, D_{01}) to each error term, as shown in Figure 6b.

Calibration Standards

The calibration standards need to be characterized, including their associated uncertainties (shown as block S in Figure 5). Depending on the level of accuracy required, this can be obtained from the manu-

facturer, a calibration laboratory or a national metrology institute, with the characterization traceable to SI units.[10] It has been demonstrated that coaxial calibration standards can be characterized more accurately and more consistently by including the effects of the connectors in the characterization.[11] When performing the VNA calibration to estimate the error coefficients, these uncertainties are propagated together with the other contributions to the error coefficients.

Once all the sources of error and influences are modeled and estimated, VNA calibration and error correction can be performed. Uncertainty contributions are propagated through the full measurement model to the measurement results. This will be sufficient to have confidence in the measurement if the following conditions are met:

- All sources of significant errors and influences are included in the models (see the error models described previously).
- The sources are estimated realistically, i.e., these errors are characterized based on the real measurement conditions; in some cases, supplier specifications may not be sufficient.
- The calibration standards are characterized accurately with realistic uncertainties.

The first condition is usually satisfied for most measurement setups. The second depends mostly on the operator estimating the uncertainties, and the third depends on the source characterizing the standards.

Using this approach will enable engineers to determine an uncertainty budget and the major contributions to the overall uncertainty. This is a powerful tool because it shows where to improve system accuracy if the uncertainty is too high. To illustrate, in the amplifier measurement (see ***Figure 7*** and ***Table 1***), cable stability and connector repeatability represent more than 90 percent of the total uncertainty.

VERIFICATION AND VALIDATION TOOL

Several methods and techniques are used to validate a calibration. Some use T-checkers or Beatty standards, others use pre-characterized verification standards. The quality of a calibration can be "bad" due to sources of error, such as mixing

TABLE 1

UNCERTAINTY CONTRIBUTORS, FIG. 7 MEASUREMENT

Source	Magnitude (x 10^{-3})	Percentage (%)
VNA Noise Floor	1.145	0.104
VNA Noise Trace	4.520	1.615
VNA Linearity	7.163	4.056
VNA Drift Tracking	0.5132	0.021
VNA Drift Symmetry	0.5444	0.023
Cable Transmission	33.26	87.47
Cable Reflection	8.630	5.887
Connector Reflection	3.227	0.823


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standards, damaged standards and cables, loose connections or sudden noise in the system due to environmental changes. Since these significant sources of error are usually not accounted for in the characterization of the uncertainty contributors, they will not be considered in the uncertainty budget, which will degrade the quality of the calibration and, hence, measurement accuracy.

This section addresses verification devices, because they enable the validation of the calibration accuracy and estimate the level of precision achievable. Verification per the International Vocabulary of Metrology (VIM) definition[12] provides objective evidence that the calibration fulfills specified requirements; however, as these requirements can be specified quite arbitrarily, more important than the verification is the validation[13], which is the verification whose specified requirements are adequate for measuring the devices intended for measurement.

Most of the current verification devices are not characterized with uncertainties, and it is difficult for the user to specify an adequate requirement for the validation. In most cases, the user compares the reference characterization with the actual measurement and estimates how close the two are. This is quite subjective, as shown in ***Figure 8a***, which shows a difference in magnitude; the question is whether this is sufficient. Had the results included uncertainties, the user could proceed more systematically and quantitatively as follows:

- Choose a verification standard which has been previously characterized with uncertainties and is representative of the measurement. For example, a fixed load different than one used as a calibration standard can be selected for a one-port, low reflection measurement.
- Validate that the uncertainties of the setup are not too large by 1) comparing the setup uncertainty with the uncertainty provided by the manufacturer of the verification device; 2) comparing the setup uncertainty at the 95 percent confidence level with the design tolerance of the DUT. The expanded uncertainty for the 95 percent confidence interval should always be smaller than the design tolerance; and 3) if the uncertainties do not satisfy the above two conditions, re-evaluate the VNA, cable, connector and the calibration kit used for the calibration.
- A normalized error can be used to finalize the validation,[7] where the scalar version is defined by:

$$e = \frac{1}{1.96}\frac{\left|\hat{d}\right|}{u\left(\hat{d}\right)} \quad (3)$$

Where $\hat{d}$ is the estimate of the difference between the measurement and verification device and $u(\hat{d})$ is the estimate of the standard uncertainty of the difference. The factor 1.96 corresponds to a 95 percent coverage condition, which is quite common in conformity assessment. ***Figure 8b*** shows the uncertainties of the

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same amplifier measurement from Figure 8a. Areas of insufficient overlap of the two uncertainties result in values of e>1 and indicate a failed verification.

CONCLUSION

As technologies evolve and requirements become more challenging, implementing processes that increase confidence in measurements and ensure accurate and reliable characterization—and product performance—are critical. Characterizing and quantifying measurement uncertainty is one such process to achieve the desired results. Uncertainty can aid in definitively verifying a VNA calibration before measuring a DUT. Uncertainty can help understanding how the various components in a measurement system impact the overall uncertainty of the DUT measurement. Identifying, quantifying and reducing the major sources of uncertainty in a test setup will improve the accuracy of the overall measurement. Referring to the original amplifier scenario shown in Figure 1, quantifying measurement uncertainty can provide the confidence that the true performance of the DUT is reflected in the measurements, and the design will not pass one test and fail another.■

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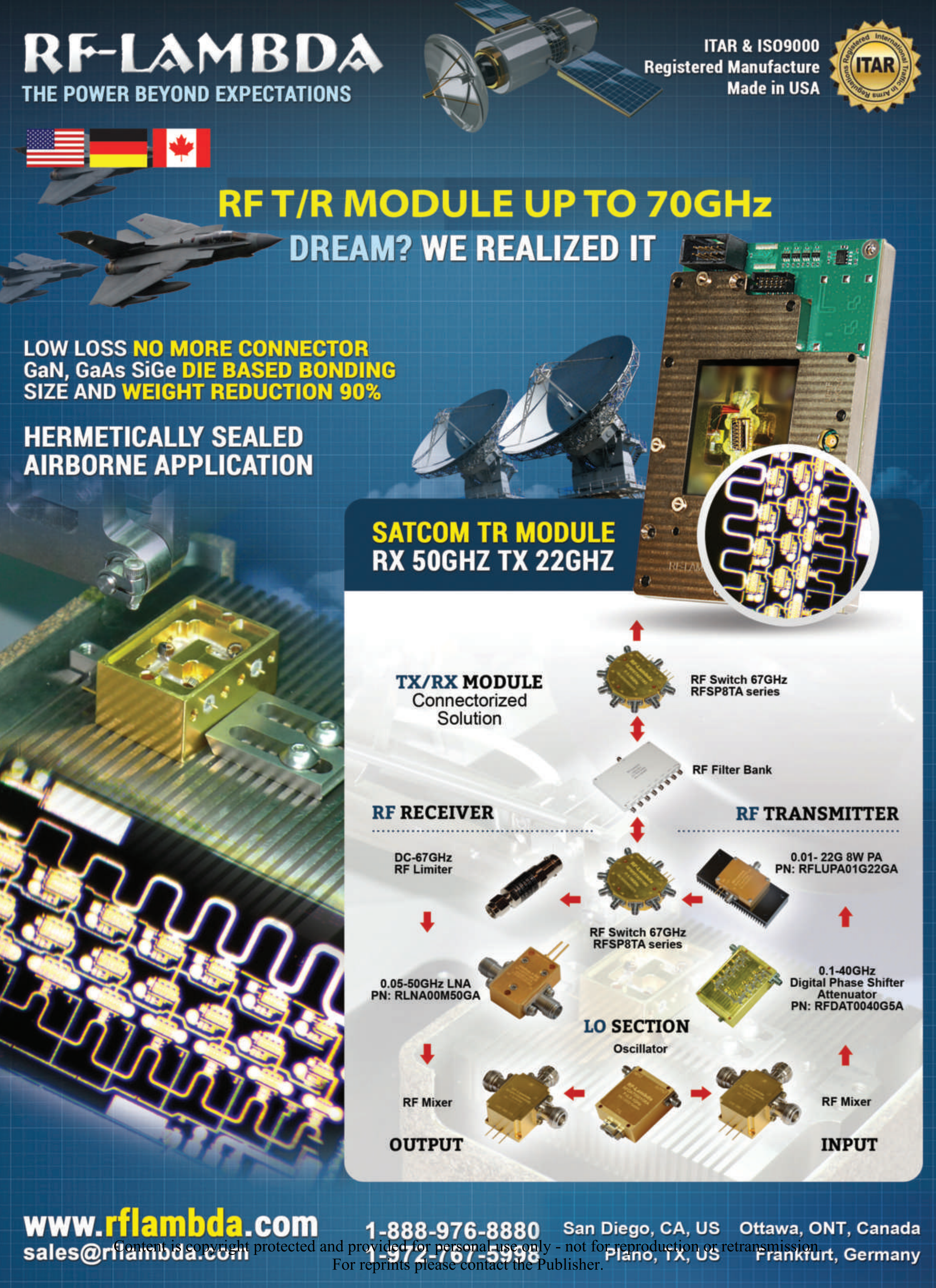

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INVITED PAPER

JUPITER High Throughput Satellite System—500 Gbps from Space

Yezdi Antia, Sam Morrar and Dave Roos
Hughes Network Systems LLC, Germantown, Md.

