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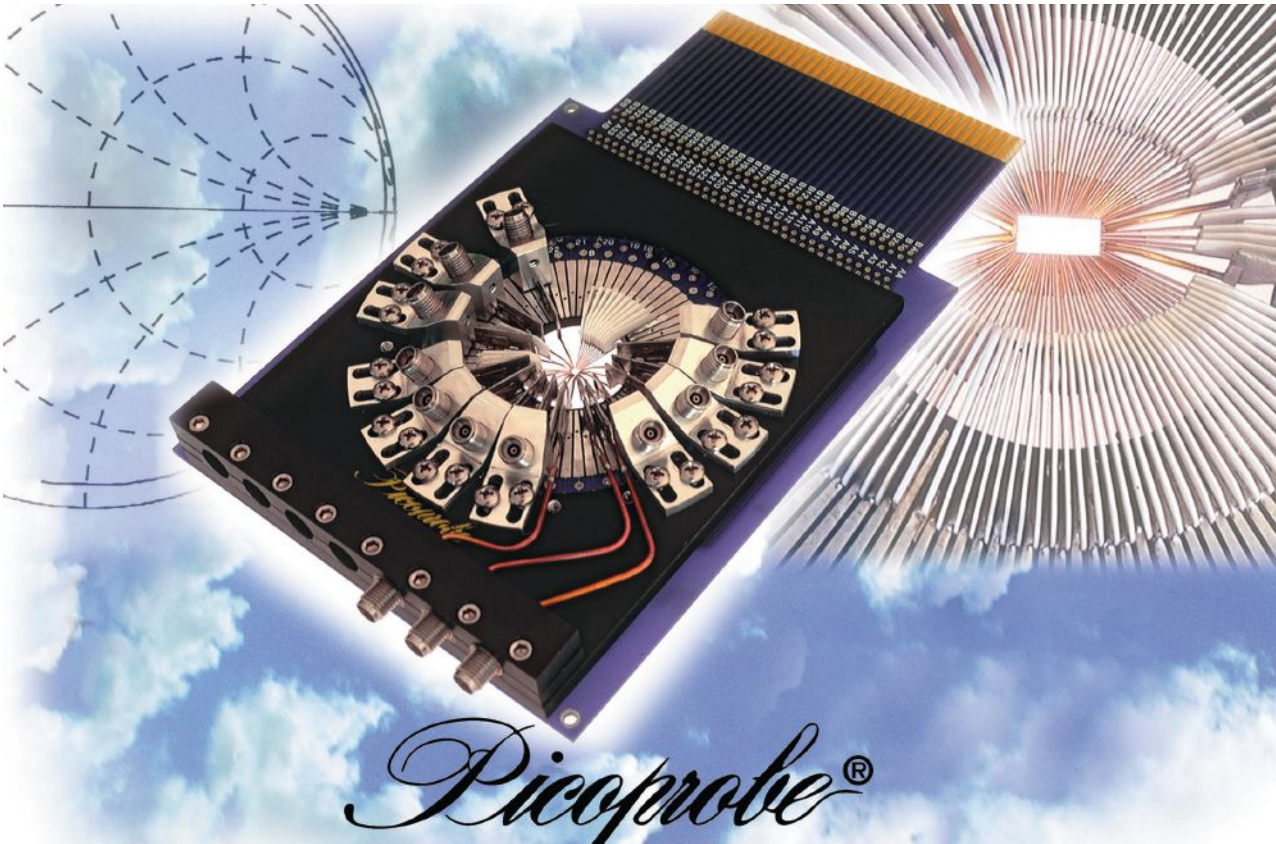

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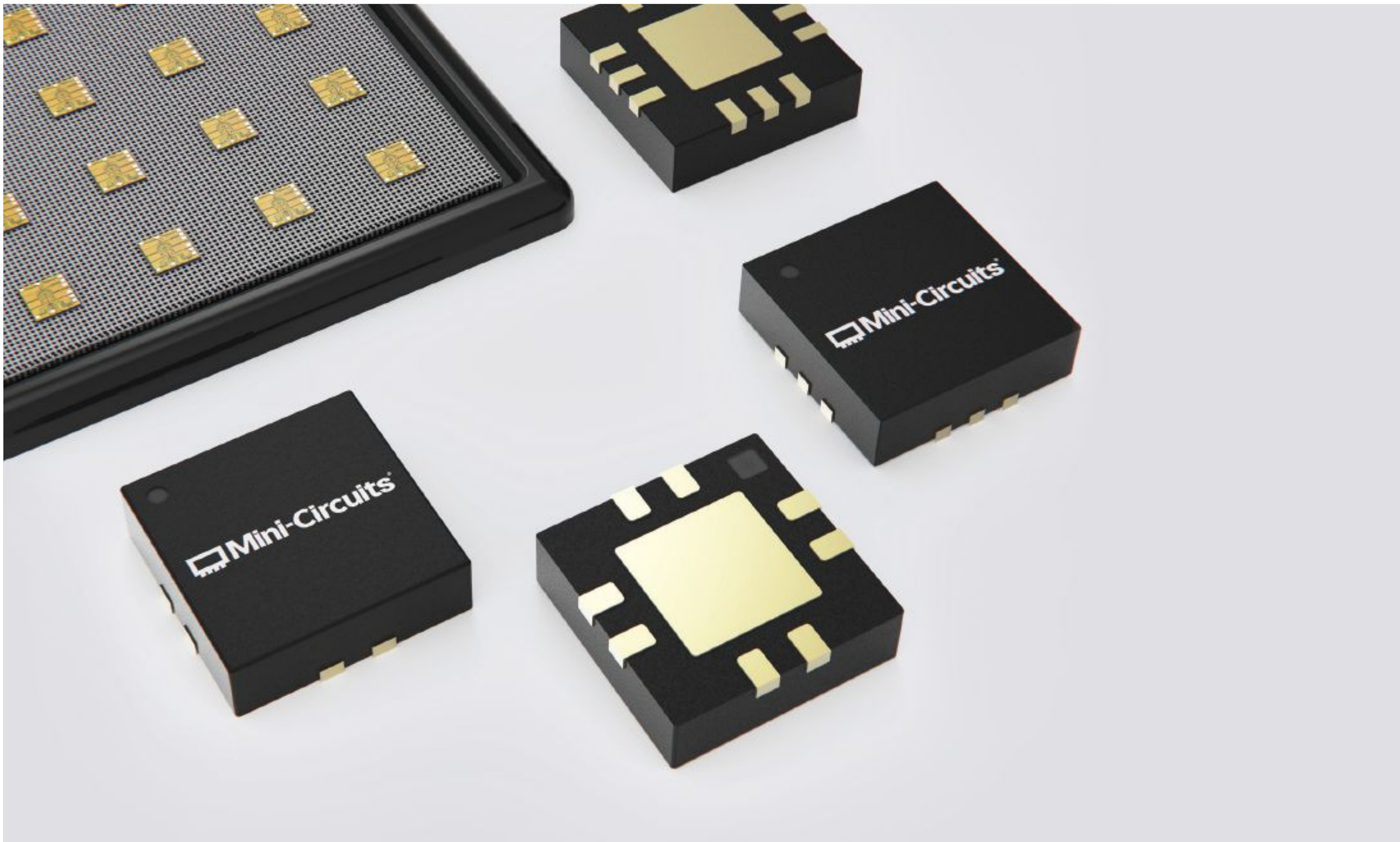

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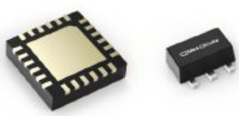

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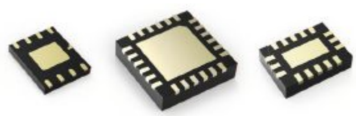

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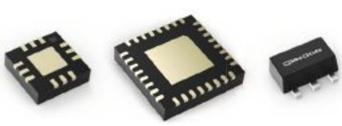

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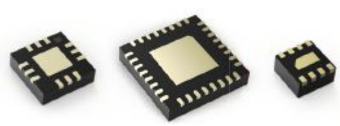

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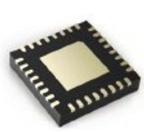

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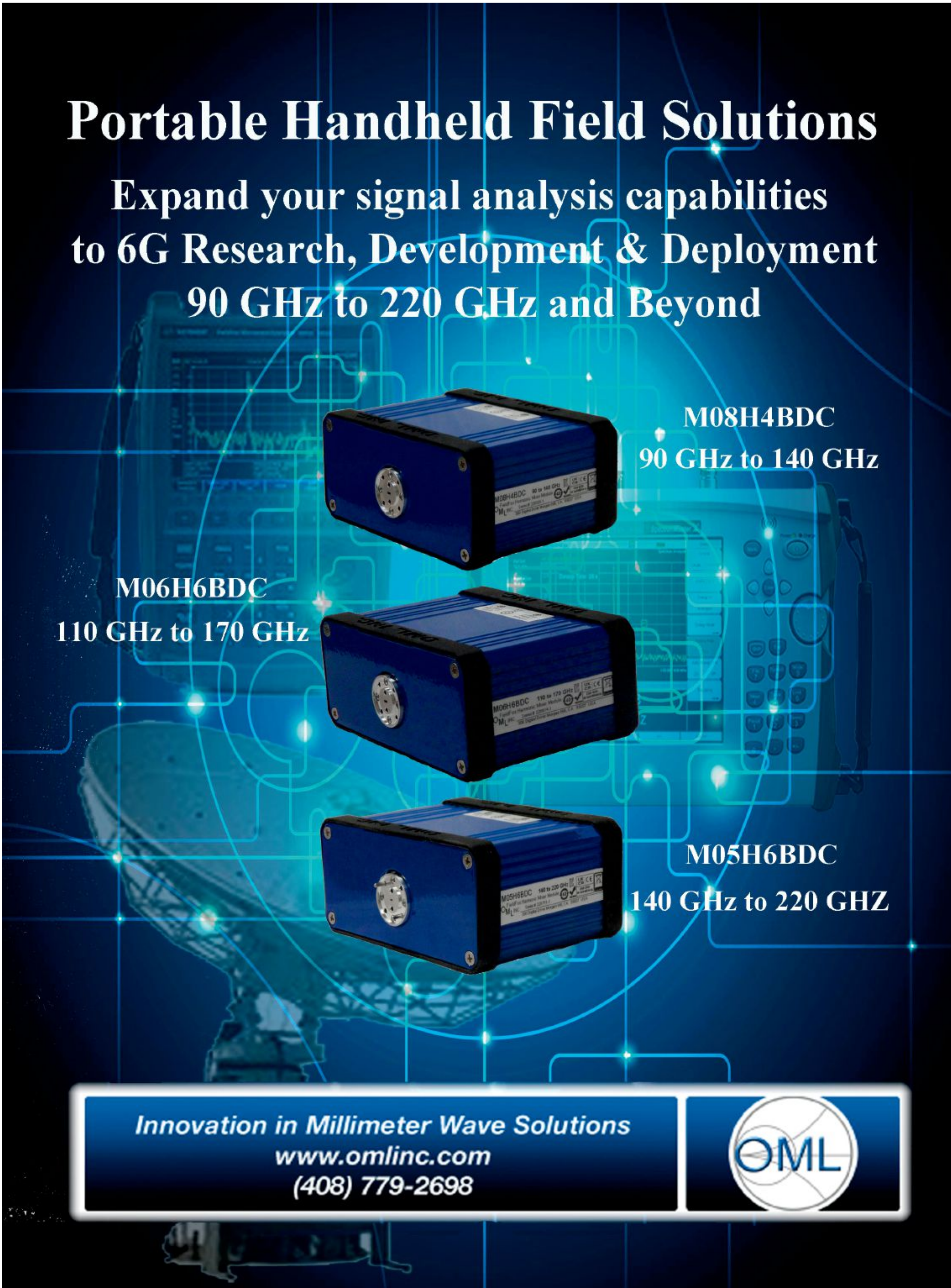
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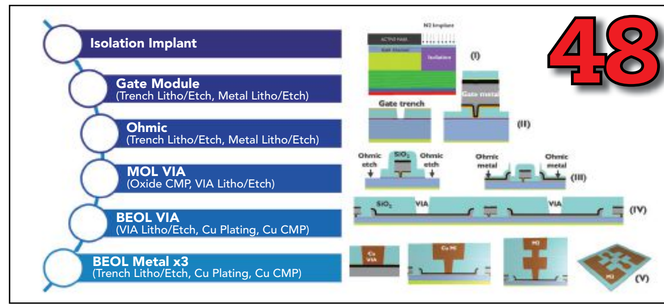

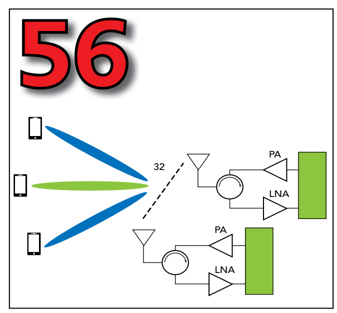

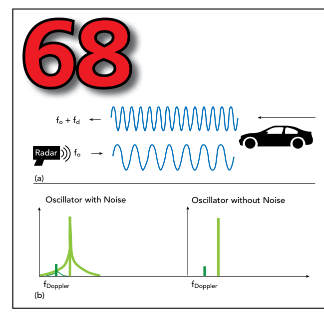

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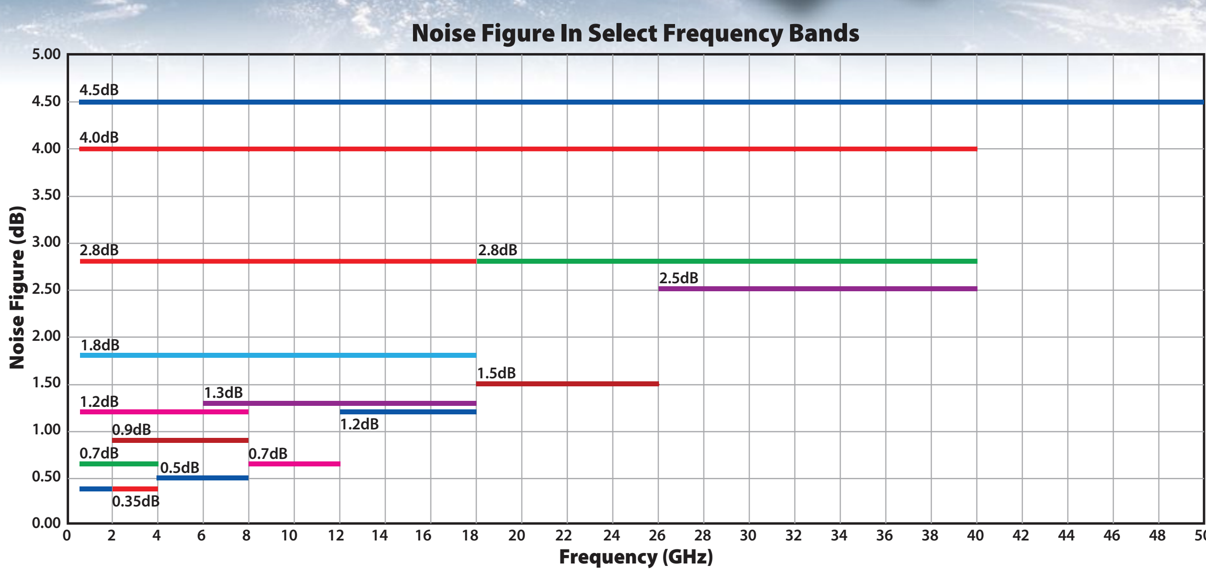

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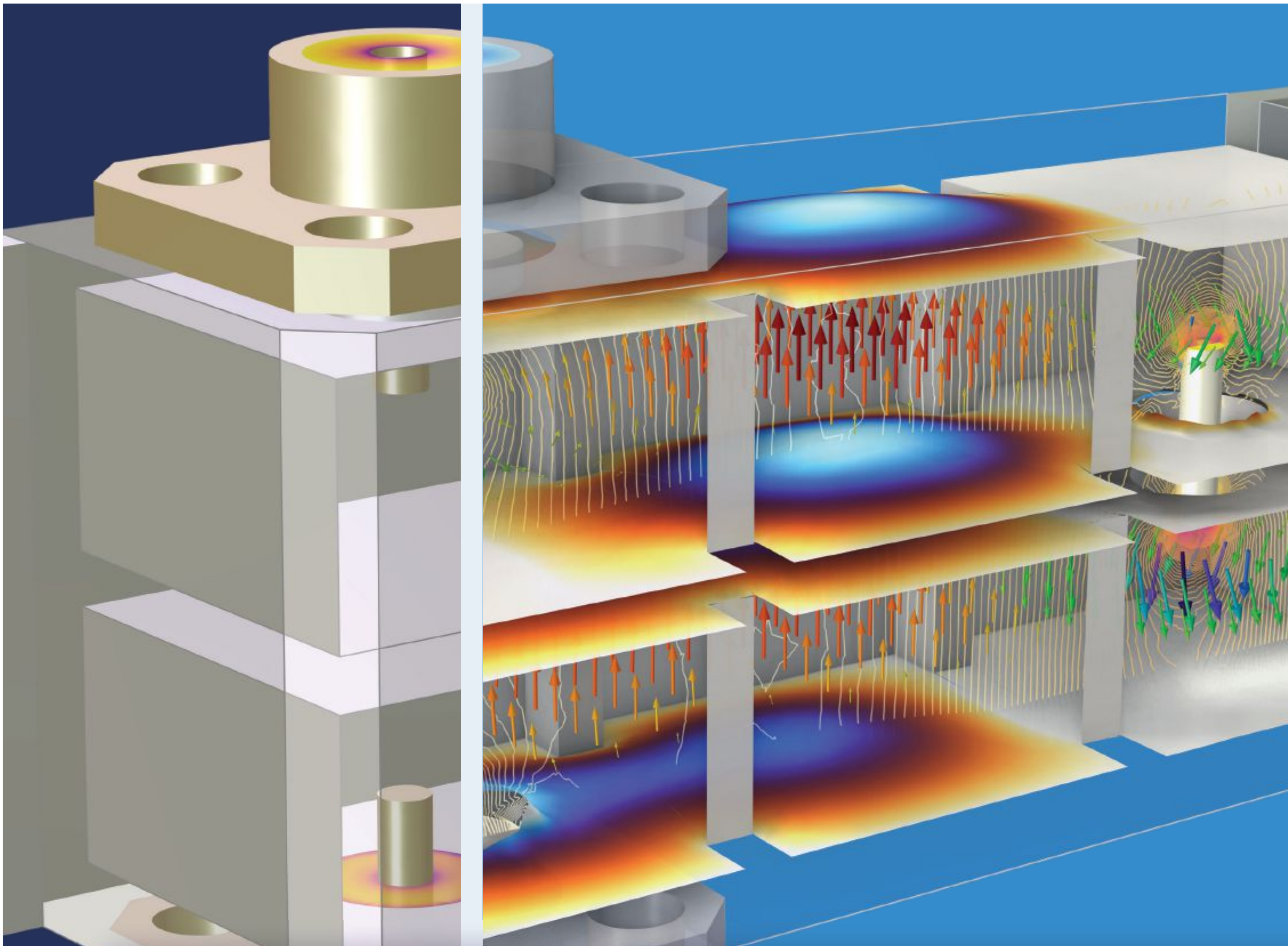

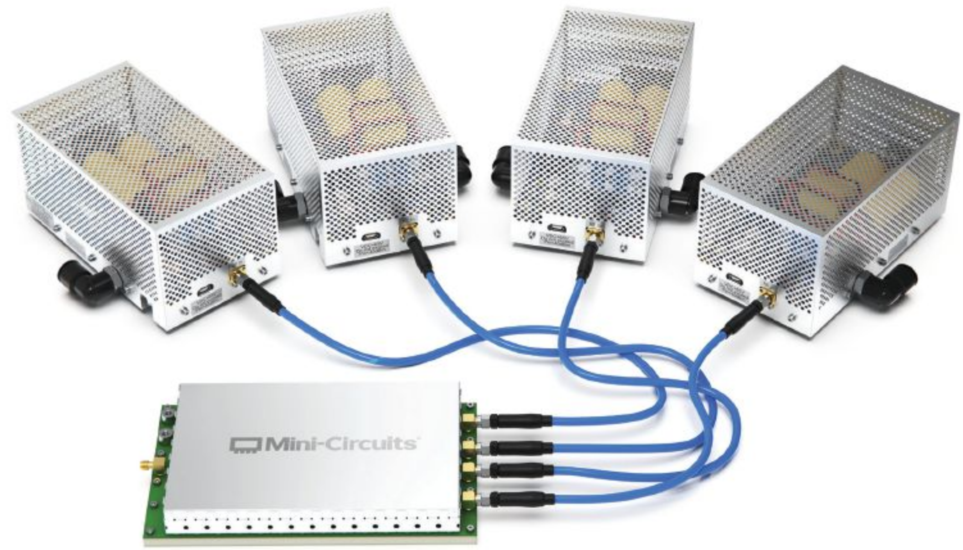

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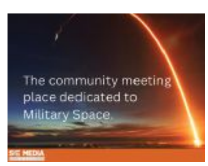

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Novel Design and Manufacturing Techniques Revitalize mmWave TWTs

Diana Gamzina and Richard Kowalczyk
Elve, Inc. Davis, Calif.

The mmWave spectrum offers many compelling advantages for communication applications. Compared to microwave systems, mmWave offers larger blocks of less contested and less regulated bandwidth for high data rates. The shorter wavelength allows reduced antenna size for a given antenna gain for compact systems. Compared to optical, mmWave losses in the atmosphere are modest and it is possible to "burn through" inclement weather to maintain a link. Additionally, with enough power the spot size at the receiver can be relatively large, providing tolerance for imperfect antenna pointing accuracy.

Wireless communications systems are finding increasing applications because of their reduced capital costs, ease of deployment and reduced environmental impact over physical carriers such as fiber. Wireless transmitters have long played an essential role in satellite communications (satcom) and are used terrestrially as point-to-point relays to carry backbone traffic where the deployment of physical lines is difficult. Recently mmWave systems have seen rapid adoption for point-to-point terrestrial links up to W-Band and in satcom for gateway uplinks up to V-Band. Access to bandwidth at these frequencies enables competitive data rates with those available over fiber optic cables. ***Figure 1*** shows the large swaths of frequency blocks available with the 71 to 76 GHz and 81 to 86 GHz bands each offering 5 GHz of continuous bandwidth. At W-Band, 92 to 114 GHz and at D-Band, 130 to 174.5 GHz, even larger bandwidths are being considered for near-term network growth.[1] Future systems will operate at G-Band frequencies spanning 200 to 300 GHz ranges.[2]

The power amplifier (PA) is usually one of the last components in the RF chain before the antenna, playing a key role in system performance. Making use of mmWave for communications and imaging requires acquiring the signal at the receiver with a suitable signal-to-noise ratio. Practical systems that function over appreciable distances in various weather conditions often need tens of watts of power to meet requirements.

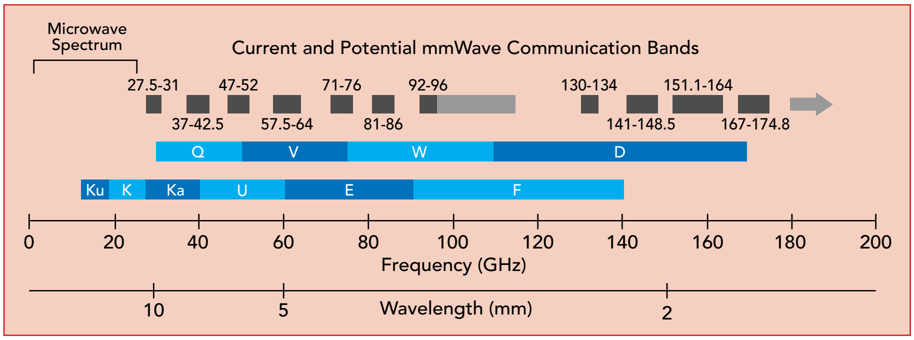
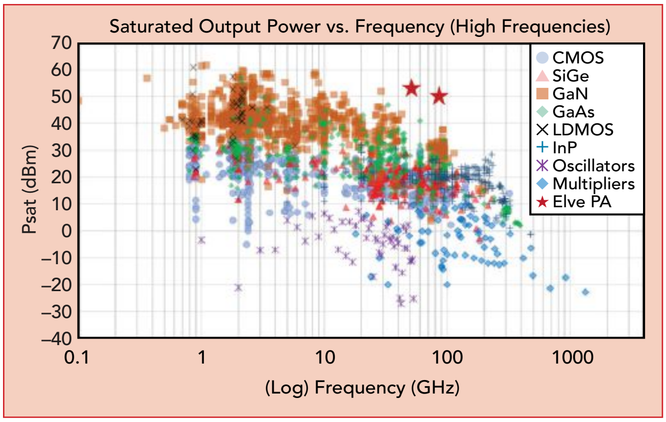
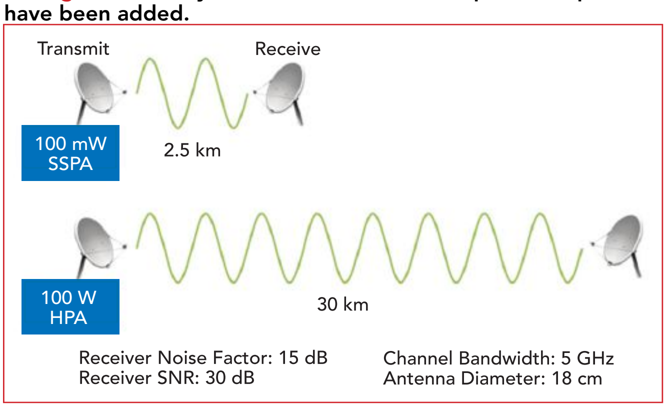


Fig. 1 mmWave spectrum bands.



▲ Fig. 2 Summary of available SSPAs.[3] Elve power amplifiers have been added.



▲ Fig. 3 Range enhancement with an E-Band TWT.