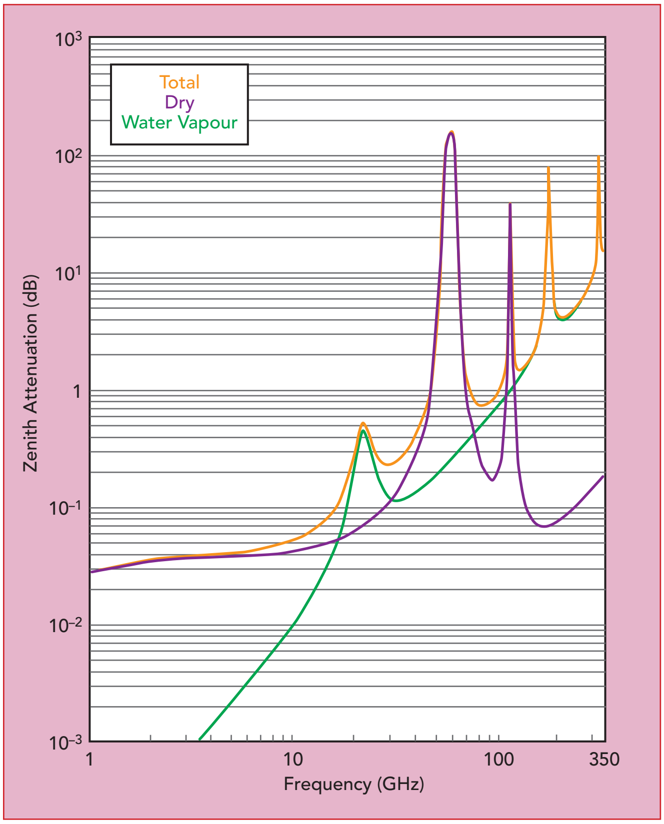
In the mid-1980s, Hughes Network Systems introduced the first commercial very small aperture terminal (VSAT) network. Since then, Hughes has maintained leadership in satellite networks and services, manufacturing and shipping more than 7 million terminals to customers in more than 100 countries. The HughesNet® high speed satellite internet service now serves more than 1.4 million subscribers in the Americas, making it the world's largest such network. This article describes the elements of a geosynchronous Earth orbit (GEO) satellite-based network providing broadband internet access and the design considerations to ensure high user availability.

The increasing demand for high speed internet service necessitates more satellite capacity to serve rural and underserved areas of the globe. With a finite number of orbital slots available, each satellite must have as much data capacity as possible while maintaining functionality. The first VSAT networks used leased transponders from multiple conventional satellites, and each satellite provided approximately 1 Gbps capacity. In 2007, Hughes launched SPACEWAY® 3, which provided 10 Gbps. Hughes launched EchoStar® XVII (JUPITER™ 1) in 2012, followed by EchoStar XIX (JUPITER 2) in 2017, providing 100 and 220 Gbps, respectively. The next satellite in the series will be EchoStar XXIV (JUPITER 3), planned for launch in 2021, which will achieve more than 500 Gbps.

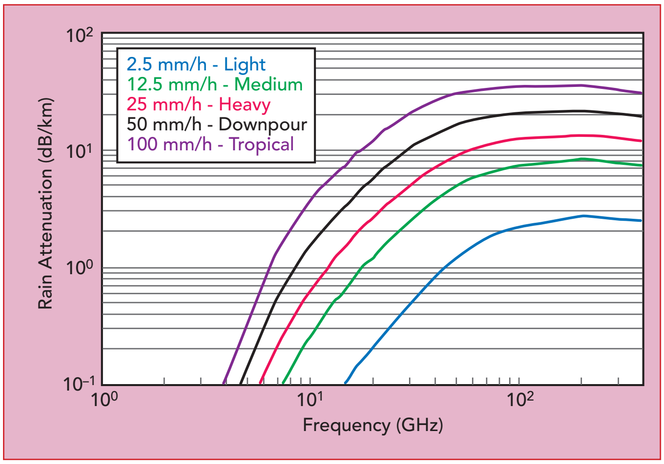
SYSTEM ELEMENTS

The JUPITER System encompasses satellites, gateway stations and ground processing to provide connectivity to the internet; terminals to provide users connectivity; and infrastructure to manage and control the system. Significant advances in technology have enabled the capabilities of each to increase with each generation.

System coverage is provided via hundreds of spot beams from the satellite to users, served through gateway (GW) beams between ground stations and the satellite.



▲ **Fig. 1** Dry air, water vapor and total atmospheric attenuation from sea level to the zenith.



▲ **Fig. 2** Rain attenuation vs. frequency and rain density.

The JUPITER 3 satellite will provide broadband fixed satellite service (FSS) over the Americas using frequency segments at Ka-Band (26.5 to 40 GHz), Q-Band (33 to 50 GHz) and V-Band (40 to 75 GHz). The Q- and V-Band links will provide significantly more bandwidth to enable the higher capacity design of JUPITER 3, although operating at these frequencies poses challenges. For example, emissions in the 50.2 to 50.4 GHz band must be limited to protect the Earth Exploration Satellite Service (EESS). The narrow EESS band is bounded on both sides by the GW V-Band uplinks, creating a challenging filtering problem. The appropriate limit is being studied by the International Telecommunications Union (ITU)—ITU-R Working Party 4A—and will be proposed for adoption at the upcoming World Radiocommunication Conference 2019 (WRC-19), which will be held later this year in Egypt. To protect the EESS, WRC-19 will set the limits for FSS power levels in adjacent frequency bands, which will be implemented in the ITU regulations.

GW LINK TRADES

The use of the V- and Q-Band feeder links makes meeting the availability goals at the GWs challenging, given the higher atmospheric losses at these frequencies (see ***Figure 1***).[1] The gaseous attenuation at 50 GHz is 1.8 dB, compared to just 0.23 dB at 30 GHz. Rain further attenuates the signal (see ***Figure 2***).[2] For example, with a rain rate of 12.5 mm/hour, rain attenuation is 6 dB/km at 50 GHz compared to 2.5 dB/km at 30 GHz. Therefore, it is critical to place the GWs in a relatively dry region, ideally in rain regions B, D and E (see ***Figure 3***).[3] Convenient fiber backhaul is also a factor when deciding where to locate a GW, and the GWs need spatial isolation to

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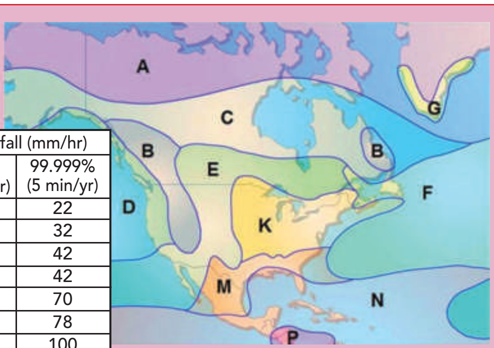
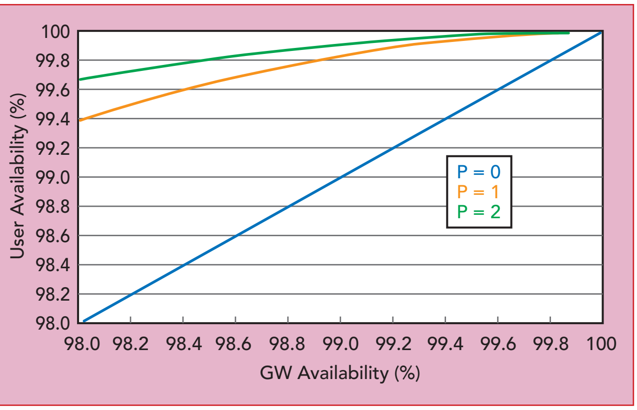


ITU Rain Region	Rainfall (mm/hr) 99% (8 hr/yr)	99.999% (5 min/yr)
A	2	22
B	3	32
C	5	42
D	8	42
E	6	70
F	8	78
K	12	100
M	22	120
N	35	180

▲ **Fig. 3** **North American rain regions defined by ITU.**



▲ **Fig. 4** **Probability of a user outage vs. GW availability and diversity.**

minimize the amount of GW-to-GW satellite interference.

Despite placement of GWs in low rain regions, the link must accommodate a substantial amount of rain fade as well as increased free space path loss (FSPL), which increases as the square of the frequency:

$$FSPL = \left(\frac{4\pi df}{c}\right)^2 \quad (1)$$

where FSPL is a ratio, d is the distance, f the frequency and c the speed of light. The gain of each antenna, both satellite and ground, also increases as the square of the frequency, f:

$$G = k\left(\frac{\pi Df}{c}\right)^2 \quad (2)$$

where G is the gain (a ratio), D the antenna diameter, k the antenna efficiency factor and c the speed of light. Since there are two antennas in the GW link, as frequency increases, one antenna's gain will increase to compensate for the FSPL increase, and the other antenna's gain will at least partially compensate for the increased loss from rain.

It may seem that the higher antenna gain can be used to reduce antenna size at these higher frequencies; however, the higher gain is needed to overcome the higher atmospheric loss. One alternative is to increase the output power of the GW and satellite power amplifiers (PA). Unfortunately, with satellite power being such a precious resource and the PAs in the user equipment already as large as practical, to reduce user antenna size, another solution is needed.

One option is a parabolic antenna. The performance of a parabolic antenna is, in part, determined by the manufacturing accuracy of the reflecting surfaces. Ruze's equation predicts the loss of gain in an antenna due to RMS surface imperfections as:

$$\Delta G = -685.81\left(\frac{\varepsilon f}{c}\right)^2 \quad (3)$$

where ΔG is the change in gain in dB and ϵ is the RMS surface imperfection.[4] As ΔG is proportional to f^2 for constant surface accuracy, at higher frequencies the surface roughness can become a significant limitation. Some of the "extra gain" of the antenna at the higher frequency is degraded by the increased surface roughness.