Achieving this at mmWave frequencies is a challenge. The advantages of mmWave systems have been acknowledged for decades, but the lack of availability of mmWave PAs has impacted mmWave deployment. Local heat dissipation limits achievable power in a single MMIC, so reaching watts of output power requires power combining that reduces efficiency. Low efficiency, low system-level power density, high thermal load and design complexity of mmWave solid-state power-combined systems are some of the challenges of deploying mmWave systems. While several technologies have been explored to deploy mmWave PAs,[3] GaN and GaAs are the solid-state solutions that offer the most potential for high power levels as shown in ***Figure 2***. New technologies offering increased power efficiently in compact forms are needed.

Traveling wave tube (TWT) amplifiers (TWTAs), consisting of a TWT and its power supply, or electronic power conditioner are a well-established highly reliable technology[4,5] that has demonstrated high power efficiency in a compact form at mmWave frequencies. We believe that the technology outperforms solid-state power amplifiers (SSPAs), but is often overlooked for deployment in high data rate communications systems. As shown in ***Figure 3***, a 100 W TWTA allows data to be transmitted at the same rate 10x as far as a 100 mW amplifier.

LINEAR BEAM AMPLIFIER OVERVIEW

Many vacuum devices are used to generate or amplify mmWave power. Linear beam devices, such as klystrons, TWTs and backward wave oscillators (BWOs) provide power that is unachievable in solid-state devices. Klystrons are narrowband amplifiers with resonant circuits, producing high peak power. They are used in radar and some communication systems. TWTs employ a non-resonant circuit that allows significantly wider bandwidth, typically at lower power levels than klystrons. BWOs have a circuit that is designed for an unstable interaction with a backward traveling wave so the devices generate RF without an input signal, effectively amplifying noise.

THE TWT

TWTs are the vacuum amplifiers used most commonly in communication systems. Dr. Rudolf Kompfner is credited with the invention of the TWT,[6] but Dr. John R. Pierce quickly realized the potential of the device to enable the type of communications he was working on at Bell Laboratories. He developed much of the engineering needed to design and build practical devices.[7]

TWTs amplify a signal using the kinetic energy carried by electrons traveling in a vacuum environment. The operation starts with an electron gun that creates an electron beam that is electrostatically focused into a narrow stream. Most TWTs employ a thermionic cathode, where a low work function material is heated to emit electrons into the vacuum. The hot cathode evaporates the emissive material, leading to a finite lifetime of electron emission. Electron energies are given by a Maxwellian distribution in the cathode and only those with energies above the cathode work function can travel into the vacuum. Higher electron emission requirements mean a hotter cathode for a given cathode material work function. A voltage applied to the anode accelerates the electrons and lenses electrostatically focus them into a compact beam. If the cathode surface is large and the focused beam small as in a high frequency TWT, this focusing may reduce the beam's cross-sectional area by a factor of a hundred, requiring extreme precision in the lenses.

Next, the electron beam, carrying kinetic energy established by the electrostatic acceleration, enters a magnetic field that counteracts the electrostatic repulsion of the electrons, maintaining a constant cross-section as the electrons travel through the interaction circuit. The circuit starts with an RF input port where power is injected. The RF is carried on a transmission line that wraps around the beam so that the electric field from the RF input power is aligned with the electron beam's axial motion. The alternating electric field speeds up some electrons and slows down others, forming electron bunches. As the modulated electron beam travels with the RF wave, the electron beam induces current on the circuit, causing the amplitude of the circuit wave to grow at the expense of the electron kinetic energy.

The electron beam and the electromagnetic wave must travel at similar speeds to form the electron bunches. Otherwise, the electron sees a sinusoidally-varying electric field with velocity increasing and decreasing, but on average retaining its initial energy. Electrons moving at a similar speed to the wave are continuously accelerated in the accelerating phase and

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The amplified RF is coupled out at the end of the circuit and the spent electron beam goes to a collector. In most TWTs, the collector contains multiple electrodes, each depressed below ground to a different electric potential level. The electrons give up kinetic energy as they climb the potential hill created by these biased electrodes, allowing the power supply to recover energy, significantly improving the overall operating efficiency of the device. This energy recovery is one of the reasons that TWTs can achieve significantly higher efficiency than solid-state amplifiers.

The technique of bunching the beam by adjusting electron velocity with an electromagnetic signal is commonly used in vacuum amplifiers. First demonstrated in klystrons in the 1930s, velocity modulation can produce high gain in the interaction circuit since small changes in velocity result in patterns of high and low current density downstream. Since all this happens in a collisionless vacuum environment, the approach allows these devices to scale to very high frequencies.

The most used TWT circuit is a helix, or more specifically a coaxial transmission line with the center conductor twisted into a helical path. The quasi-TEM mode on the transmission line follows the helical path, causing the axial velocity to slow. The electron beam travels through the center of the helical line where the electric field of the electromagnetic wave acts on the beam along the direction of the beam propagation.

On a coaxial line with a vacuum dielectric, the electromagnetic wave propagates at the speed of light. In a TWT, the helix pitch, the distance between each turn, reduces the electromagnetic wave's net velocity in the beam direction. ***Figure 4*** shows this with a "dispersion curve," the relationship between frequency $\omega=2\pi f$ and wavelength. Frequency is plotted on the y-axis and inverse wavelength, called β on the x-axis. Since the velocity of a wave is given by frequency multiplied by wavelength, the velocity at

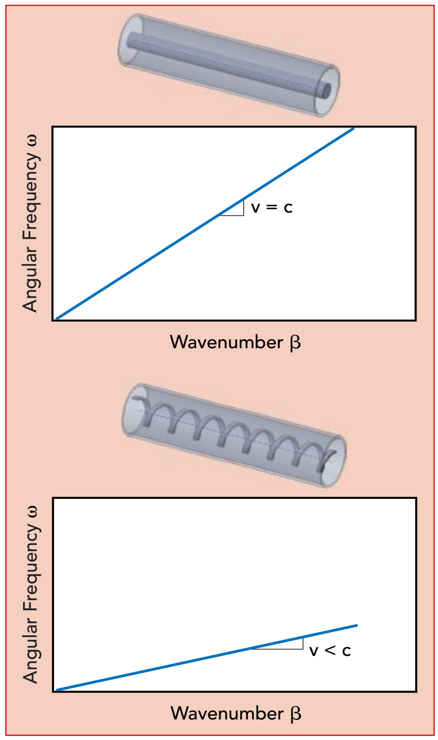

Fig. 4 **Dispersion curves for coaxial line and helical delay line.**

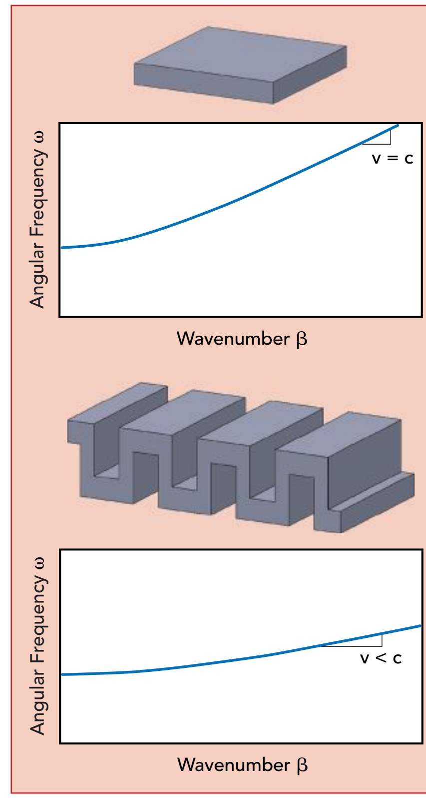

Fig. 5 **Waveguide and folded-waveguide dispersion diagram.**

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REMC08G11GE 8-11GHZ 400W

any point on the curve is ω/β .

TWT circuits based on two-conductor transmission lines can be extremely wideband since they use the TEM mode, which has no cutoff frequency. Unfortunately, the center conductor must be electrically isolated from the outer conductor. This requires ceramics to support the helix, resulting in non-ideal heat paths for electrons that intercept the circuit and ohmic losses generated in the helix. For applications requiring smaller bandwidths, single-conductor transmission line circuits are preferable. These circuits can be all metal, improving thermal power handling. Many traditional TWTs are made from coupled cavities that use a series of resonant cavities connected with irises or slots to create a winding RF path.

A folded-waveguide circuit employs a waveguide bent back on itself many times, reducing the effective speed of the RF along the beam propagation.[8] A beam tunnel hole is punched through the circuit. Starting with the dispersion curve of the waveguide, the net velocity of the RF following the waveguide path is reduced as shown in ***Figure 5***.

The periodic structure results in a periodic dispersion curve shown in ***Figure 6***. The direction of the electric fields reverses each time the waveguide folds back on itself. As the electron beam passes through the folded-waveguide structure, it sees an additional 180-degree phase shift every half period as shown in ***Figure 7***.

Figure 8 shows the resulting dispersion curve. Appropriate values of waveguide cross-section and path can be chosen to achieve a phase velocity that matches the beam velocity. The circuit can be optimized for a relatively constant phase velocity over the band, resulting in flat gain over frequency for a wideband amplifier.

MMWAVE TWTS

Many TWTs using helix circuit designs to generate hundreds of watts of power at Ka-Band for communications systems are available today. Suppliers include Stellant, CPI, Thales, Photonis, Teledyne and NEC. These TWTs can have efficiencies over 50 percent with output power densities around 100 mW/cm^3.

For applications where size or weight are at a premium, mini-TWTs are often used. These devices have shorter circuits and reduced gain that is offset by higher-power solid-state drivers. Lower voltages allow for a very compact high-voltage power supply to be packaged with the TWT. At Ka-Band, up to 100 W is available with power densi-

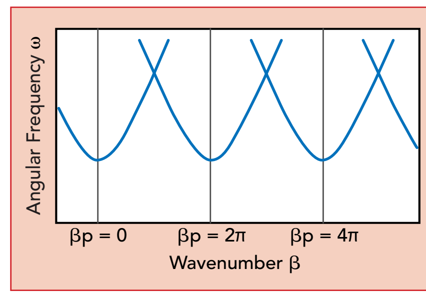


Fig. 6 Folded-waveguide periodic dispersion curve.

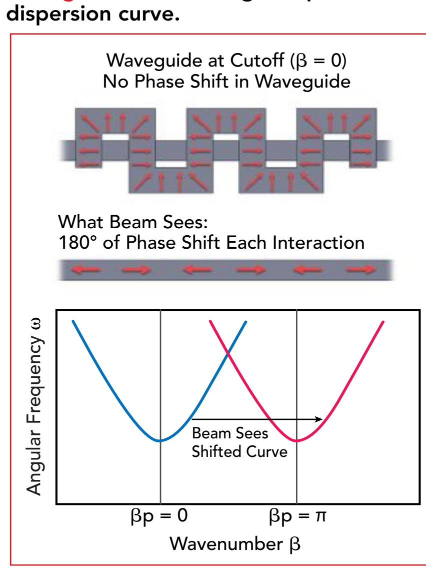


Fig. 7 Folded waveguide field as seen by electron beam.

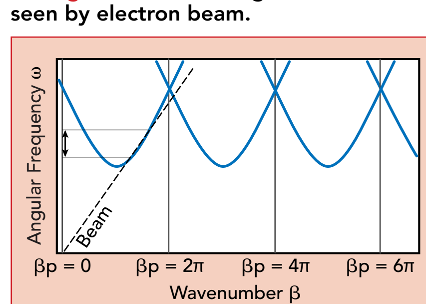
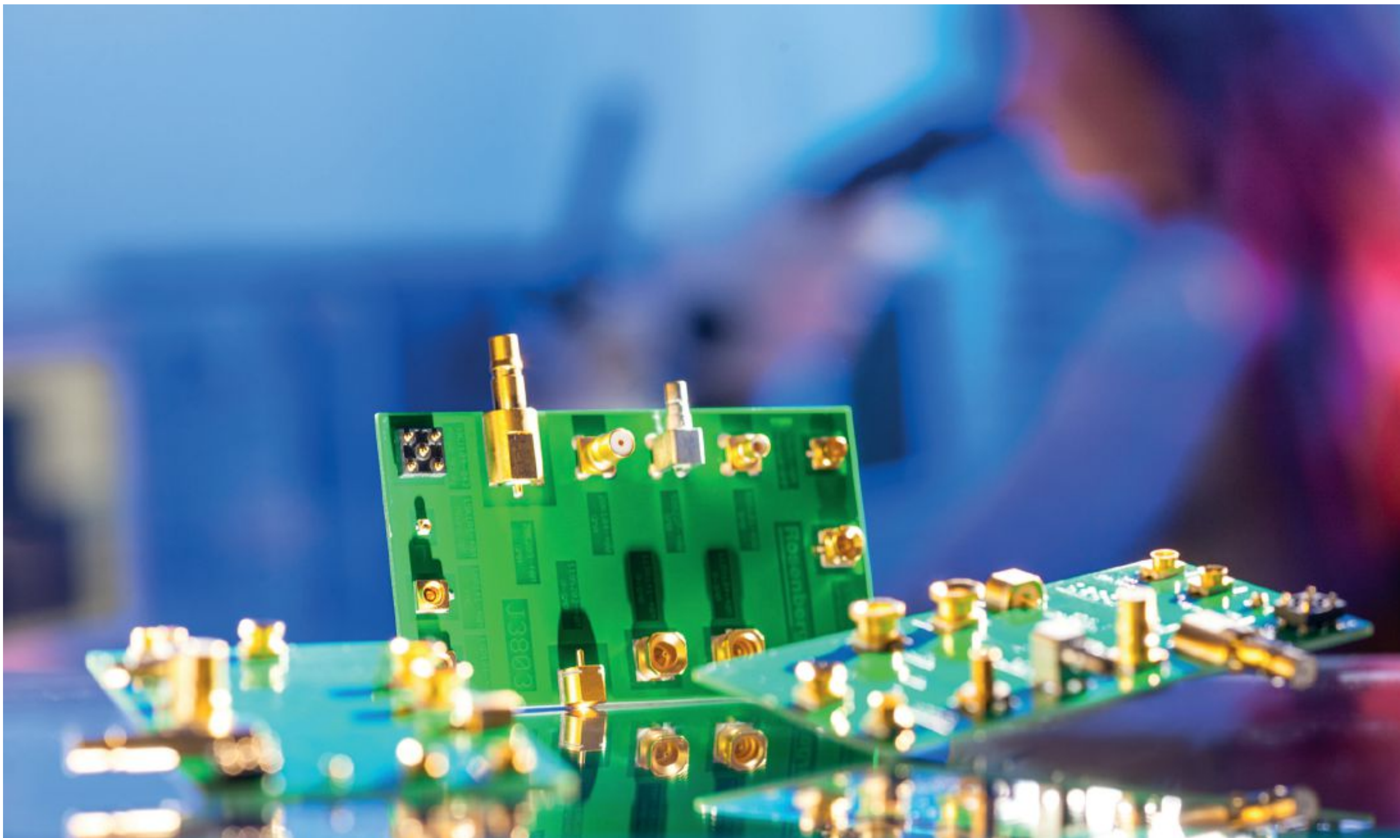


Fig. 8 Dispersion curve for folded-waveguide TWT interacting with an electron beam.



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- Excellent transmission quality
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Rosenberger

	Elve	SSPA A	SSPA B	SSPA C	MPM
Frequency	81-86 GHz	81-86 GHz	81-86 GHz	81-86 GHz	81-86 GHz
Power	100 W sat	5 W sat	2.5 W sat	4 W sat	200 W sat
Size	23 x 15 x 8 cm	9 x 15 x 15 cm	12 x 13 x 9 cm	11 x 10 x 5 cm	38 x 27 x 8 cm
Power Density	37 mW/cm^3	2 mW/cm^3	2 mW/cm^3	7 mW/cm^3	26 mW/cm^3
Efficiency	32%	3%	5%	6%	30%

Fig. 9 **Comparison of E-Band amplifiers.**

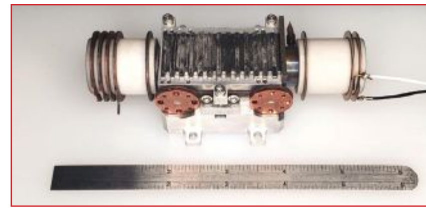

Fig. 10 **Elve E-Band TWT.**

ties of hundreds of mW/cm^3. At E-Band frequencies there are fewer commercially available options, as shown in ***Figure 9***.

ELVE TWTAS

The construction of vacuum electronic devices, such as TWTs, is often an artisan process; it requires extremely high-precision machining and assembly. The tolerances become more exacting as the frequency increases. Each mmWave circuit is constructed and assembled individually and can take months to complete. Fabrication techniques for the circuit include micromachining (milling or EDM) as well as electroplating around LIGA molded photoresist, etched silicon or 3D-printed polymer structures.[9,10,11,12] These processes do not easily accommodate design changes to individual circuits with minimal process adjustments. The processes used to date have significant limitations in the rate of production.

Elve has developed TWT design and fabrication techniques suitable for making mmWave TWTs in volume. The TWTs employ nanocomposite scandate tungsten emitters, which have a significantly lower work function than traditional TWT emitter materials. These special materials allow the emitted electron current density to be higher for the same temperature. As a result, a smaller emitter can be employed enabling the devices to be robust to minor dimensional errors in the beam-focusing structures while maintaining a long lifetime.

Elve TWTs use a "sheet" beam with an elliptical, rather than round, cross-section of the electron beam perpendicular to the direction of travel. The elliptical geometry reduces space charge density and power density in the beam, reducing the magnetic field requirements to confine the beam. Maintaining one of the ellipse dimensions small relative to wavelength enables good circuit efficiency, the ratio at which electron beam kinetic energy is converted into RF energy. The planar sheet beam configuration is well-suited for modern manufacturing techniques.

Elve has developed an additive manufacturing technique to fabricate the circuits. Using this approach, circuits of different frequencies can easily be fabricated using the same process. Other devices that interact with electron beams, like klystrons or gyrotrons, can be made with this approach. The circuit technology is critical to Elve's ability to rapidly iterate TWT designs. In production, it allows circuits and TWTs to be made quickly and consistently at volume. The compact planar design of an Elve TWT is shown in ***Figure 10***.

Traditional microwave TWTs have demonstrated decades of reliable operation in space applications. Elve is designing and testing amplifiers to meet the same rigorous standards. The cathodes are the most sensitive portion of the TWT, so samples from each batch of powder are tested to verify the work function and emitted current. Elve is putting complete units through environmental testing including cathode heater cycling, operational on/off cycling, vibration testing and operation at temperature extremes

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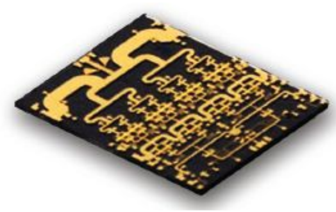

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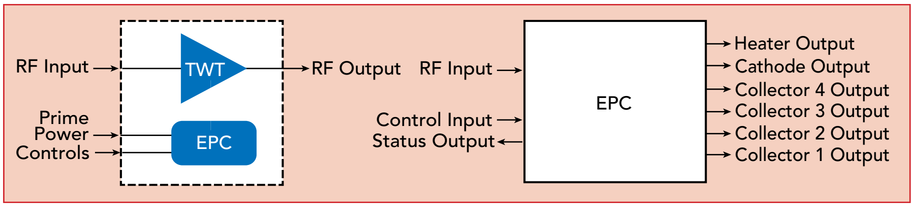

Fig. 11 **EPC powering the TWT heater, cathode and collectors.**

TABLE 1

E-BAND AMPLIFIER RF PERFORMANCE SUMMARY

Parameter	Result
Frequency	81 to 86 GHz
RF Output Power	100 W minimum
RF Input Power	34 dBm maximum saturation
Duty Cycle	CW
AM/PM Conversion	3°/dB maximum
RF Input/Output	WR-12

Fig. 12 **Elve E-Band PA including TWT and EPC.**

to identify and resolve any potential reliability issues.

A complete TWT-based amplifier contains an electronic power conditioner (EPC) shown in ***Figure 11***, which produces the operating voltages for the TWT. A compact TWT requires a negative cathode voltage of several kilovolts, typically in the range of -3 to -20 kV. The cathode voltage must be tightly regulated with extremely low ripple to enable ideal RF performance from the TWT. The cathode heater, floating at cathode potential, requires a few watts of power. The multi-stage depressed collector is biased with voltages between cathode potential and ground to enable efficient recovery of spent electron beam energy. In addition to generating the TWT electrode voltages, an EPC also provides the control logic and user interface to allow system integration.

The Elve Vermillion E-Band amplifier shown in ***Figure 12*** covers 81 to 86 GHz. The amplifier has a small signal gain of 20 dB, with other parameters shown in ***Table 1***. Transfer curves are shown in ***Figure 13*** with simulated linearity performance shown in ***Figure 14***.

The behavior under multi-tone input waveforms is shown in ***Figure 15***. When driven by 30 dBm input power per carrier to produce more than 100 W of total output power, split between two carrier frequencies, third-order intermodulation distortion is around 16 dB.

There have been impressive mmWave and THz TWT results reported by Stellant[13,14] and Northrop,[15] demonstrating a technological path to mmWave vacuum power devices. The volume has been low, but Elve has spent the past 18 months developing a high volume TWT fabrication process. Elve's process is evolving with early prototype amplifiers providing feedback to improve subsequent units. Prototype gain performance is shown in ***Figure 16*** with temperature performance shown in ***Figure 17***.

CONCLUSION

TWTs have been a workhorse in communications, radar and imaging applications. They have an opportunity to return to the spotlight and showcase unprecedented performance at mmWave frequencies. Decades of demonstrated reliability, high power and efficiency are some of the advantages TWTs offer. Elve's focus on large-quantity manufacturability ensures access to TWT advantages to enable the next generation of connectivity. ■

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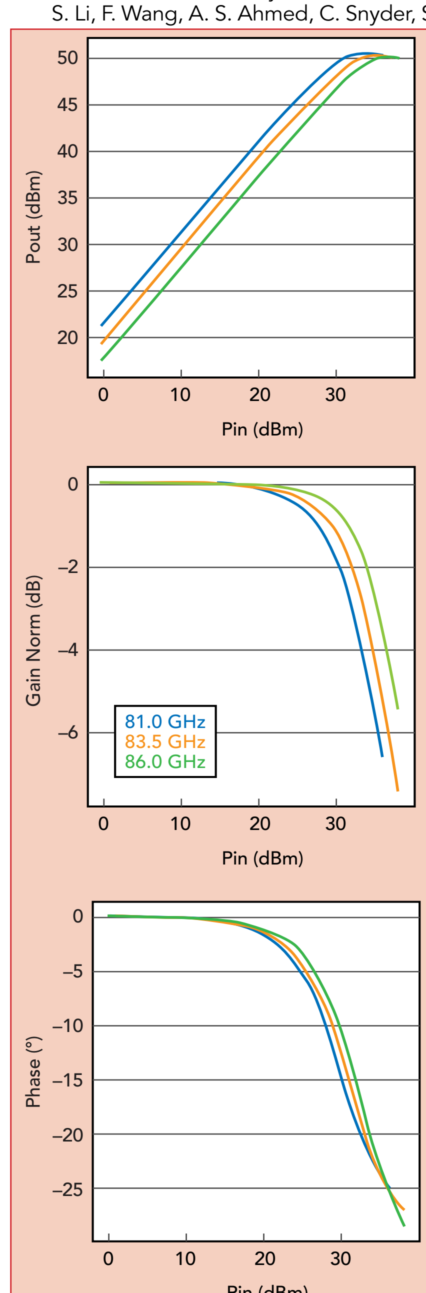
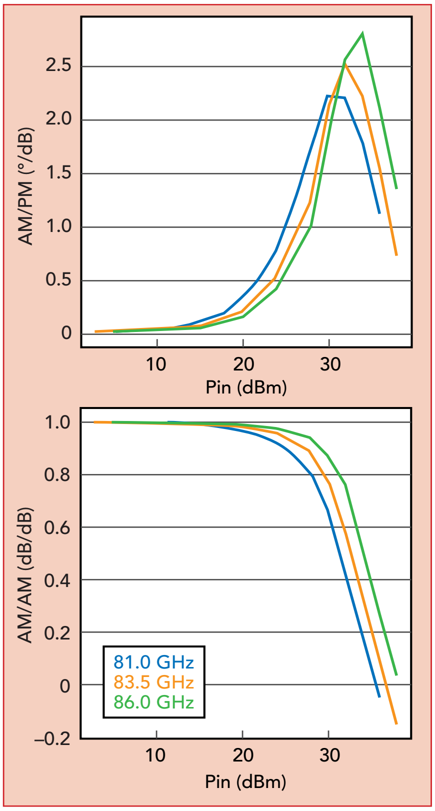
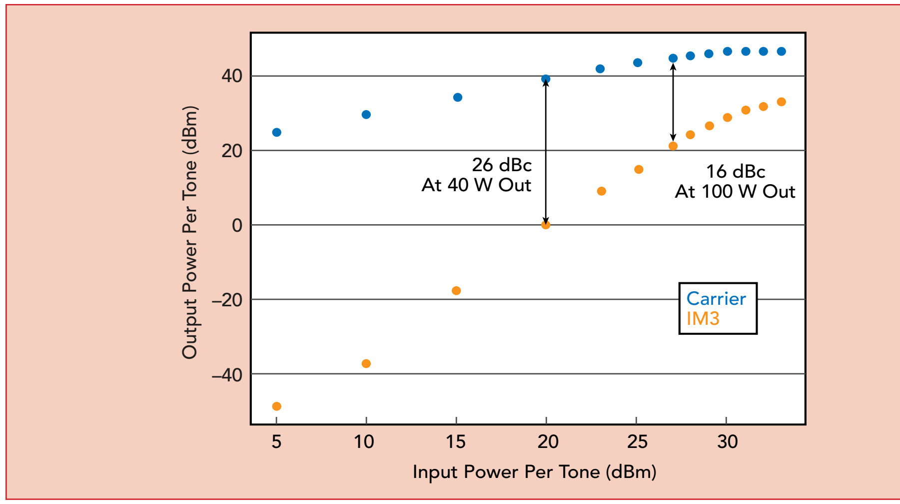