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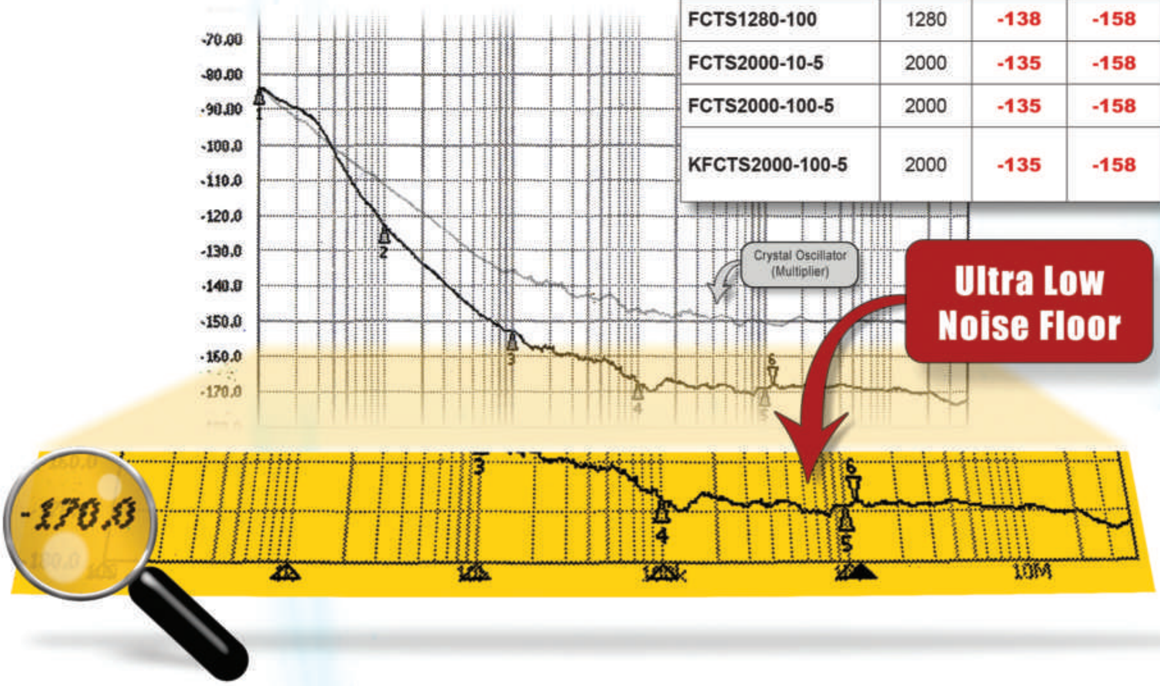
VFCTS128-10	128	-155	-160	
FCTS800-10-5	800	-144	-158	
KFCTS800-10-5	800	-144	-158	
FSA1000-100	1000	-145	-160	
KFSA1000-100	1000	-145	-160	
FXLNS-1000	1000	-149	-154	
KFXLNS-1000	1000	-149	-154	
FCTS1000-10-5	1000	-141	-158	
KFCTS1000-10-5	1000	-141	-158	
FCTS1000-100-5	1000	-141	-158	
FCTS1000-100-5H	1000	-144	-160	
FCTS1040-10-5	1040	-140	-158	
FCTS1280-100	1280	-138	-158	
FCTS2000-10-5	2000	-135	-158	
FCTS2000-100-5	2000	-135	-158	
KFCTS2000-100-5	2000	-135	-158	



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ENSURING AVAILABILITY

The end-to-end links are designed to have most of the noise plus interference contributors on the user side of the link. Uplink power control is used at each GW to reduce the interference from an unfaded GW uplink into a separate, faded GW uplink, with only a small impact to the clear sky end to end carrier-to-noise (C/N) ratio. During rain events, the uplink power control compensates for the additional rain loss only up to a certain point. At higher levels of rain attenuation, the forward capacity drops as the feeder link C/N becomes a more significant contributor to the end-to-end C/N. The same is true of the return link; however, because there is no power control in the feeder link, the capacity degrades as soon as the rain begins.

GW diversity is one option to combat large rain fades at V- and Q-Band. Schemes to achieve GW diversity are 1:1 and N+P. With 1:1 diversity, a diversity GW is deployed within the GW beam and separated at a sufficient distance to decorrelate the rain events at the two GWs. While this simplifies the satellite architecture, it nearly doubles the ground equipment and associated cost. N+P diversity uses N active GWs and P diversity GWs, where all the GWs have sufficient spatial separation to ensure rain events at each are independent. When a primary GW (PGW) experiences rain fade and the power control range has been exhausted, the GW switches to the diversity GW (DGW). The DGW switches back to the PGW once the fade at the PGW has subsided. A disadvantage of the N+P scheme: it requires N+P GW spot beams and GWs, with a switch matrix and switching algorithms on the satellite.

The availability achieved with N+P diversity depends on the network size and number of redundant GWs.[5] ***Figure 4*** plots the probability of a user outage versus GW availability and diversity, showing the improvement achieved with up to two redundant GWs. With no redundancy, the availability of a user equals the availability of a GW; adding redundant GWs, the availability improves significantly.

Q/V-BAND COMPONENTS

Another challenge using Q- and V-Band spectrum is the availability of commercial and space-qualified TWT amplifiers (TWTA). The satellite transmits to the GW at Q-Band, and the GW uses V-Band. On the satellite, power is precious, so the efficiency of the TWTA is a key requirement. These emerging components have lower efficiency than their more mature Ka-Band cousins; however, because the total power required for the Q-Band feeder links is a relatively small fraction of the total satellite power consumption, this efficiency shortfall is not a major problem. Improved efficiency will enable greater capacity in the future. At the GW, TWTA efficiency mainly affects system cooling and operating costs and is not as critical.

The GW feed represents another design challenge. For any given bandwidth, the Bode-Fano criterion establishes the reflection coefficient limit that can be achieved with a matching network, including a feed

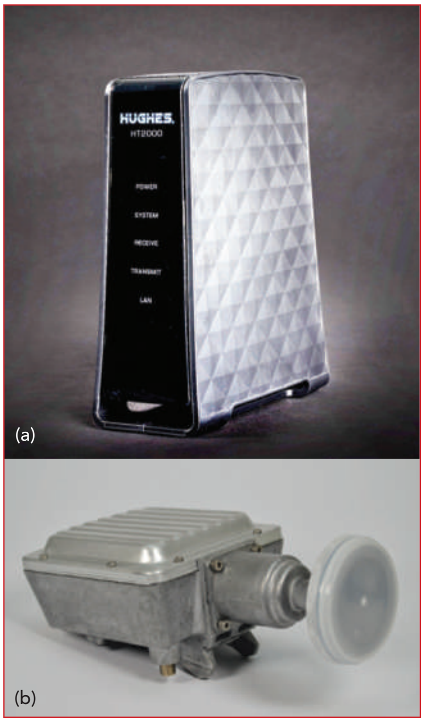

Fig. 5 Hughes satellite router (a) and outdoor unit (b).

design, and, hence, the losses incurred. Although using as much spectrum as possible in the feeder links is desired, covering the Ka-Band receive signal below 20 GHz to the top of V-Band at 51.4 GHz is more than an octave and implies a feed with multiple sections—complicating the design and incurring excessive loss. A reasonable compromise between the bandwidth to the feeder links and complicating the feed design is using only a Ka-Band uplink around 27.5 GHz with Q-Band downlinks and V-Band uplinks to ~51.4 GHz—a span of 0.93 octave.

The JUPITER System VSATs have benefited greatly from improvements in technology.[6] The first designs consisted of multiple printed circuit boards containing microprocessors, modems, frequency converters and discrete RF components. Today's VSAT has been reduced to a system on a chip (SoC) with a handful of components, including GaAs MMICs. The RF components operating to 30 GHz are assembled in surface-mount packages and manufactured on high speed, automated assembly lines. Today, VSATs can receive greater than 1 Gbps on a single carrier using DVB-S2x codes. Adaptive coding and modulation techniques allow the system to provide the highest throughput the link will allow to individual users, while maintaining connectivity to severely disadvantaged users. ***Figure 5*** shows a typical indoor modem and outdoor unit.

OUTLOOK

For more than 30 years, the demand for satellite-based internet connectivity has been increasing, measured both at an individual terminal and aggregating all satellite terminals. This demand drove the industry to increase the capabilities of GEO satellites to achieve higher data densities (Gbps/square mile) and now to develop constellations with hundreds to thousands of satellites in low Earth orbit (LEO), which will provide ubiquitous coverage and low transmission delay. These LEO constellations require the ground terminals to track the moving satellites, a similar problem for mobile terminals tracking GEO satellites. This mobility will require VSATs to adopt low cost phased array technologies or other steering mechanisms. The future satellite-based network could evolve as a hybrid, with both kinds of satellite systems providing the service optimal for each.

As data rates continue to increase, the demand for more spectrum will increase. The next band designated for FSS after V-Band appears to be E-Band (71 to 76 and 81 to 86 GHz). To use this spectrum will require developing new components that are available in commercial quantities with reliability comparable to today's Ku- and Ka-Band components. Regardless of the spectrum, some requirements will be the same: cost, performance, efficiency, reliability. Manufacturability will be a new driver, i.e., how to build these complex, very high frequency satellites efficiently and reliably using miniscule waveguides and how to manufacture, test and maintain the ground equipment portion of the link. Despite these challenges, the future is bright: there is a market and the design problems can be solved using today's and tomorrow's technologies.■

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Antenna Coupler for Smart City Street Lights: 5G NB IoT Ready

RF Savvy Technologies LLC
Santa Rosa, Calif.

Smart cities are popping up all over the world, in the U.S., Europe, China and other regions. The LED lighting boom has driven up energy efficiency and reduced the carbon footprint of cities, while enabling increasing connectivity. Streetlight poles are serving as hosts for radios used in cellular and mesh networks for IoT and other applications (see ***Figure 1***).

As was the case with millions of smart meter deployments during the last decade—which used inefficient, stamped-metal antennas inside the housings—LED street light installations are expected to have network connectivity issues, either a loss of network coverage or gaps in the desired coverage areas in 5 to 10 percent of the installations. To boost range and coverage, local authorities and wireless service providers can deploy external booster antennas outside the photocell housings (see ***Figure 2***). Doing so requires careful attention to ensure the safety and integrity of the electrical isolation between the antenna and the pole, which is usually constructed from extruded metal. Often, the radio is powered directly from the 120/240 V AC power. Without isolation, the radio is vulnerable to lightning surges in the kV range, creating a shock hazard to utility workers and the general public.

To address this, RF Savvy has developed an ultra-wideband 50 Ω coupler isolation circuit, providing up to 10 kV isolation while covering all the major communications bands:

Fig. 1 Typical LED streetlight with topside photocell containing a radio.

Fig. 2 External booster antenna. Courtesy: Panorama Antennas.

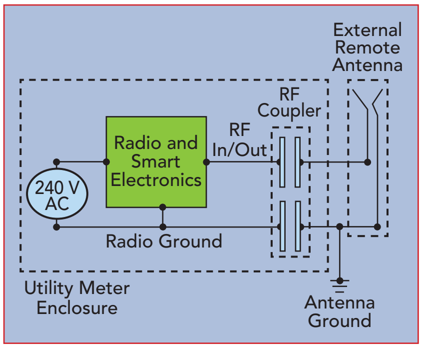

Fig. 3 Block diagram of a typical application using the coupler.

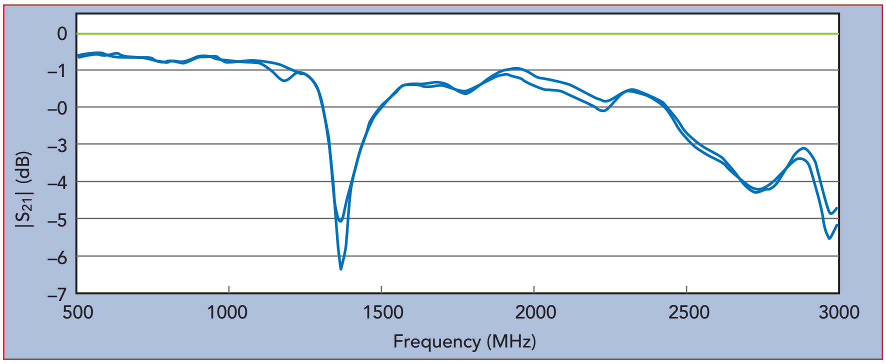

Fig. 4 Typical insertion loss of the RF coupler.