Fig. 13 **Simulated RF transfer characteristics.**



▲ **Fig. 14** **Simulated linearity characteristics.**



▲ **Fig. 15** **Two-tone intermodulation distortion at band center.**

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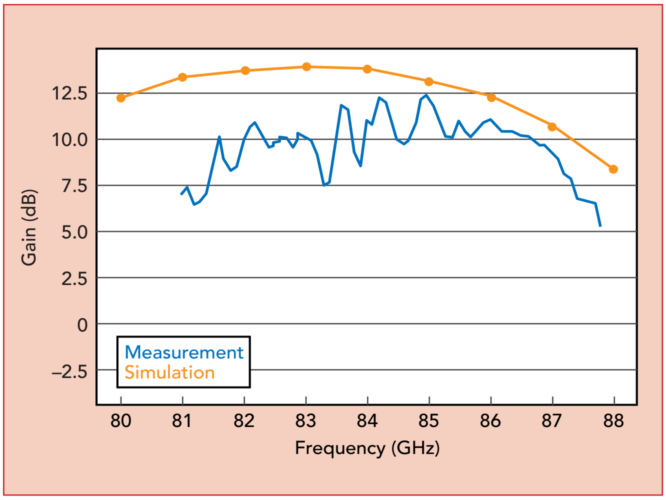

Fig. 16 **Simulated and measured data for an early Elve prototype TWT.**

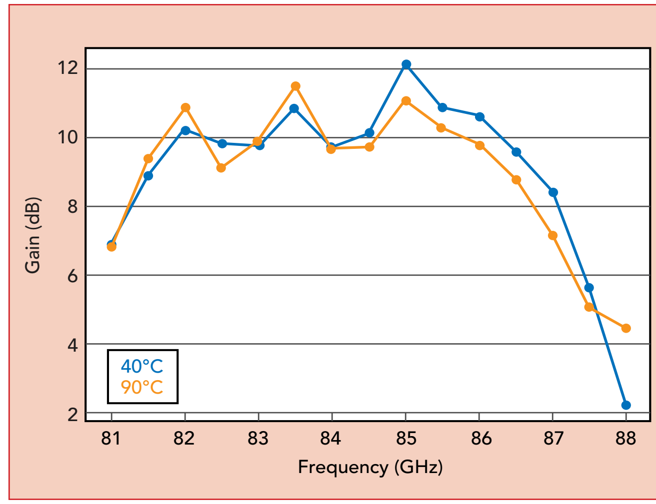

Fig. 17 **TWT temperature performance.**

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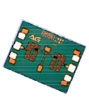
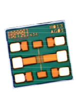



Low Noise Amplifiers

Part Number	Frequency (GHz)	Gain (dB)	G.F. (dB)	N.F. (dB)	I/O VSWR	P@1dB (dBm)	V (V)	I (mA)
APT6-02200240-0515-D44	2.2-2.4	60	±0.5	0.3	1.3:1/1.5:1	+15	+15	300
APT4-07250775-0710-D6	7.25-7.75	30	±0.5	0.4	1.5:1/1.5:1	+10	+15	100
APT4-10951275-0810-D6	10.95-12.75	35	±1.0	0.7	1.5:1/1.5:1	+10	+15	100
APT22-12001800-1515-D22	12.0-18	45	±2.0	1.2	2.0:1/2.0:1	+15	+15	300
APT4-18004000-3005-D20	18-40	45	±3.0	2.7	2.5:1/2.5:1	+5	+15	250

SATCOM Amplifiers

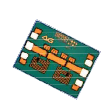
Part Number	Frequency (GHz)	Gain (dB)	G.F. (dB)	N.T. (K)	I/O VSWR	P@1dB (dBm)	V (V)	I (mA)
APTW5-07100840-35K10-WR112D6	7.10-8.40	50	±1.0	35	1.5:1/1.5:1	10	+15	200
APTW5-10951275-40K15-WR75D6	10.95-12.75	50	±0.5	35	1.5:1/1.5:1	15	+15	200
APTW5-17702120-100K10-WR42D22	17.3-22.0	50	±1.0	85	1.3:1/2.0:1	10	+15	175
APTW5-19251940-82K20-WR42D22	19.25-19.40	45	±0.5	70	1.3:1/1.3:1	+20	+15	250
APTW5-25502700-140K10-WR34D22	25.5-27.0	48	±1.5	130	1.4:1/1.4:1	+10	+15	250

MMIC Amplifiers

Part Number	Frequency (GHz)	Gain (dB)	G.F. (dB)	N.F. (dB)	I/O VSWR	P@1dB (dBm)	Single Bias V (V)	I (mA)
AGM-058	2-4	34	±0.5	0.6	1.5:1/1.3:1	13	+4	150
AGM-003	4-8	26	±0.5	0.9	1.3:1/1.7:1	10	+5	125
AGM-001	1.5-24	15	-	2.5	1.5:1/1.4:1	10	+5	45
AGM-040	17-20	21	±1.0	-	1.1:1/1.4:1	Psat +35	+28	100
AGM-052	27-31	22	±0.5	-	1.5:1/1.7:1	Psat +35	+18	210





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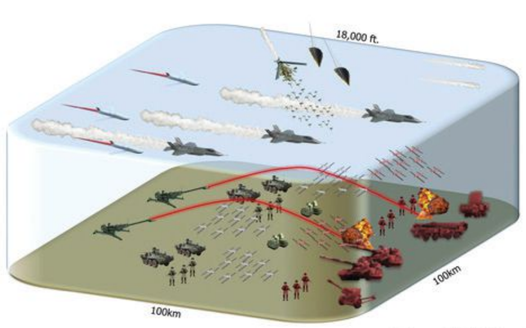
DARPA Services Demonstrate Battlefield Airspace Deconfliction Software

DARPA's Air Space Total Awareness for Rapid Tactical Execution (ASTARTE) program recently demonstrated new automated flight-path-planning software that successfully deconflicted friendly missiles, artillery fire and manned and unmanned aircraft while avoiding enemy fires in a simulated battle in contested airspace. In a demonstration held at the U.S. Army's Mission Command Battle Lab, Ft. Leavenworth, Kan., the ASTARTE software seamlessly integrated with the Army's Integrated Mission Planning and Airspace Control Tools (IMPACT) software suite.

The ASTARTE program is a joint collaboration between DARPA, the Army and the U.S. Air Force to enable efficient and effective airspace operations and de-confliction in a highly congested anti-access/area denial environment. The program's goal is to provide an accurate, real-time common operational picture of the airspace over an Army division, enabling long-range fire missions, as well as manned and unmanned aircraft operations, to occur safely in the same airspace.

ASTARTE performer Raytheon Technologies developed an automated flightpath-planning capability for fixed and rotary wing aircraft, which includes the capability to deconflict airspace use by routing through or around defined airspace coordinating measures, in both space and time. General Dynamics Mission Systems (GMDS) developed the Army's IMPACT suite, which adds a Joint All-Domain Command and Control (JADC2) class of data-enabled, over-the-horizon tools to existing airspace management systems to form a multi-domain capability supporting the Army's 2030 Multi-Domain Operations vision.

During the demonstration, GDMS and Raytheon identified the interfaces allowing the ASTARTE flight-path planner to receive flight path requests with associated constraints from IMPACT (e.g., timing, altitude range, start and end points), and returned complete deconflicted flight paths back to IMPACT on demand.



ASTARTE (Source: DARPA)

HENSOLDT Receives Contract as Part of German-French-Spanish FCAS

Sensor solutions provider HENSOLDT is developing essential core elements of the novel sensor network in the German-French-Spanish Future Combat Air System (FCAS). As a member of the German Future Combat Mission System (FCMS) consortium, HENSOLDT has been awarded a contract worth approximately €100 million by the French procurement authority DGA for the development of demonstrators in its core competence fields of radar, reconnaissance and self-protection electronics and optronics as well as the overarching networking of sensor technology.

FCAS (Source: HENSOLDT)

In the FCAS project, the participating nations want to develop, among other things, a successor system for the Eurofighter and Rafale fighter aircraft as well as a novel system of networked sensors. By 2025, several technology demonstrators will be developed to show the possibilities of a platform-independent networked solution. This sensor network with different platforms will then be further developed in the other FCAS demonstrator phases.

The respective technology leaders of the industry from the three countries are involved: Under the overall management of INDRA (Spain), Thales for France and the FCMS consortium for Germany, consisting of HENSOLDT, Diehl Defence, ESG Elektroniksystem – und Logistik-GmbH and Rohde & Schwarz, are working together in the so-called demonstrator Phase 1b. HENSOLDT leads the FCMS consortium and therefore, in addition to its technical work packages, also takes on essential tasks in project management and in the central architecture work packages.

Lockheed Martin Awarded Initial Contract to Provide Nation's First Sea-Based Hypersonic Strike Capability

The U.S. Navy awarded Lockheed Martin a contract worth more than $2 billion, if all options are exercised, to integrate the Conventional Prompt Strike (CPS) weapon system onto ZUMWALT-class guided missile destroyers. CPS is a hypersonic boost-glide weapon system that enables long-range missile flight at speeds greater than Mach 5, with high survivability against enemy defenses.

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

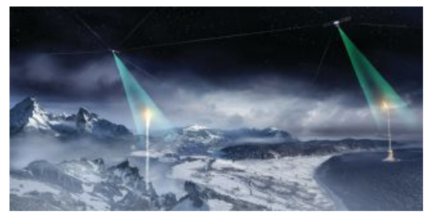

CPS (Source: Lockheed Martin)

Under this contract, prime contractor Lockheed Martin will provide launcher systems, weapon control, All Up Rounds (AURs), which are the integrated missile components, and platform integration support for this naval platform. The company, along with subcontractors Northrop Grumman and General Dynamics Mission Systems, is on track to provide the CPS surface-launched, sea-based hypersonic strike capability to sailors by the mid-2020s. The contract also provides for additional AURs plus canisters for the U.S. Army's long range hypersonic weapon (LRHW) testing, training and tactical employment.

CPS shares a common AUR with the Army LRHW and can be launched from multiple platforms including surface ships, submarines and land-based mobile launchers. The combination of the CPS capability, and the stealth and mobility of the ZUMWALT-class destroyer, will provide the nation's first sea-based hypersonic strike capability.

Raytheon Awarded Contract for Missile Warning and Tracking

Raytheon Technologies received an award valued at more than $250 million to design, develop and deliver a seven-vehicle missile tracking satellite constellation, as well as support launch and ground operations by the Space Development Agency.


SAT Constellation (Source: Raytheon Technologies)

A constellation of low earth orbit (LEO) satellites provides missile warning, missile tracking and enhanced situational awareness.

Once deployed, the LEO constellation of networked satellites will become the fifth plane of satellites providing missile warning and tracking for the Department of Defense. The program is a key element of the Proliferated Warfighter Space Architecture.

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6G: Why is it Needed and What are the Challenges?

Compared to its predecessor, 6G is expected to offer significantly better communication capabilities, such as Tbps-level peak data rates, microsecond-level latency and 99.99999 percent network dependability.

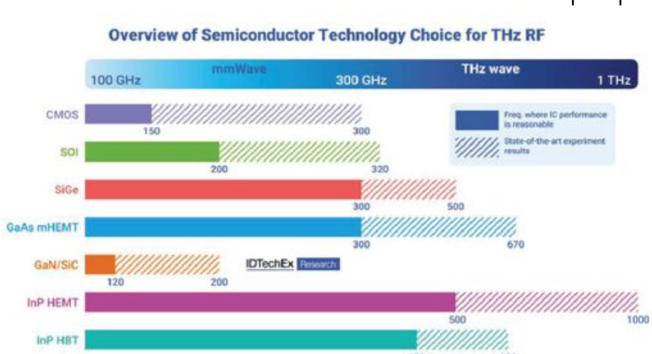
Even though several important companies and nations have already begun 6G research, the telecom industry needs to address several issues before seeing the success of 6G. Difficulties include THz technology and identifying applications that will fuel 6G adoption.

6G will use a spectrum above 100 GHz and will ultimately reach THz. The advantages of employing such a high frequency are obvious: huge bandwidth may be used, allowing for Tbps peak data flow with microsecond-level latency. However, there are several limitations to employing such a high frequency spectrum.

One of the most significant challenges ahead is that the THz signal attenuates considerably in the air, restricting the transmission range and making it easily blocked by obstructions. Because the laws of physics cannot be ignored, the most crucial element for creating a device for high frequency communication is to provide enough energy to achieve a reasonable transmission range, even as part of an antenna array.

Choosing the right semiconductors to increase link range is the most critical. When it comes to frequencies above 200 GHz, a combination of CMOS for logic and III-V transistors for low noise amplifiers and power amplifiers will be the way to go. SiGe BiCMOS technology currently provides the best compromise in terms of performance, low-cost and simplicity of integration from 200 to 500 GHz. InP could be the ultimate THz technology and may be suitable in applications where cost is not the primary concern.

Despite carriers' touting the superior performance that 5G mmWave provides, the mmWave market has yet to take off despite years of 5G's commercialization. The vast majority of 5G build-outs continue to use 5G sub-6 GHz. The reasons? The one reason that most people



Semiconductor Technology (Source: IDTechEx)

mention, according to IDTechEx's primary interviews, is the absence of applications that can be only enabled by mmWave and no other technologies. The same question about 6G will be asked: why is it needed?

From a consumer's perspective, having a Tbps data link and microsecond-level latency but paying a higher subscription fee will probably not be attractive if the applications on their mobile devices are similar to what they have right now.

For more details, see the IDTechEx 6G market research report, "6G Market 2023-2043: Technology, Trends, Forecasts, Players."

Soaring Demand for Global Connectivity Drives Satcom Terminal Sales

Satcom has entered a period of renewed interest with innovative technological advances, mainly driven by ballooning investment dollars in the high-growth space technology segment and the demand for global connectivity. The satcom ecosystem has two segments: ground equipment and space. ABI Research foresees sustained ground segment growth from the satcom terminals market, potentially reaching a market value of $15.6 billion by 2030.

Interest has been growing in how satcom might complement or even integrate with terrestrial communications networks. Dean Tan of ABI Research explained, "The 3GPP, the satcom industry and the terrestrial wireless vendors have been studying and evaluating technology to enable non-terrestrial network (NTN) mobile applications. NTN Mobile is still very nascent, but very-small-aperture terminal (VSAT) and Broad Global Area Network (BGAN) satellite solutions are very much the mainstays of the current satcom terminals industry."

From the research findings, ABI Research has also found that the VSAT satcom solutions will have the lion's share of the satcom market revenue, at over 80 percent. VSAT systems will remain largely the satcom choice throughout the forecast period.

In different aspects of product differentiation, various models, technological innovations and the sheer number of manufacturers, VSAT satcom systems also have a substantial lead over BGAN satcom systems. The satcom terminals market will be largely represented by Gilat Satellite Networks, Cobham satcom, Intellian, Viasat, Hughes Network Systems, KVH and ST Engineering's iDirect. These key players will be the driving force in technological and product innovation in the satcom terminals market.

ABI Research found that the North American region, particularly the U.S., will be the dominant region in demand and revenue for satcom. ABI Research also estimates that the North American region would make up over 30 percent of the global satcom terminals market.

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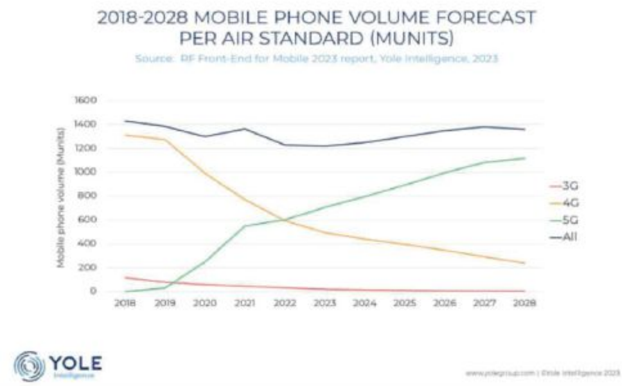
RF Front-End: At the Heart of the Turmoil?

In 2022, the smartphone industry was seriously impacted following a global macroeconomic downturn: a market decline with high inflation caused by geopolitical tensions such as the Russia-Ukraine war and tensions between China and Taiwan. This downturn resulted in consumer hesitancy in purchasing new phones, thus pushing OEMs to enter an inventory correction phase. In addition, the Zero-COVID policy in China further destabilized the smartphone manufacturing industry.

Yole Intelligence released its RF annual report, RF Front-End for Mobile 2023. With this report, the company aims to provide a comprehensive view of the RF front-end market from the system level down to the wafer level. It encompasses the ecosystem and technology landscape while providing insight to anticipate technology disruption.

The RF front-end market leaped forward in 2021, reaching over US$19 billion as an effect of the post-COVID-19 recovery and 5G penetration. But the 2022 calendar year ended flat following the smartphone market decline associated with lower-than-expected 5G penetration. Consequently, the BOM growth engine has been in low gear.



Mobile Phone Forecast (Source: Yole Group)

As per the moderate smartphone growth expected toward 2028, along with the limited potential for 5G penetration, Yole Intelligence forecasts a mid-single digit CAGR for the RF front-end market, which is expected to reach US$26.9 billion by 2028. Meanwhile, the market opportunity is huge, and new 5G technical features will keep driving RF front-end technology innovations. Mid- to long-term, there are developments in the pipeline and investments are being made to prepare for the next growth wave, which will emerge from 5G advanced and the forthcoming 6G.

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

MACOM Technology Solutions Holdings Inc. announced that it has acquired **Linearizer Communications Group**, a developer of industry-leading products located in Hamilton, N.J. Linearizer was founded in 1991 by Dr. Allen Katz and specializes in non-linear microwave predistortion for use in terrestrial, avionic and space-based applications and high performance microwave photonic solutions for use in the industrial and defense markets. The Linearizer team uses proprietary design and manufacturing techniques to produce its high performance components and subsystems. Linearizer has a long history of service to its loyal customer base, which is primarily in North America.

NI announced the acquisition of **SET GmbH**, longstanding experts in aerospace and defense test system development and recent innovators in power semiconductor reliability test. Together, the companies will reduce time to market for critical, highly differentiated solutions and accelerate semiconductor-to-transportation supply chain convergence with power electronic materials such as SiC and GaN. NI first announced a strategic minority investment in SET in 2020 to help aerospace and defense companies solve soaring development costs and integration challenges. The collaboration enhanced a system-on-demand and model-based test approach delivered to shorten time to market schedules, reduce program risk, integrate labs and optimize data and assets.

Infineon Technologies AG and **GaN Systems Inc.** announced that the companies have signed a definitive agreement under which Infineon will acquire GaN Systems for US$830 million. GaN Systems is a global technology leader in the development of GaN-based solutions for power conversion. The company is headquartered in Ottawa, Canada, and has more than 200 employees.

COLLABORATIONS

I-PEX and **Teramount Ltd** announced they are collaborating to advance Si photonics optical detachable connectivity for data centers and for other high speed datacom and telecom applications. The collaboration between I-PEX and Teramount will provide a breakthrough solution of detachable fiber to chip connectivity based on Teramount's self-aligning optics technology and I-PEX's ultra-precision plug and holder systems.

Anritsu Corp. announced a strategic partnership with **Spirent Communications** in Open RAN test solutions. This collaboration will play a key role in helping equipment vendors, carriers, system integrators, cloud service providers and others to configure an Open RAN ecosystem by measuring wireless RAN O-RU characteristics, fronthaul conformance tests and end-to-end tests connecting O-DU, O-CU and Core.

NEW STARTS

Copper Mountain Technologies' (CMT) Cyprus location is now offering repair and annual verification services for European CMT customers. CMT opened its European location in 2022 to house its R&D department and support production at the manufacturing facility in Israel. It is now expanding to include service capabilities. The company is focused on supporting engineers using CMT VNAs and offers a more convenient repair location to its current and future customers in Europe, the Middle East and Asia. Customers can now select their preferred CMT service location when filling out an RMA request on the CMT website. This new service capability is added to support the growing number of CMT customers and partners around the globe.

ACHIEVEMENTS

Maja Systems Inc. announced that the U.S. Patent and Trademark Office has issued a new patent No. 11,511,640 B1 (the '640 patent) adding to the company's intellectual property position and coverage for its products in multi-gigabit wireless data connectivity. The '640 patent titled "Vehicle to Infrastructure Autonomous Data Backhaul" further strengthens the company's intellectual property position for multi-gigabit wireless peer to peer data connectivity products.

CesiumAstro announced it has been awarded a contract through the Department of Defense's (DoD) Space Development Agency to advance the company's multi-beam L-Band active electronically scanned array (AESA) antenna. Building upon prior efforts, CesiumAstro will continue developing the Link 16–compatible AESA ahead of the agency's migration to the Proliferated Warfighter Space Architecture global satellite network, the low earth orbit-based satellite constellation built to enable key DoD space capabilities. Work will focus on optimizing the antenna to support U.S. and allied military forces' common operating picture across the global battlespace.

PEOPLE

▲ *Mike Winterling*

Junkosha has reported changes to its executive team to take the business forward. Changes to the international management line-up were triggered by the announcement of the planned retirement of **Joe Rowan** from the role of president and CEO of the U.S.-based subsidiary. Rowan will remain in an advisory role, stepping aside for **Mike Winterling** to take over as COO.

For More Information For up-to-date news briefs, visit mwjournal.com

Around the Circuit

▲ *Elif Balkas*

Wolfspeed Inc. announced the promotion of **Elif Balkas** to CTO, succeeding the late **Dr. John Palmour**, a co-founder of Wolfspeed. In her role as vice president of R&D in Wolfspeed's materials organization, Balkas shaped the company's technical strategy on wide bandgap materials and drove its development execution to maintain Wolfspeed's position as a leader in SiC for power and RF device applications. She has overseen multiple significant technology milestones during her tenure at the company, including the development of 150 mm and 200 mm boule growth systems and processes, the dramatic reduction in crystal defect levels that saw higher device yields and advancements in wafer processing.

▲ *Gilberto "Gil" Gonzalez*

Quantic Wenzel announced that **Gilberto "Gil" Gonzalez** has joined the company as the new director of engineering. Gonzalez has held multiple engineering and program management leadership roles, previously at BAE Systems, GE Aviation, MIT Lincoln Laboratory and Raytheon. Gonzalez holds an M.S. engineering, electrical engineering from Walden University and an M.B.A. from the Jack Welch Management Institute.

▲ *Geoffrey Key*

MegaPhase announced that **Geoffrey Key** has joined the company as vice president of sales. Key will lead the sales team, working closely with the company's worldwide network of sales representatives and the solutions team to support and expand the company's growth. Most recently, Key occupied the role of vice president of sales and marketing for Dynawave/Winchester Electronics, and has held leadership positions in sales and marketing for Phonon (acquired by Microsemi Corporation), Micro Networks/Integrated Device Technology, C&M Corporation, Volex, Burndy Corporation and Thomas and Betts.

▲ *Norm Hansen*

Stellant Systems Inc. announced the appointment of **Norm Hansen** to director of sales. In this capacity, Hansen is responsible for managing all sales activities across the entire Stellant enterprise. This includes managing customer and sales channel relationships, achieving order intake goals and helping to identify new growth opportunities and product strategies while maintaining overall successful customer relationships. In this role, Hansen will report to Steve Shpock, COO.

INVITED PAPER

GaN-Based Devices for Advanced RF Applications Puts Technology Building Blocks in the Spotlight

Bertrand Parvais and Hao Yu
imec, Leuven, Belgium

THE POTENTIAL OF GAN HEMTS FOR MMWAVE MOBILE COMMUNICATION

As the demand for bandwidth continues to grow and existing radio spectrum bands get congested, the telecom industry is looking for novel technologies to meet the requirements for future mobile communication. The quest for more bandwidth is inextricably linked with the use of higher radio frequencies and higher operating frequencies mean more available bandwidth. While researchers examine new III-V materials such as indium phosphide for frequencies above 100 GHz, they expect GaN-based technology to play a significant role in the lower mmWave part (i.e., below 50 GHz) of the RF spectrum. Because of this, GaN is expected to serve the next generation of 5G networks and possibly, early versions of 6G.

GAN ADVANTAGES

GaN technology owes its potential for RF/lower mmWave communication to its outstanding physical properties: it has high current density, high electron mobility and high breakdown voltage. The technology can handle switching frequencies higher than today's Si-based technology because of its high mobility. Beyond speed, GaN-based technology is touted for its power handling capabilities, which make it capable of delivering high output power with good energy efficiency. These features can make GaN an attractive technology to use in the power amplifiers (PAs) that reside in the front-end modules of next-generation mobile handsets and small cells. These front-end modules send the RF signals to and from the antennas. The higher power handling capabilities of GaN compared to conventional Si- or SiGe-based technologies translate into a higher transmission range and/or into a smaller number of elements needed to drive the antennas.