- Cellular at 600, 700, 850, 900, 1800, 1900 and 2100 MHz.
- ISM at 900 MHz and 2.4 GHz.
- GPS at 1575 MHz.
- Iridium LEO satellites at 1616 MHz.

The RFC001B-A RF coupler is compact with a low profile, measuring 45 mm × 45 mm × 0.8 mm, enabling the coupler to be deployed inside the photocell unit on the top of the lightpole. ***Figure 3*** shows a block diagram of the typical application, with the RF coupler electrically between the radio and external booster antenna. The capacitive coupling structure isolates both the signal and ground paths of the RF circuit, incurring less than 1 dB insertion loss in the sub-1 GHz frequency bands. ***Figure 4*** shows the typical insertion loss. For NB-IoT applications at 600 MHz, the insertion loss is less than 1 dB. The coupler's frequency response extends through the 2.4 GHz ISM band, with an insertion loss typically less than 2.5 dB at the upper end. The typical VSWR is better than 1.3:1 across the communications bands.

Input and output connections to the coupler are via MMCX jack surface-mount connectors. The maximum RF input power is rated at 2 W, and the coupler has a specified operating temperature range from −40°C to +85°C. The exterior coating is UL 94V-0 rated.

Tens of thousands of these couplers have been implemented on LED streetlights in cities across the U.S. and Europe, enabling a wide range of smart city applications.

RF Savvy Technologies LLC
Santa Rosa, Calif.
www.RFSavvy.com
(707) 360-8915

RF Front-End Family Enables Compact 5G Massive MIMO Network Radios

Analog Devices
Norwood, Mass.

Massive MIMO (M-MIMO) radios have seen their popularity surge in the late stage deployment of 4G LTE cellular base stations, particularly in dense urban areas where small cells effectively filled the cellular coverage voids while boosting higher data speed services. The success of this architecture clearly proved its worth. It is poised to be the architecture of choice for nascent 5G network radios, as required spectral efficiency and transmission reliability characteristics are inherent to this architecture. The challenge to making 5G a reality is that designers must vastly increase the number of simultaneous transceiver channels operating in multiple bands, while also squeezing all the necessary hardware into a form factor that is as large as or smaller than in the previous generation's equipment.

The implications of doing so are:

- More channels which means higher concentrated RF power in and around the base station, so the problem of isolation between channels without mutual interference is exacerbated.
- Receiver front-end components must have improved dynamic range performance in order to remain robust in the presence of high-power signals.
- Solution size is important.
- Thermal management must be addressed with the increased electronics' and transmitters' power.

In this quest for higher data rates to support a variety of wireless services and different transmission schemes, system designers face higher circuit complexity but must meet similar budgets for size, power and cost. Adding more transceiver channels in a base station tower yields higher throughput but utilizing each channel at a higher RF power level is equally essential for keeping system com-

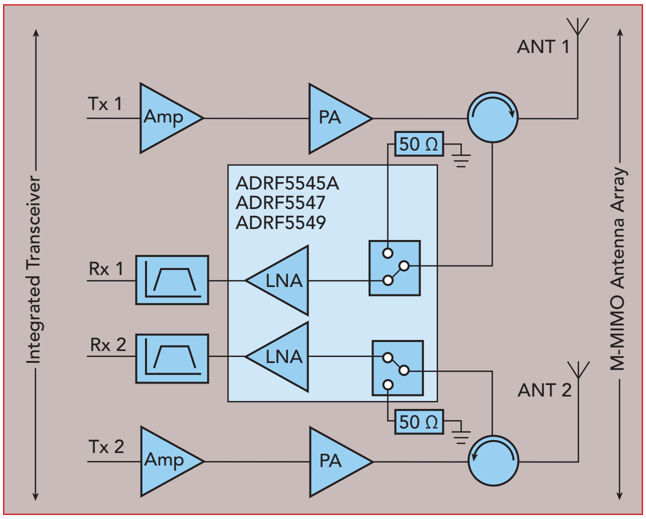

Fig. 1 M-MIMO RF front-end block diagram.

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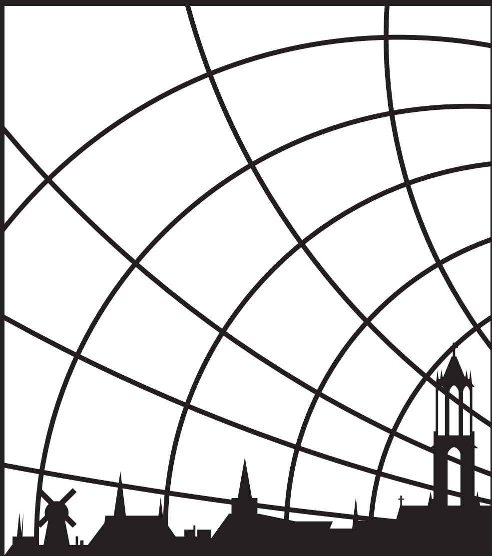


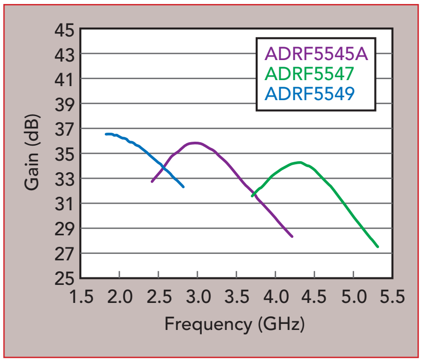


Fig. 2 **ADRF5545A/ADRF5547/ ADRF5549 gain characteristics.**

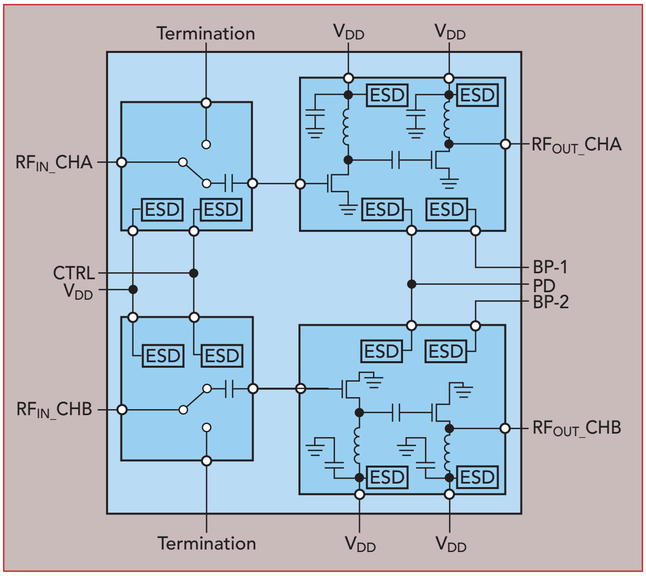


Fig. 3 **ADRF5545A/ADRF5547/ADRF5549 circuit architecture.**

plexity and cost at acceptable levels. For higher RF power, hardware designers do not have many alternatives in their RF front-end design but to rely on legacy solutions that need high bias power and complex peripheral circuits, which makes achieving design goals more difficult.

Analog Devices recently introduced an integrated high-power switch with a low noise amplifier (LNA) in multichip modules for time division duplex (TDD) systems. The ADRF5545A/ADRF5547/ADRF5549 family covers cellular bands from 1.8 to 5.3 GHz and it is optimally designed for M-MIMO antenna interfaces. Incorporating a high-power switch in a silicon process and a high performance LNA in GaAs process, this new family of devices offers high RF power handling capability together with high integration without any compromise—meaning it is the best of both worlds.

DUAL-CHANNEL ARCHITECTURE

An ADRF5545A/ADRF5547/ ADRF5549 application block diagram for a M-MIMO RF front-end design is shown in ***Figure 1***. The device has channels that incorporate a high-power switch followed by a two-stage LNA. During receive mode operation of the transceiver, the switch routes the input signal to the LNA input. During transmit mode, the input is routed to a 50 Ω termination to ensure proper matching to the antenna interface and to isolate the LNA from any reflected power from the antenna. The integrated dual-channel architecture allows designers to easily scale their MIMO to exceed the legacy equipment's limit of 8×8 configurations—to 16×16, 32×32, 64×64 and beyond.

WIDE OPERATION BANDWIDTH

ADRF5545A/ADRF5547/ ADRF5549 gain characteristics of each device and their respective frequency coverage is shown in ***Figure 2***. Parts are optimized for commonly used cellular bands and aligned with other tuned components used in the same design, such as power amplifiers and filters.

HIGH-POWER PROTECTION SWITCH

The device incorporates a high-power switch designed in silicon process that does not need any external components for bias generation. The switch runs on a single 5 V supply with only 10 mA current consumption and can interface to standard digital microcontrollers directly without need for any negative voltages or level shifters. Compared to an implementation using PIN diode-based switches, the silicon switch saves the user around 80 percent bias power and 90 percent circuit board area.