REDUCING FORM FACTOR AND COST: TOWARDS A VIABLE GAN-ON-SI TECHNOLOGY PLATFORM

To be suitable as a PA in user equipment and small cells, the cost and form factor of the device can become as important as its electrical properties. As stated before, GaN helps reduce the form factor of the front-end module thanks to the inherent properties of the technology. But achieving highly-scaled form factors requires integrating the miscellaneous components of the RF front-end technology. To help achieve this goal, imec is tuning its GaN-on-Si technology platform towards RF applications, as part of its Advanced RF program.

imec has selected GaN-on-Si rather than GaN-on-SiC for cost-saving reasons: not only are Si substrates cheaper, but the CMOS-compatible process also enables large-scale manufacturability. GaN-on-Si technology was initially developed for power electronics applications and envisioned to enable power conversion within battery chargers, computers, servers, automotive, lighting systems and photovoltaics. However, several technology innovations are required to make GaN-on-Si suitable for mobile RF applications. Parasitics within the device structures must be suppressed as much as possible to reach high frequencies. Examples of these efforts include reducing the source access resistance with methods like developing technology modules with raised source/drains and reducing gate-related parasitic capacitances. Optimizing the device for higher operating frequencies will also require a further downscaling of the gate length. This benefits a higher f_T and f_{max}, which is a measure of the intrinsic speed of the device. Furthermore, the buffer layer must be made RF-compatible

to minimize the RF substrate losses.

imec's GaN-on-Si process flow for RF starts with the metal-organic chemical vapor deposition growth of an epitaxial structure on 200 mm Si wafers. The epitaxial structure is comprised of a proprietary GaN/AlGaN buffer structure, a GaN channel, an AlN spacer and an AlGaN barrier. GaN HEMT devices with TiN Schottky metal gate are subsequently integrated with a low temperature three-level Cu back-end-of-line process as shown in ***Figure 1***. imec researchers used this CMOS-compatible platform to fabricate GaN HEMTs, as demonstrated at the 2020 International Electron Devices Meeting (IEDM 2020). Optimizations of the gate metal stack, contact resistance and gate length scaling up to 110 nm resulted in devices with an f_{max} of 135 GHz, which represents a step forward towards mmWave applications. Key figures of merit for PAs are the output power and the efficiency that the transistors can deliver. Competitive results are obtained on imec's GaN-on-Si platform, reaching a power-added efficiency (PAE) of 60 percent and a saturated power output (PSAT) of 2 W/mm for an 0.19 µm gate length (L_G) device at 6 GHz. These results, presented at European Microwave Week 2022, are shown in ***Figure 2a***. ***Figure 2b***, presented at IEDM 2022, benchmarks the performance of the imec GaN-on-Si process versus other GaN-on-Si and GaN-on-SiC processes. The imec data in red is among the best reported for GaN-on-Si devices and comparable to GaN-on-SiC devices. Using shorter gate lengths improves the measured performance at 28 GHz.

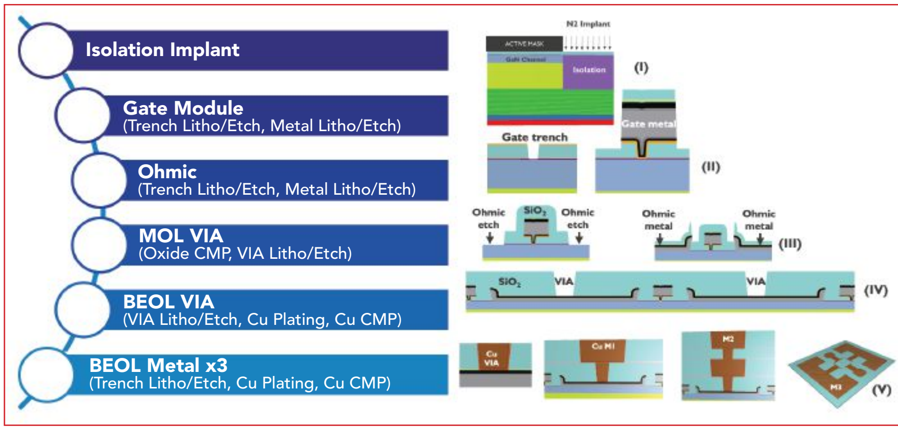


Fig. 1 Three-level Cu back-end-of-line process flow for GaN-based mmWave devices.

With these improvements, imec believes that the PAE of amplifiers designed to meet user equipment requirements and fabricated with a GaN-on-Si process achieve parity with equivalent GaN-on-SiC amplifiers for the first time.

Driven by the growth of the power electronics market in recent years, GaN-on-Si technology has become quite mature, mainly due to the development of technology that was initially intended for power electronics applications. Given the level of maturity, digging into the physics behind device operation provides an additional tool to improve the device characteristics. imec complements technology development with modeling activities that will ultimately help achieve better performance and reliability. The insights gained will not only benefit the development of GaN HEMT devices for mmWave applications, but they will also enable performance improvements in other application domains, including GaN-based power electronics.

DEVICE ISOLATION BY ION IMPLANTATION

As an example of these modeling activities, this section focuses on device isolation. This is one of the technology building blocks of the GaN-on-Si platform. When integrating GaN HEMTs in a common Si platform, the devices must be electrically isolated from each other, with as few leakage paths as possible between neighboring devices. This electrical isolation reduces power loss and improves the breakdown behavior of active devices. For GaN HEMTs, the ion implantation technique has already proven to be an attractive isolation approach over other isolation techniques, such as mesa etching, providing lower leakage and higher breakdown voltage of the isolation regions. The technique was initially developed for GaN-based power electronics applications, where it is still one of the isolation techniques actively being used today.

Ion implantation introduces several defects into the GaN hetero-

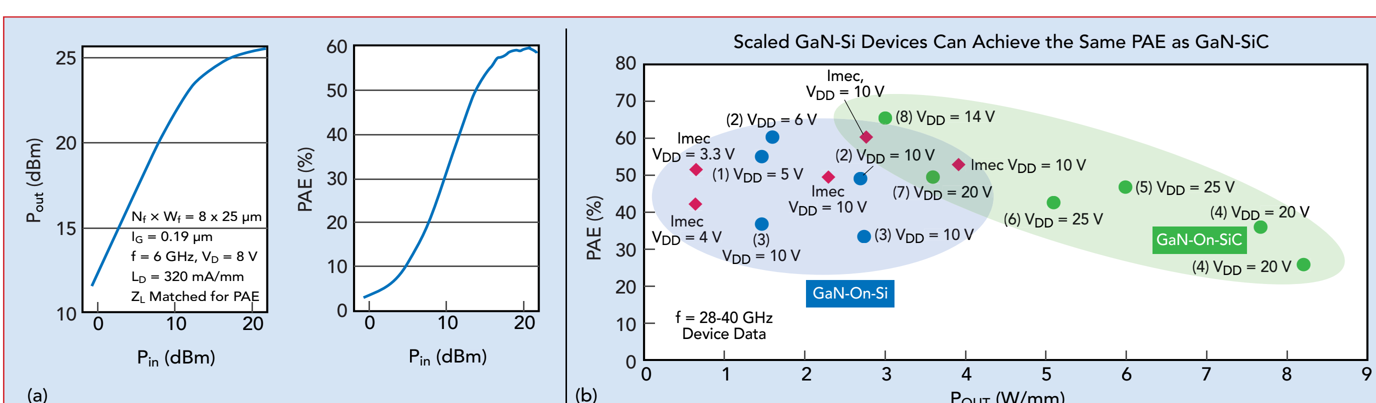


Fig. 2 (a) Large signal performance of imec's GaN-on-Si transistors. (b) GaN-on-Si benchmarking data.

structure that act as trapping centers for the charge carriers. In terms of physics, these defects pin the Fermi level away from the conduction or valence band of GaN. Implanting ions, such as nitride (N) ions, in the region surrounding the devices will reduce the number of conductive free carriers, creating an electrically insulating region. In experiments, researchers have also observed that the ion implantation-induced damages disappear after annealing at high temperatures, typically above 600°C, thereby compromising isolation quality. Featuring a low post-epitaxy thermal budget, imec's GaN-on-Si manufacturing flow guarantees high-quality isolation of HEMT devices. imec has already demonstrated a GaN HEMT ion implantation isolation technique that contributes to the highest reported sheet resistance, with values in the range of 10^{13} to 10^{15} Ω/sq. This is an essential metric for quantifying isolation. ***Figure 3a*** and ***Figure 3b*** illustrates benchmarks of the sheet resistance (R_{sh}) of AlGaN/(AlN)/GaN heterostructures subjected to ion implantation isolation with varying activation energy magnitudes and peak heating temperatures. The benchmark in Figure 3a suggests a common physical mechanism behind isolation, while the benchmark in Figure 3b indicates the dominant impact of processing temperature on isolation quality.

THE MECHANISM BEHIND ION IMPLANTATION ISOLATION: A FUNDAMENTAL INSIGHT

Why this technique works so well and precisely where the remaining current leakage path is formed has remained a mystery. A fundamental understanding and modeling of the leakage mechanism in ion-implanted regions is needed. This could help improve the process conditions such as thermal budget, implantation dose and energy for various applications, including mmWave communication.

There is a reason why it is so difficult to understand the exact mechanism behind the insulation. The ion-implanted region is full of defects of various natures. There are point defects, such as vacancies or interstitial atoms, defect complexes, foreign ion impurities and lattice disorder to name a few. In addition, polarization charges reside at the interface between AlGaN and GaN. This complex cocktail of defects and charges makes it highly challenging to simulate the behavior of the charges within the isolated heterostructure and to locate the leakage path.

By combining experimental and modeling work, imec researchers have unveiled the leakage mechanism in isolated GaN-based heterostructures for the first time. The details of this work have recently been published in the *Journal of Applied Physics*.[9] By setting up dedicated experiments with varying AlGaN and AlN thicknesses, researchers extracted and analyzed the sheet resistances of the isolated regions and the corresponding activation energies. The conclusion from these experiments was that the dominant leakage occurs via an ohmic path of electrons at the GaN surface. Revert to the terms of physics, this translates into a downward bending of the GaN conduction band near the GaN surface. These insights laid the foundation for more detailed modeling of the isolated heterostructure and for reconstruct-

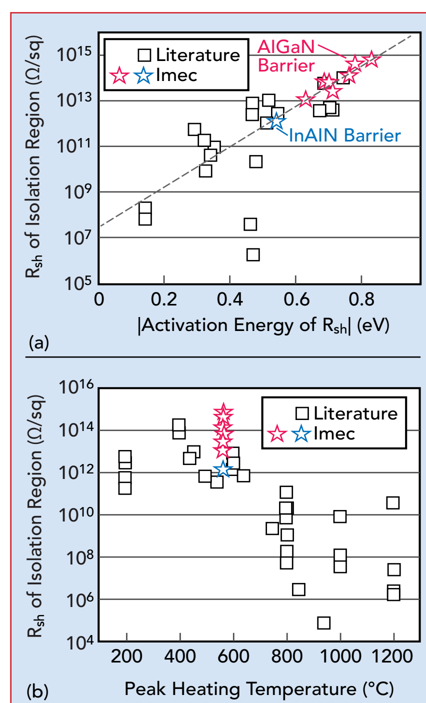


Fig. 3 **(a) Benchmark of sheet resistance versus activation energy magnitude. (b) Benchmark of sheet resistance versus peak heating temperature.**

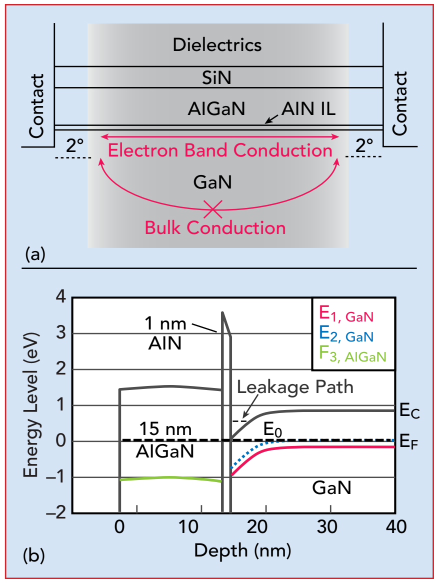


Fig. 4 **(a) Diagram illustrating surface and bulk leakage paths in transmission line model structures. (b) Energy band diagram of the AlGaN/AlN/GaN heterostructure showing band bending at the GaN surface.**

ing its energy band diagrams. The theory helped extract the net defect densities in these isolated implanted regions, which amounted to ~2×10^{19}cm^{-3} and ~2×10^{18}cm^{-3} for GaN and AlGaN, respectively for these experiments. The majority of those defects are found as point defects. The point defects were created by ion implantation techniques and preserved from recombination with imec's low thermal budget HEMT fabrication. The high densities of point defects are essential to limit the GaN surface energy band bending and thus limit the leakage. ***Figure 4a*** and ***Figure 4b*** illustrate the leakage mechanism in GaN heterostructures. Figure 4a shows the surface path leakage path versus bulk leakage path in transmission line model structures. Figure 4b illustrates the energy band diagram of the AlGaN/AlN/GaN heterostructure showing band bending at the GaN surface.

CONCLUSION

For the first time, imec researchers have unveiled the exact mechanism behind ion implantation as a technique for electrically isolating GaN HEMT devices. These insights help improve the process conditions to obtain good isolation quality when targeting RF/mmWave communication. The findings can be extended to power electronics applications as well. Moreover, the study led to a novel method to estimate the net defect density in isolated GaN-based heterostructures. These activities fit into the broader framework of GaN device optimization for RF applications through both technology and modeling. The efforts and the results illustrate how uncovering the physics secrets behind the technology building blocks can help take these GaN-based devices to the next level of maturity. ■

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INVITED PAPER

RF SOI Enables 5G mMIMO Active Antenna Systems

Payman Shanjani and Vikas Choudhary
pSemi Corporation, San Diego, Calif.