The switch can handle 10 W average RF signal with 9 dB peak-to-average ratio (PAR) in continuous operation and can withstand double the rated power in a fault condition. The ADRF5545A/ADRF5547/ ADRF5549 are the first products in the market that feature 10 W power handling capability, which makes them ideal for high-power M-MIMO designs. If more power can be transmitted from each antenna element, the number of transmit channels can be reduced to get the same RF power out of the base station. The ADRF5545A/ADRF5547/ ADRF5549 architecture is shown in

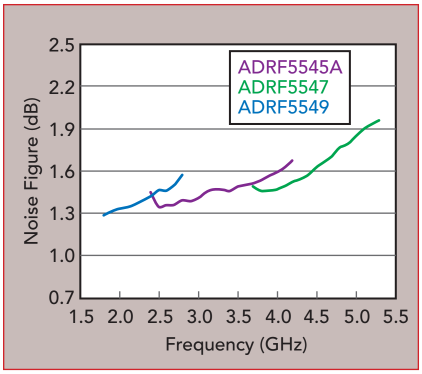


Fig. 4 **ADRF5545A/ADRF5547/ ADRF5549 noise figure.**

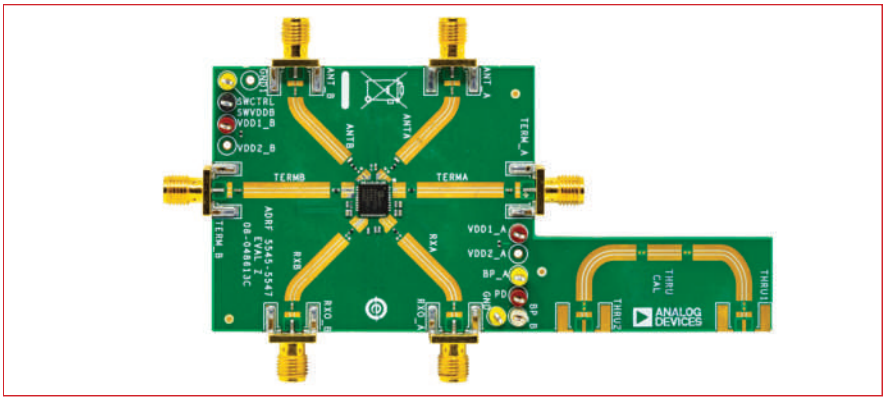


Fig. 5 **ADRF5545A/ADRF5547/ADRF5549 evaluation board.**

Figure 3, which shows that the high-power switch for both channels are supplied and controlled on the same device pin. The LNAs have their supplies and control signal separate.

LOW NOISE FIGURE

A two-stage LNA is designed in GaAs process, supplied by a single 5 V supply, and does not need any external bias-tee inductors. The gain has flat characteristics over frequency and is programmable to 32 and 16 dB in high and low gain modes, respectively. The device also features a low power mode to save bias power where the LNAs can be powered down during transmit operation. The device has a noise figure of 1.45 dB including the insertion loss of the switch, which is well suited both for high power and lower power M-MIMO systems. ***Figure 4*** shows the noise figure performance of the ADRF5545A/ADRF5547/ADRF5549 in specified bands.

COMPACT SIZE, MINIMUM SET OF EXTERNAL COMPONENTS

Besides the primary decoupling capacitors on supply pins and DC blocking capacitors on the RF signal pins, the device does not need any tuning or matching components. The RF input and outputs are 50 Ω matched. The LNA has the matching and bias inductors integrated in the design. This reduces the bill of material for expensive components such as inductors but also simplifies the hardware design for channel-to-channel crosstalk between adjacent transceivers. The device comes in a 6 mm × 6 mm surface mountable package with a thermally enhanced bottom paddle. The device is specified to operate at case temperature in the range from −40°C to +105°C. All three parts are assembled in the same package and have the same pinout. They can be used interchangeably on the same circuit board. The device is shown as mounted on its evaluation board in ***Figure 5***. Evaluation boards are available from ADI directly or through its distributors.

VENDORVIEW

Analog Devices
Norwood, Mass.
www.analog.com

67 GHz Cabling Interconnect Solution

Junkosha USA Inc.
Irvine, Calif.

Today's 5G business model aims to provide mobile and fixed internet access at broadband speeds about 100× faster than possible with current technologies. The business drivers behind this include the need to transport significantly larger volumes of data more quickly; reducing latency across the network for applications that include the IoT, real-time manufacturing and process control; and the general need to increase the number of devices on the network, for innovations including connected and autonomous vehicles.

This upgrade to a 5G network brings a range of challenges, as the technical approach to attain higher data rates and lower latency is more complex than previous generations of mobile infrastructure. At mmWave frequencies, the interconnects become very small, making connector design complicated. "Phase performance that endures" is a performance benchmark that cabling and interconnects must achieve, especially in the test & measurement environment. The amount of bending and stress the cabling sees is significant, reflecting an environment that requires phase stable cables.

For 5G to work, much higher frequency bands with greater bandwidth are a must, and the cabling and interconnects become critical components of the system's performance. This is why it is important to use cabling and interconnects designed and built for a 5G world. After all, if the cabling is first to let the engineer down, it remains the most system critical element, in terms of reliability.

MWX161 INTERCONNECT

To withstand the rigors of operating at this level of system performance, Junkosha has developed a new generation of cables operating well into mmWave frequencies and designed for high temperature and extreme flexure environments. The MWX161 has a frequency range to 67 GHz and a slim, low profile design with a maximum thickness of 7.9 mm, smaller than a HEX coupling nut. The small diameter of the interconnect was

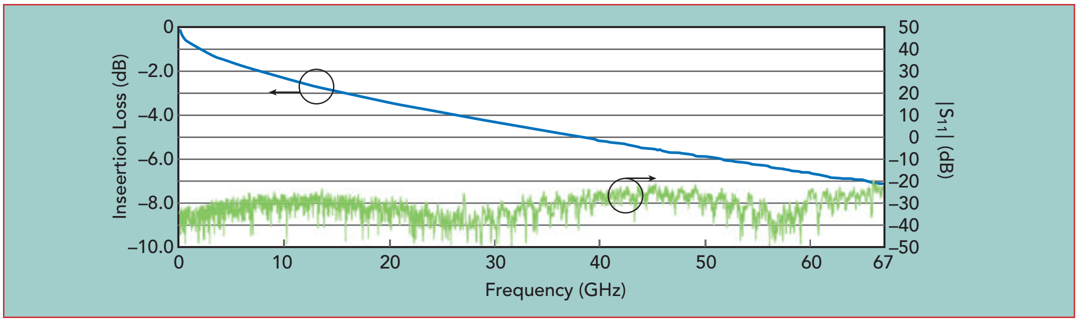


Fig. 1 Typical insertion loss and $|S_{11}|$ of a 1 m cable assembly with two 1.85 mm connectors.

designed for easy connection to a 16- to 24-port vector network analyzer (VNA). To aid such dense connections, a torque driver is available to mount the interconnect onto a face with multiple connectors arranged in a narrow pitch. In addition to multi-port VNAs, typical uses for the MWX161 include narrow pitch RF matrix switchers, which route RF signals among multiple inputs and outputs, and multiple connector device under test (DUT) boards, which serve as an interface between the automatic test equipment and the DUT.

The MWX161 achieves low insertion loss and return loss across the full 67 GHz band (see ***Figure 1***), as well as excellent insertion loss and phase stability with bending (see ***Figure 2***). The MWX161 is rated for operation from −65°C to +125°C, and the phase change from −65°C to +85°C is typically within ±40 degrees.

The interconnect has a low dielectric constant due to Junkosha's precision expanded PTFE tape wrapping technology, key to achieving a low dielectric constant, high flexure and phase stability with both flexure and temperature deviation. Junkosha's legacy fluoropolymer expertise and precision engineering enable this unique expanded PTFE tape wrapping capability. This process, uniquely implemented by only two manufacturers in this sector, allows Junkosha to deliver a flexible cabling assembly achieving "phase performance that endures" at mmWave frequencies.

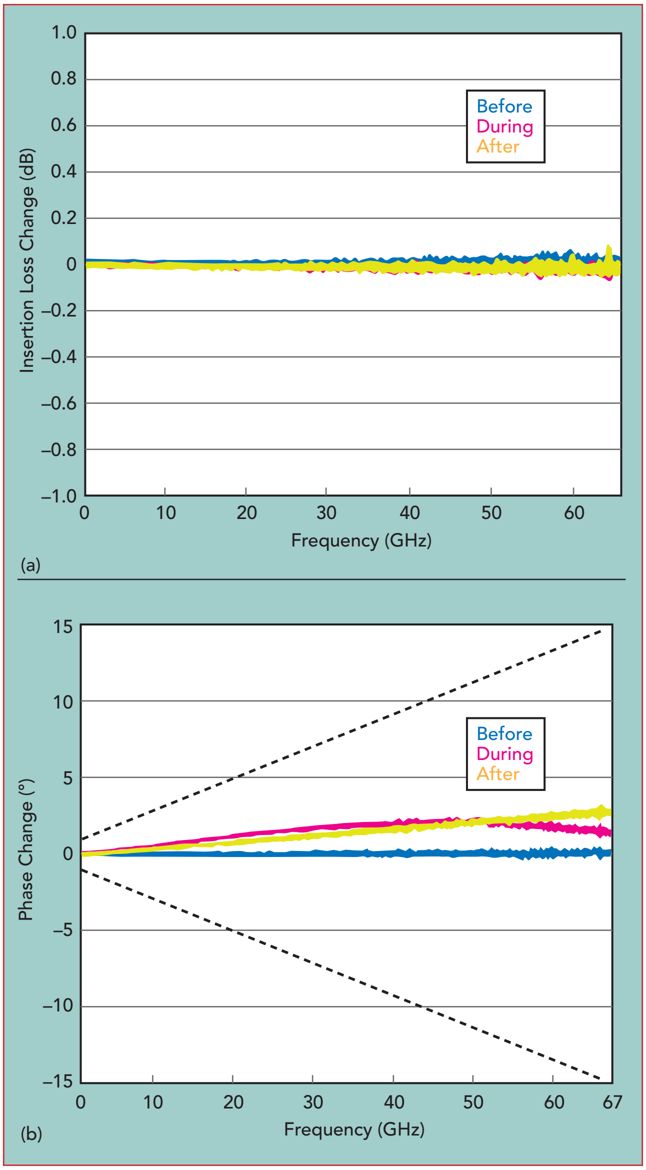


Fig. 2 Change in insertion loss (a) and phase (b) with static bending, using a 30 mm bend radius.

The MWX161 interconnect solution is available with four connector options: 1.85 mm with performance to 67 GHz; 2.4 mm with performance to 50 GHz; 2.92 mm to 40 GHz; and 3.5 mm to 26.5 GHz. Custom cable assembly lengths are available.

During the last 10 years, applications for mmWave cabling and interconnects have increased, moving from the military and space sectors to commercial markets, including security and smart cities. Airports are deploying high performance body scanners, using advanced multi-port arrays. Emerging volume markets are automotive communications and radar, growing as smart sensors and wider smart infrastructure are being deployed. Junkosha developed the MWX161 to support 5G and communications applications through 67 GHz and will continue to advance its interconnect technology to serve even higher frequency applications.

Junkosha USA Inc.
Irvine, Calif.
https://www.junkosha-mwx.com

125 MSPS AWGs for Cost-Effective Multichannel Signal Generation

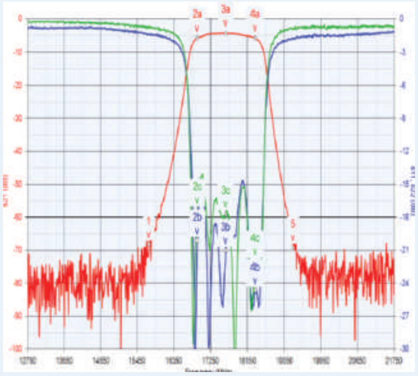
Spectrum Instrumentation has released a line of arbitrary waveform generators (AWG) with exceptional multichannel capabilities. The AWGs of the 65 series are available as PCIe cards (M2p.65xx, with eight versions), LXI/Ethernet instruments for mobile use (DN2.65x, with six versions) and in a rack format (DN6.65x, with eight versions). They feature precision signal generation using the latest digital-to-analog converter (DAC) technology. Each channel has its own DAC with 16-bit resolution and output rates up to 125 MSPS for generating signals with frequency content from DC to 60 MHz.

The small PCIe cards are available with one, two, four or eight channels. Plugging one into any PC with a vacant PCIe slot turns it into a versatile signal source. Using Spectrum's Star-Hub option, multiple cards can be connected to create unique AWG systems with up to 80 fully synchronized channels in one PC—a cost-effective solution for multichannel applications. The 14 different standalone units have similar capabilities, offering four to 48 channels. Full remote control is enabled via an Ethernet connection to any PC or local area network, for easy integration into almost any test system.

Standard features include onboard memory of 512 MSPS per card, up to ±6 V output swing, exceptional dynamic performance and a variety of operating modes for generating long and complex waveforms, including FIFO streaming. The AWGs come with all the tools necessary to generate an unlimited variety of waveforms. Spectrum's SBench 6 Professional software controls the units from a simple, easy-to-use graphical user interface and handles waveform creation, data analysis and documentation. Alternatively, users can write custom control programs in most any popular programming language, including MATLAB and LabVIEW.

VENDORVIEW

Spectrum Instrumentation GmbH
Grosshansdorf, Germany
www.spectrum-instrumentation.com



Custom Thin Film Filters and Switched Filter Banks

Networks International Corp. (NIC), a custom manufacturer of RF components, has developed a thin film filter capability for frequency bands from 1 to 20 GHz, with bandwidths from 1 to 60 percent. Using alumina and titanate substrates and thin film lithography, NIC's filters provide repeatable performance, with low insertion loss and high selectivity. The high dielectric constant substrates enable the filters to be compact and low profile—less than 75 mils high—and compatible with surface-mount assembly.

One example of NIC's filter capability is a 17.6 GHz thin film filter with a minimum 3 dB bandwidth of 1.4 GHz. The filter has 4.5 dB maximum insertion loss at the center frequency, with 12 dB or better return loss over the passband. Out-of-band rejection is a minimum of 60 dBc from 12 to 15.73 and 19.26 to 27 GHz. The surface-mount package measures 0.45 in. × 0.15 in. × 0.075 in.

Combining thin film and LC filter designs with PIN diode switches, NIC has developed a four-channel switched filter bank to demonstrate the company's capabilities to develop custom filters. The four passbands cover 4.75 to 7, 9 to 11.8, 12.6 to 14.25 and 14.3 to 15.3 GHz with a maximum passband insertion loss of 5, 5, 7 and 8 dB, respectively. The passband VSWR is 1.5:1 or better and the out-of-band rejection is at least 50 dB. The maximum input power is +23 dBm and switching speed is under 200 ns, controlled with a TTL compatible voltage. The unit is biased with ±5 V and measures 1.8 in. × 1.6 in. × 0.19 in. The surface-mount design meets the vibration, mechanical shock and hermeticity requirements of MIL-STD-202 and MIL-STD-883.

Networks International Corp.
Overland Park, Kan.
www.nickc.com

CatalogUpdate

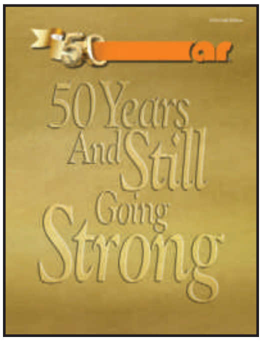
Product Selection Guide

American Technical Ceramics' Product Selection Guide highlights all products by frequency and application. The catalog has a color-coded table that defines specific market and application categories. This makes it easy to directly select from the family of ATC products to quickly find those that match a specific requirement. Product performance specifications are listed in each color coded section throughout the catalog. ATC products include a wide range of quality RF/microwave, mmWave components and specialty thin film products.

American Technical Ceramics
http://atceramics.com/products.aspx

50 Years and Still Going Strong

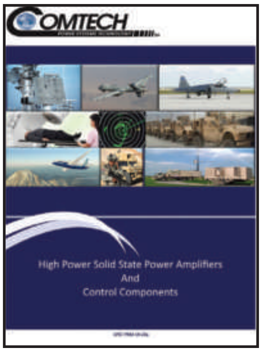
VENDORVIEW



This one, comprehensive catalog includes virtually everything necessary for RF and EMC testing. You will find important information on everything from RF/microwave amplifiers to antennas, probes, analyzers, accessories and integrated test systems that make testing quicker, easier and more accurate. You will discover innovative new products like MultiStar Field Analyzers and Test Systems that use groundbreaking technology to perform multiple tasks simultaneously, reducing test times from days to hours. The latest developments in hybrid power modules and dual band technology are also represented here.

AR RF/Microwave Instrumentation
www.arworld.us/

New Capabilities Brochure



Comtech PST just released a new capabilities brochure that highlights products and markets served. The catalog is available as a download via their website. Comtech PST manufactures high-power solid-state amplifier modules and amplifier systems and high-power control components, including pin diode switches, limiters, attenuators and multifunction assemblies. Comtech PST offers state-of-the-art catalog and custom products that can be designed to meet customer requirements. For further information, contact sales@comtechpst.com.

Comtech PST
https://comtechpst.com/

Modular Building Block SSPA X-Band Solution

VENDORVIEW

CPI Beverly Microwave Division's high efficiency, modular, 1 kW compact X-Band, SSPA VSX3695 uses proven GaN technology and can be easily combined to create high-power X-Band radar transmitters to meet most any power requirement. CPI designs and manufactures a broad range of RF and microwave products for radar, communications, electronic warfare, medical and scientific applications. Contact them at BMDMarketing@CPII.com regarding any of their high-power microwave components.

CPI Beverly Microwave Division
www.CPII.com/BMD

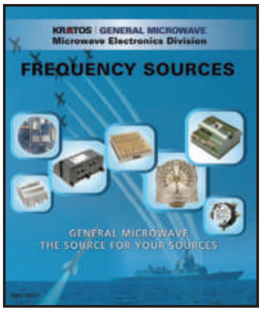
Updated Product Selection Guide

VENDORVIEW

Custom MMIC is the RF/microwave MMIC innovation leader with over 170+ high performance products in the company's standard product portfolio. Custom MMIC offers a variety of standard MMICs spanning from DC to 70 GHz with higher bandwidths coming soon. Have a look for yourself in their recently updated product selection guide.

Custom MMIC
www.CustomMMIC.com

Frequency Sources Short Form Catalog



General Microwave Corp. has designed and manufactured cutting edge microwave frequency sources since 1987. This Short Form Catalog includes sources ranging from free running voltage and digitally controlled oscillators to fast (1 usec) indirect synthesizers, company profile and a wideband frequency modulation applications and techniques tutorial. Specially featured is the Series SM60 family of fast indirect synthesizers capable of analog and digital frequency modulation while center frequency remains in the pure locked mode.

General Microwave Corp.
www.kratosmed.com

Visit Download Section

K&L Microwave designs and manufactures a full line of RF and microwave filters, duplexers and subassemblies, including ceramic, lumped element, cavity, waveguide and tunable filters. K&L supplies many of today's most significant military and homeland security electronics programs. Applications include space flight, radar, communications, guidance systems and mobile radio base stations, as well as air traffic communication and control. Visit their website to download K&L's complete catalog, sections of interest or new brochures.

K&L Microwave
www.klmicrowave.com

New Product Guide – Q2

Mini-Circuits released over 400 models in 2018, and the company continues to develop new products at a rapid clip. Their Q2 2019 product guide highlights some of the latest additions to their portfolio to keep you informed. Highlights in the Q2 2019 New Product Guide include new MMIC amplifiers, couplers and equalizers, waveguide bandpass filters, ultra-wideband connectorized passives and more.

Mini-Circuits
www.minicircuits.com

High Q/Low ESR Ceramic Capacitors

Passive Plus Inc. (PPI), ISO9001:2015 certified, manufactures high performance RF/microwave passive components for the medical, semiconductor, military, broadcast and telecommunications industries, specializing in high Q, low ESR/ESL capacitors, broadband capacitors, single layer capacitors, non-magnetic resistors (high-power and thin film) and trimmer capacitors. Known for its outstanding customer service, high quality products, competitive pricing and quick delivery times. PPI is committed to deliver product, depending on the capacitor and quantities needed, stock to 2 to 4 weeks. Contact Passive Plus at sales@passiveplus.com.

Passive Plus Inc.
www.passiveplus.com/

Precision Microwave Components

RLC Electronics has been a major supplier for the military and defense market over its 60 years in business, providing both surface mount and connectorized solutions across multiple product areas. Originally founded as a switch and filter manufacturer (both low- and high-power), RLC also manufactures detectors, power dividers, couplers, attenuators, pickoff tees, DC blocks, terminations and more. The RLC catalog represents about 30 percent of their products sold and is meant to be used as a brochure of capabilities, with much of their work being custom tailored around customer-specific requirements or applications.

RLC Electronics
www.rlcelectronics.com

Test & Measurement Catalog 2019

Almost 300 pages full of information about the Rohde & Schwarz test & measurement instruments, systems and software. It includes a short description and photos of each product, the most important specifications and the ordering information. You can download this catalog as a PDF from the Rohde & Schwarz website or order from Customer Support (Order number: PD 5213.7590.42, Version 08.00).

Rohde & Schwarz GmbH & Co. KG
www.rohde-schwarz.com

2019 Adapter Handbook

The new handbook shows, at over 500 pages, in detail 34 adapter categories, standard MIL- and DIN-products, as well as the Spectrum Elektrotechnik developments, In- and In-between Series. Waveguide, WR and WRD to coax adapters with a variety of connector types are shown in a special part. This most complete handbook is in each section headed by a reference table, indicating the contents of the section and referencing related products. Specification sheets show the electrical, mechanical and environmental performance of the series with interface dimensions.

Spectrum Elektrotechnik GmbH
www.spectrum-et.com

NEW PRODUCTS

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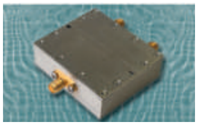
COMPONENTS

DC to 7 GHz Resistive Power Divider Series



BroadWave Technologies announced a new Resistive Power Divider series with an operating frequency range of DC to 7 GHz. Models 151-271-002 and 151-271-004 are 50 Ω 2- and 4-way power dividers. These units have an average power rating of 2 W with 1.5:1 max VSWR. The insertion loss above theoretical loss is ±1.5 dB nominal, amplitude tracking is ±0.5 dB max, the operating temperature range is −20°C to +100°C and RF connectors are SMA female. Model 151-271-002 is pictured.

BroadWave Technologies Inc.
www.broadwavetechnologies.com

High-Power Attenuator

VENDORVIEW

Cernexwave's CFA series fixed setting attenuators are offered with an attenuation of 1 to 60 dB in more than 20 different waveguide bands from 5 to 500 GHz or coaxial versions from DC to 110 GHz in a multitude of different bands. Model CFADC0430200 has a frequency range of DC to 4 GHz, an attenuation of 30 dB and a VSWR of 1.4:1 with an average power handling capability of 200 W or 10 kW peak.

Cernexwave
www.cernexwave.com

Chip Inductors

The 0402CT Series features a ceramic core and has a maximum height of just 0.45 mm—a 30 percent lower profile than competitive products. Offered in 23 inductance values from 1.2 to 56 nH (with 5, 3 or 2 percent tolerance), the 0402CT provides excellent Q-factor performance—up to 84 at 2.4 GHz. It also offers self-resonant frequencies as high as 27.5 GHz and current ratings up to 2.3 A (Irms).

Coilcraft
www.coilcraft.com

Tunnel Diode Detectors

Fairview Microwave Inc., an Infinite Electronics brand, has released a full line of coaxial-packaged tunnel diode detectors that are available with no minimum order quantity (MOQ) and same-day shipping. These detectors are ideal for proof-of-concept and prototype applications for military and commercial radar, aerospace and defense, SATCOM, test & measurement applications and more.

Fairview Microwave Inc.
www.fairviewmicrowave.com

Compact Directional Coupler

VENDORVIEW

KRYTAR Inc. announces a new directional coupler operating in the frequency range of 6 to 40.05 GHz offering nominal coupling of 10 dB in a compact package. KRYTAR's new directional coupler, Model 106040010, is uniquely designed for systems applications where external leveling, precise monitoring, signal mixing or swept transmission and reflection measurements are required.

KRYTAR Inc.
www.krytar.com

N Male 10 W Resistive Termination

MECA's latest addition to their extensive line of resistive and low PIM terminations announces a new resistive 10 W, N Male, 50 Ω load (410-1). Precision designed as a high performance, cost effective solution for applications up to 12.4 GHz. Offering max VSWR specifications of 1.15:1 DC to 3 GHz, 1.2:1 3 to 6 GHz and 1.5:1 up to 12.4 GHz. Made in the U.S. with 36 month warranty.

MECA Electronics Inc.
www.e-meca.com

Waveguide Bandpass Filter

VENDORVIEW

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. Model WVBP-783-WR12+ has a passband of 76 to 81 GHz.

Mini-Circuits
www.minicircuits.com

Air Tubular Trimmer Capacitors

Passive Plus Inc. (PPI) is now offering air tubular trimmer capacitors. These air tubular trimmer capacitors set new standards with extreme adjustment accuracy, mechanical precision with the highest Q-factor. Available in 11 standard capacitor styles and hundreds of variations. PPI will work with a customer to develop a custom air tubular trimmer capacitor according to the engineer's specific requirements. All products are RoHS compliant and available in non-magnetic terminations. Typical delivery is two to six weeks.

Passive Plus Inc.
www.passiveplus.com

High Frequency Couplers

VENDORVIEW

Pasternack, an Infinite Electronics brand, has launched a new series of high frequency couplers that are ideal for 5G telecommunication, automotive radars, SATCOM, point-to-point radios and aerospace applications. Pasternack's new line of high frequency RF directional couplers consists of 24 models that have a high max operating frequency range from 26.5 to 67 GHz. These new couplers deliver excellent isolation, low insertion loss and very good return loss.

Pasternack
www.pasternack.com

Tunable Bandpass Filters

Pole/Zero has released their next generation line of NANO-POLE®tunable bandpass filters. Features include +30 dBm in-band power handling: for BW 3 dB filters ≥ 7percent, +27 dBm for 5 percent filters. ND +23 dBm for 3 percent filters. +42 dBm IIP3 typical, 10 μs typical tune time. 15 dBc typical selectivity at fc ±10 percent: 5 percent, 3 percent filters provide more selectivity; yet have higher insertion loss. For

NewProducts

optimum filter performance, 1.5:1 tuning ratios are recommended.
Pole/Zero
www.polezero.com

Programmable Attenuator

VENDORVIEW

PMI Model No. DTA-1G18G-60-7-CD-1-HERM is a non-reflective 7 bit programmable 60 dB pin diode attenuator with a step resolution of 0.5 dB over the frequency range of 1 to 18 GHz. This model is in a hermetically sealed package. It has a max insertion loss of 5 dB and a max VSWR of 2:1. This unit is outfitted with SMA female connectors and a 15-pin Micro-D female connector in a hermetically sealed housing measuring 2 × 2.79 × 0.66 in.

Planar Monolithics Industries Inc.
www.pmi-rf.com

RF Bandpass Filters

PolyPhaser has expanded its RRF series of bandpass filters engineered to function between 219.5 to 222 MHz frequencies for positive train control (PTC) communications. The new RRF-ITC-219-NFF filter reduces interference issues by blocking unwanted signals due to co-location. The filter also incorporates > 60 dB of attenuation at 88 to 108, 160 to 162, 210 to 216 and 452 to 458 MHz.
PolyPhaser
www.polyphaser.com

Miniature SPDT Switch

RLC Electronics introduced an addition to their miniature SPDT switch product line. This switch is offered in a unique package with connectors in a "T" configuration for ease of connection/mating at the system level, and is a perfect drop-in replacement for pin diode switches. The switch is offered in both surface mount and connectorized versions and operates from DC to 18 GHz. Standard options are available include Indicators and TTL Drivers. The switch measures 1 × 1 × 0.9 in.
RLC Electronics Inc.
www.rlcelectronics.com

Faraday Isolator

Model STF-34-S1 is a full band Faraday isolator that operates from 22 to 33 GHz. The Faraday isolator is constructed with a longitudinal, magnetized ferrite rod that causes a Faraday rotation of the incoming RF signal. The Faraday isolator offers 28 dB typical isolation and a 1.3 dB nominal insertion loss with good flatness. The return loss of the isolator is 14 dB. The input and output ports are WR-34 waveguides with UG-1530/U flanges.
Sage Millimeter
www.sagemillimeter.com

CABLES & CONNECTORS

Cable Assemblies

MilesTek's low-smoke zero-halogen (LSZH) MIL-STD-1553B cable assemblies were specifically designed to address confined space connectivity applications. Typically used in poorly ventilated areas, low-smoke zero-halogen cable jackets are used in applications where it is critical to protect people and equipment from toxic and corrosive gases in the event of a fire. To address these applications MilesTek now stocks 78 Ω Twinaxial and 50 Ω Triaxial LSZH cable assemblies with TRB 3-slot plug, blunt end, insulated and non-insulated bulk head 3-Lug connectors.

MilesTek
www.milestek.com

AMPLIFIERS

X-Band Solid-State Power Amplifier Module

COMTECH PST introduces a new GaN amplifier for applications in the X-Band radar market. The AB linear design operates over the 9.2 to 10 GHz frequency range intended for use in radar applications. The amplifier design features include options for control of phase and amplitude to allow for integration into high-power systems utilizing conventional binary or phased array combining approaches for power levels of up to 10 kW.

COMTECH PST
www.comtechpst.com

Ka-Band Amplifier MMICs

VENDORVIEW

Custom MMIC is proud to introduce two new Ka-Band amplifier MMICs to its growing portfolio of higher frequency packaged products. Both the CMD242K4 (distributed amplifier) and CMD299K4 (low noise amplifier) operate up to 40 GHz while being packaged in a small 4 × 4 mm air-cavity QFN plastic package designed for surface mount applications. This new “K” series designation signifies a new high frequency plastic package being utilized by Custom MMIC for 20 GHz and above products demanded by aerospace, defense and instrumentation customers.

Custom MMIC
www.CustomMMIC.com

Amplifier

VENDORVIEW

Exodus Advanced Communications’ AMP2104A is designed for broadband EMI-Lab, communications and EW applications. Instantaneous C-Band frequency range, class A/AB linear design for all single channel modulation standards. It covers 4 to 8 GHz, produces 100 W min., > 50 W P1dB with a min. gain of 50 dB. Excellent gain flatness, monitoring parameters for forward/reflected power, voltage, current and temperature sensing for superb reliability and ruggedness. The nominal weight is 44 lbs, and dimensions of 19 × 22 × 5 in.

Exodus Advanced Communications
www.exoduscomm.com

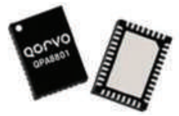
Amplitude and Control Module Series Model ACM

Designed specifically for high performance simulator and ATE systems, General Microwave’s amplitude control module provides precise amplitude control of signal amplitude and pulse modulation over a high dynamic range with fine resolution. With 10 BIT TTL control, modules provide up to 100 dB attenuation, harmonics < –60 dB and pulse modulation 80 dB, 25 ns control. Available in bands from 0.5 to 40 GHz, and can be upgraded to include optional phase control.

Kratos General Microwave
www.kratosmed.com

Flat Gain Push-Pull Amplifier

VENDORVIEW



RFMW announced design and sales support for an ultra-linear, CATV, MMIC amplifier. The Qorvo QPA8801 features a push-pull cascode design providing flat gain and ultra-low distortion. Ideal for DOCSIS 3.1 applications from 45 to 1218 MHz using a single 12 V supply, the QPA8801 offers excellent composite distortion at high efficiency consuming only 4.5 W in a 5 × 7 mm QFN package.

RFMW
www.rfmw.com

SYSTEMS

Evaluation Board

Richardson RFPD Inc. announced the availability and full design support capabilities

for an evaluation board for wireless power transfer applications from GaN Systems Inc. The GSWP050W-EVBPA evaluation board is designed to support and expedite the innovation of wireless power transfer systems. The evaluation board uses GaN Systems' GS61004B E-HEMTs in a 50 W, 6.78 MHz class EF2 power amplifier. The GSWP050W-EVBPA is the latest addition to GaN Systems' WPT line-up. It is well-suited for wireless power and charging applications in consumer, industrial and automotive markets.
Richardson RFPD Inc.
www.richardsonrfpd.com

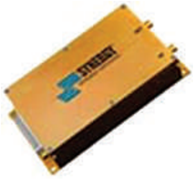
SOURCES

5 GHz Front-End Module

VENDORVIEW

Skyworks introduced the SKY85774-11, a highly integrated 5 GHz front-end module (FEM) that supports simultaneous WLAN and licensed assisted access (LAA) protocols for mobile smartphones and tablets. This advanced module incorporates a power amplifier, low noise amplifier with bypass and an SPDT transmit/receive switch. Its high performance power amplifier increases range and saves power while eliminating external devices and reducing PCB area. The SKY85774-11 comes in a compact 20-pin 2.2 × 3 package and is currently being leveraged across leading mobile connectivity reference designs.
Skyworks Solutions Inc.
www.skyworksinc.com

High Resolution Synthesizer



The MTS2500-110250-10 is a high resolution synthesizer that combines the latest in DDS and multi-loop synthesizer technologies with a high performance VCO to generate frequency signals from 1100 to 2500 MHz with as low as 1 Hz resolution. It provides ultra-low phase noise, wide bandwidth performance and low spurious, while permitting for increased loop bandwidth, faster settling time and higher stability under vibration. Power consumption is 1.2 W typical.
Synergy Microwave Corp.
www.synergymwave.com

TEST & MEASUREMENT

Bluetooth Test Set

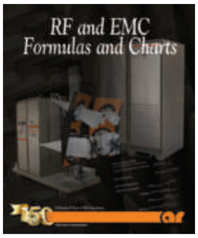
VENDORVIEW

Anritsu Co. introduced a new option for its Bluetooth Test Set MT8852B to support the latest Bluetooth® Core v5.1 (BT 5.1)

specification for evaluating new key positioning services. With the new BLE AoA/AoD Option MT8852B-037, the MT8852B can conduct efficient RF-signal angle of arrival (AoA) and angle of departure (AoD) measurements to help speed time to market and lower test costs during development, validation and manufacturing of Bluetooth Low Energy (BLE) 5.1 devices and equipment.
Anritsu Co.
www.anritsu.com

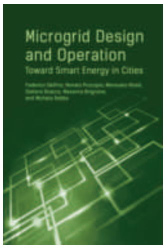
RF and EMC Formulas and Charts Poster

VENDORVIEW



Request your free copy of AR's RF and EMC Formulas and Charts Poster. This reference poster includes EMC equations, VSWR conversion charts, antenna equations unit conversions and more. Download electronically or request a hard copy of the poster from www.arworld.us/html/posterrequest.asp.
AR RF/Microwave Instrumentation
www.arworld.us

MICRO-ADS



Microgrid Design and Operation: Toward Smart Energy in Cities

Federico Delfino, Renato Procopio, Mansueto Rossi, Massimo Brignone, Stefano Bracco and Michela Robba

With the growth of renewable energy sources, microgrids have become a key component in the distribution of power to localized areas while connected to the traditional grid or operating in a disconnected island mode. Based on the extensive real-world experience of the authors, this cutting-edge resource provides a basis for the design, installation and day-by-day management of microgrids.

Professionals find coverage of the critical aspects they need to understand, from the initial planning and the selection of the most appropriate technologies and equipment, to optimal management and real-time control. Moreover, this forward-looking book places emphasis on new architectures of the energy systems of the future. Written in accessible language with practical examples, the book explains advanced topics such as optimization algorithms for energy management systems, control issues for both on-grid and island mode and microgrid protection. Practitioners are also provided with a complete vision for the deployment of the microgrid in smart cities.

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Shmuel Auster, Conference Chair
Amir Boag, Technical Program Committee Chair

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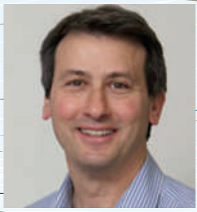
Dr. Avram Bar-Cohen
Raytheon – Space & Airborne Systems

Prof. Richard D. Gitlin
University of South Florida



Prof. Theodore (Ted) S. Rappaport
NYU-Tandon

Dr. Hava Siegelmann
DARPA

Invited Speakers (partial list)

Prof. Constantine A. Balanis
Arizona State University

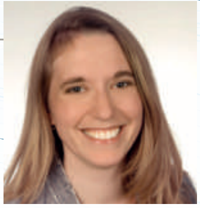
Prof. Andrea Bevilacqua
University of Padova

Dr. Charles F. Campbell
Qorvo

Prof. Larry Dunleavy
University of South Florida

Prof. Frank Ellinger
Technische Universität Dresden

Prof. Caleb Fulton
The University of Oklahoma



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University of Erlangen

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California State University

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MIT

Prof. Almudena Suárez
University of Cantabria

Dr. Horst Theuss
Infineon Technologies

For the full list of Invited Speakers, please visit COMCAS website: www.comacs.org

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FABS and LABS

Compound Semiconductor Applications Catapult

Launched in October 2017, the Compound Semiconductor Applications (CSA) Catapult is the latest Catapult to join the existing nine Catapult centres based across the U.K. The Catapult centres have been funded and established by U.K. government to help support innovation in U.K. business. Their vision? To bridge the gap between the expertise of the U.K.'s world-class research and development communities and ambitious businesses.

Compound semiconductors are at the heart of many cutting-edge electronic devices. They offer advantages such as higher speed, better efficiency and smaller form factor compared to their predecessors, such as silicon, and will be a vital part of the devices to power our future technologies. These performance benefits are applicable to a wide range of applications from wireless networks, defence/space, autonomous vehicles to smart sensing devices for the IoT and 5G applications. In addition to this, they will contribute towards challenges identified by the recent U.K. government Industrial Strategy such as an ageing society, the future of mobility, clean growth and AI and the data economy.

As part of its mission to make the U.K. a global leader by developing and commercialising new applications for compound semiconductors, CSA Catapult will bring together businesses large and small from across the supply chain and collaboratively work with them on R&D and commercial opportunities.

To support its strategy and vision, the Catapult has opened a state-of-the-art Innovation Centre based in the world's first compound semiconductor cluster (CS Connected) in Newport, South Wales. The centre gives companies access to dedicated laboratories specialising in RF and microwave, power electronics, advanced packaging and photonics to help companies develop and demonstrate new products.

The RF and microwave laboratory will offer a range of services spanning design, modelling and simulation of CS devices, circuits and systems, packaging and assembly through to characterization, evaluation and qualification of devices and modules. It will also provide access to high frequency, automatic on-wafer probing with full thermal control, load-pull characterization, 5G signal generation and analysis and a suite of equipment dedicated to burn in, life test and qualification.

The innovation centre and CSA Catapult's expertise will help to de-risk and accelerate research and development, reducing time to market giving U.K. companies a competitive advantage. CSA Catapult will deliver long-term benefits to the U.K. economy by accelerating the application of compound semiconductors in industries to create a competitive advantage and enable new products or end markets. This will drive growth in the U.K. electronics sector, keeping more companies ahead of international competition and creating new highly skilled jobs in the businesses they supply. By 2023, CSA Catapult aims to have helped create 1,000 jobs in the businesses it supports.

Over the last six months, CSA Catapult has begun to establish a unique U.K. SiC supply chain, from fabrication of compound semiconductors through to end use and deployment in electric sports cars and has led a consortium of industry partners committing over £500 million for the Industrial Strategy "Driving the Electric Revolution." It has leveraged over £23 million industrial investments with its first five CR&D projects and has translated academic excellence through collaboration in CR&D projects.

https://csa.catapult.org.uk/

CALL FOR ABSTRACTS

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Directional Couplers

Model	Type	Frequency (MHz)	Power (W CW)	Coupling (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
C8000	Bi	600-6000	100	30	0.40	SMA-Female	1.8 x 1.0 x 0.56
C10799	Dual	700-6000	100	40	0.20	N-Female	2.0 x 2.0 x 1.06
C10117	Dual	700-6000	250	40	0.20	N-Female	2.0 x 2.0 x 1.06
C10526	Dual	700-6000	300	40	0.20	N Female	2.0 x 2.0 x 1.06
C10364	Dual	700-6000	500	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10614	Dual	700-6000	500	60	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10996	Dual	700-6000	700	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C11555	Dual	700-6000	1,000	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10695	Dual	700-6500	500	50	0.20	7/16-Female	2.15 x 2.0 x 1.36

0° (In-Phase) Combiners/Dividers

Model	Type	Frequency (MHz)	Power (W CW)	Isolation (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
D11911	2-Way	600-6000	100	15	0.60	N-F / SMA-F	2.00 x 2.0 x 1.00
D11959	2-Way	600-6000	100	Non-Isolated	0.40	N-F / SMA-F	2.00 x 2.0 x 1.00
D11958	4-Way	600-6000	100	18 (PI*)	0.60	N-F / SMA-F	4.00 x 2.0 x 1.00
D11149	4-Way	700-6000	300	Non-Isolated	0.60	N-Female	4.35 x 3.9 x 1.15
D11832	2-Way	700-6000	500	Non-Isolated	0.60	7/16-Female	5.50 x 2.4 x 1.06
D10803	2-Way	700-6500	300	Non-Isolated	0.60	N-Female	5.50 x 2.4 x 1.06

(PI*) references Partial Isolation

90° Hybrid Couplers

Model	Type	Frequency (MHz)	Power (W CW)	Amp. Bal. (±dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
QH11687	90°	500-6000	150	0.7	0.75	SMT	1.28 x 1.08 x 0.13
QH11443	90°	600-6000	150	0.8	0.70	SMT	1.30 x 1.30 x 0.13
QH10756	90°	700-6000	100	0.6	0.55	SMT	0.74 x 0.45 x 0.09
QH10541	90°	700-6000	150	0.6	0.50	SMT	0.86 x 0.66 x 0.09
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	0.90	SMT	0.65 x 0.50 x 0.07

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