The superior performance of active/advanced antenna systems (AAS) compared to traditional passive antenna systems (PAS) is driving a transition towards AAS for base stations used in telecommunications applications. These AAS are composed of several to even hundreds of antenna elements that, depending on the design, require distinct RF signal chains to the antenna elements. This approach allows for MIMO and beamforming capability, but it also dramatically increases the antenna system complexity, though generally at lower RF power per signal chain. This changes the telecommunications RF front-end (RFFE) dynamic from a small number of very high-powered signal chain components to a multitude of lower-power components with different design criteria and considerations. The latest generation of RF silicon-on-insulator (SOI) component technology is well-suited to fill this new niche for telecommunications signal chain components for both sub-6 GHz and massive MIMO (mMIMO) transceivers.

TRANSITION TOWARD AAS

Traditional cellular mobile base stations are based on a homogenous cellular design with large base stations spaced sparsely to cover targeted regions. Covering these distances has traditionally required base stations to be located on large towers or the tops of tall buildings in more cluttered urban environments. Generally, the radio unit (RU) is in a location that is readily accessible to technicians with the antenna placed on top of the tower or edge of the building using a remote radio head (RRH) system. The RU routes antenna signals along lossy RF coaxial cables in a PAS.

This cellular model requires omnidirectional or directional antennas that radiate over a wide coverage area to serve as many users as possible. The amount of energy received by the user equipment (UE) is low when compared to the total radiated energy, resulting in low radiated energy efficiency. With only a single large transmitting antenna, the same signal must be sent to the entire coverage area. This scheme supports a limited number of simultaneous users from a given base station and is shown in the block diagram of ***Figure 1***.

This approach successfully served legacy devices and traditional use cases, but the number of mobile devices is growing. Growing numbers of devices and requirements for enhanced cellular performance are all factors driving the development of base stations using mMIMO antennas. These base stations are capable of supporting a significant number of UEs, but they necessitate a shift in architecture. As a result, there are significant ongoing development efforts aimed at MIMO and beamforming technologies to realize AAS.

The RF unit in an mMIMO AAS is located close to or integrated with the antenna. This makes the RF signal routing between the RU and antennas much shorter. The mMIMO arrays route transmit and receive signals to a large number of radiating elements. These antennas have at least one RFFE per group of antenna elements and may have one RFFE per antenna element. This architecture supports mMIMO access and beamforming, resulting in an antenna system with a controllable beam pattern that is compatible with spatial multiplexing. Spatial multiplexing allows for multiple simultaneous data streams between the base station and the UE to maximize capacity and coverage. The front-end of an mMIMO AAS is shown conceptually in ***Figure 2***.

These mMIMO AAS are much more compact than traditional base

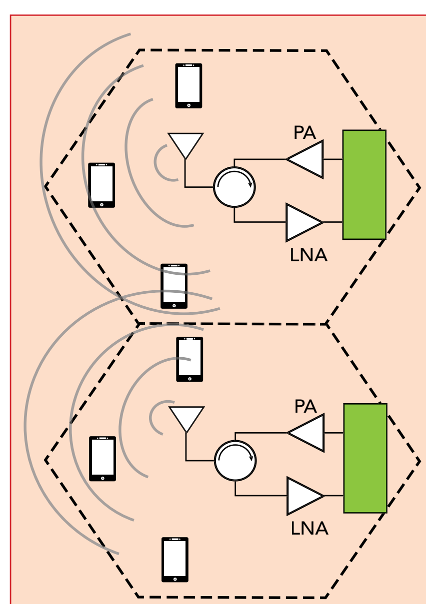

Fig. 1 Traditional microcell base station architecture.

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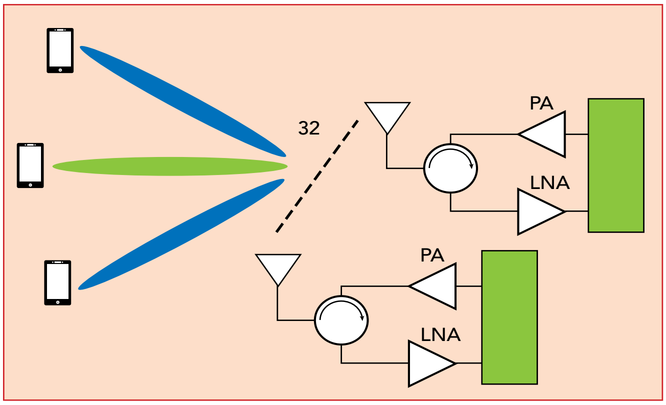

Fig. 2 **Front-end of 32-element mMIMO AAS base station.**

Macro	mMIMO	Small/Micro
• Area Coverage • Targeted Sectorizing • Rural Deployment • 4T4R-8T8R • TDD Focus • Existing Sites	• User Capacity • Urban, Semi-Urban • 32T32R (64T64R) • TDD Focus • New Sites	• User Experience • Dense Urban • 8T8R-16T16R • TDD Focus • Local New Sites

Fig. 3 **Base station differentiators.**

	Traditional	*Massive MIMO*
Number of Antennas	1-4	> 8
Throughput	✖	✔
Interference	✖	✔
Multi-User Capability	✖	✔
Sensitivity	✖	✔
Antenna Gain	✖	✔
Energy Efficiency	✖	✔
Scalability	✖	✔
Link Stability	✖	✔
Expense	✔	✖
Complexity	✔	✖
Antenna Coupling	✔	✖
Baseband Processing	✔	✖
Total Power Consumption	✔	✖
Area and Weight	✔	✖

Fig. 4 **Comparison of traditional and mMIMO antennas.** ***Source:*** **Yole Developpement, "5G's Impact on RF Front-End for Telecom Infrastructure 2021."**

stations, with a multitude of lower-power RF signal lines replacing a single large and less efficient signal path. The MIMO capability enhances radiated efficiency because beamforming architectures and mMIMO techniques enable more directional antenna patterns, concentrating the radiated energy from the base station toward the UE. ***Figure 3*** lists some of the features, advantages and use cases for different base station classifications.

Depending on the use case, MIMO and beamforming AAS can enhance the downlink and uplink signal strength and cell throughput by allocating multiple beams to one or more users. The highly directional beamforming antennas reduce transmitted and received interference. This can dramatically improve network performance within a cell and with adjacent cells, especially in interference-limited cell deployments. ***Figure 4*** compares the features and performance of traditional passive and mMIMO base station antennas.

Despite the performance benefits of AAS, there are trade-offs. The mMIMO AAS are much more complex with more internal components and routing considerations, which can make them more expensive. The enhanced performance requires more baseband and antenna processing capabilities, which can make an AAS architecture larger and heavier than traditional PAS architectures that cover the same frequencies.

Historically, wireless base stations have relied on RF transmit chains


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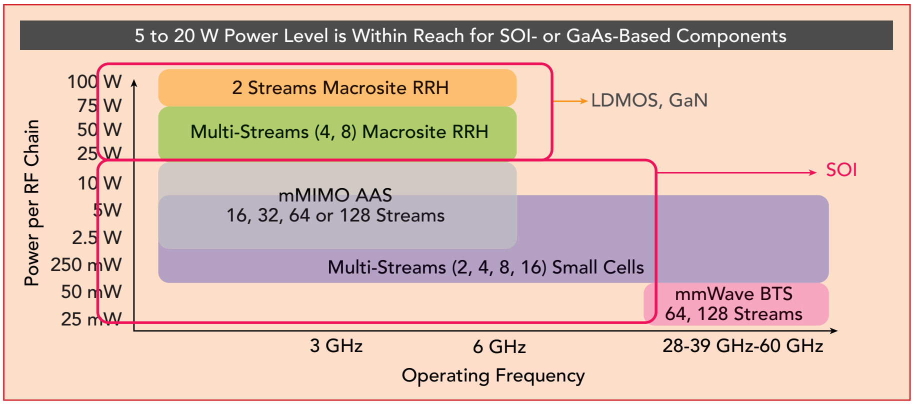

Fig. 5 RF power per chain versus operating frequency.

with output powers typically above 20 W. Power amplifiers (PAs) were fabricated with LDMOS, GaAs and more recently, GaN technologies. As higher-order AAS deploys, RF power levels per signal chain decrease and this opens opportunities for other semiconductor technologies. ***Figure 5*** shows RF power versus operating frequency for several base station configurations. The move toward mMIMO AAS is shifting the RF power market share away from LDMOS and GaN to lower-power technologies like SOI and

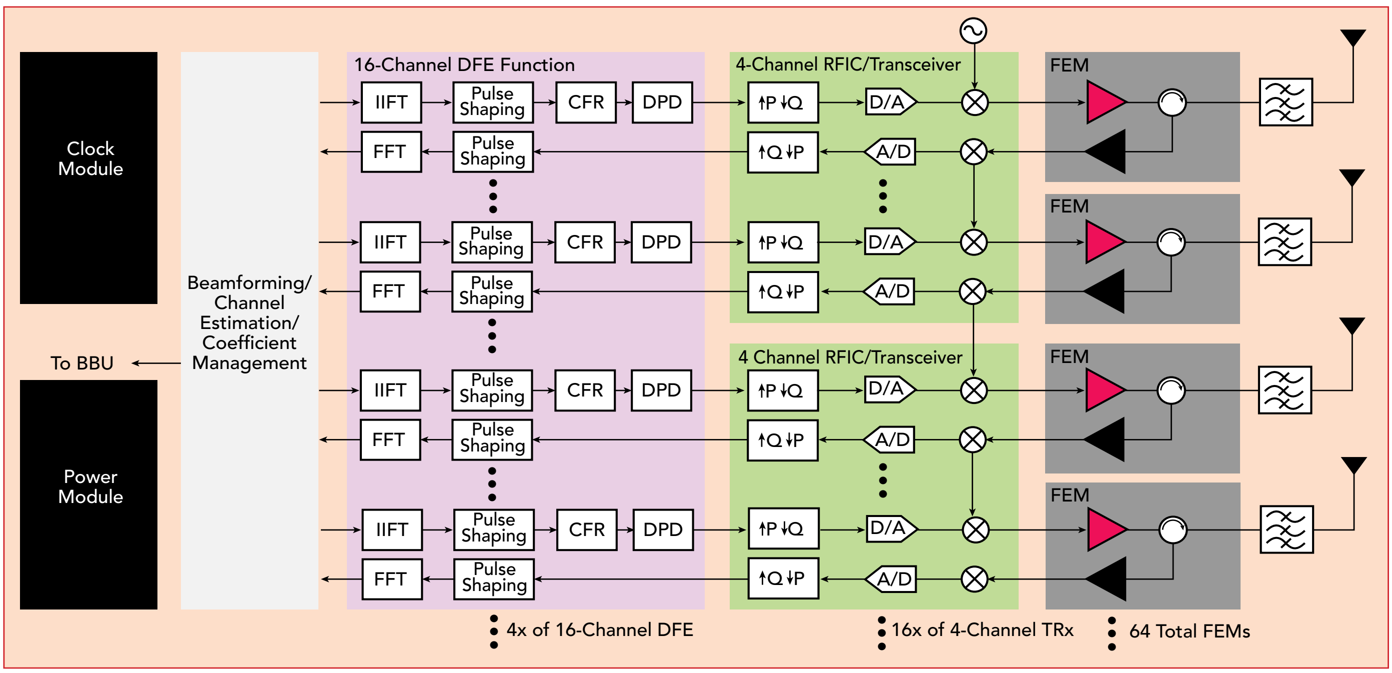

Fig. 6 64-channel MIMO RRU architecture.


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• 9.5 dB conversion loss
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• Supports 6-22 GHz RF/LO response
• 7.5 dB conversion loss
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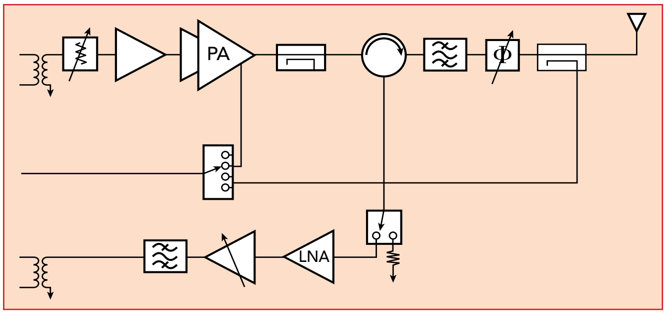


Fig. 7 **Front-end module architecture.**

GaAs. These opportunities arise as the industry appears to be converging on 32T32R and 64T64R as the wireless infrastructure architecture as shown in ***Figure 6***. ***Figure 7*** shows more detail on the front-end module (FEM) and we see the need for switches, amplifiers, attenuators and phase shifters.

AAS HERALD SOI OPPORTUNITIES

As wireless infrastructure architectures move toward mMIMO in AAS, RF designers face challenges designing, developing and fabricating RF components and antenna systems. mMIMO AAS contain more components and they are more complex to meet increasing performance demands, but subscriber revenue growth has been sluggish. Operators are struggling to maximize their return on investment and this places substantial price pressure on system and component OEMs.

There are other ramifications. The RF power per transceiver is lower, but there are many more transceivers, which require more digital baseband processing, and this increases power consumption, footprint and weight. This has direct implications for operating expense and size, pressuring RF component manufacturers to develop more efficient and more highly integrated solutions. These factors are making SOI technology a more compelling solution for wireless infrastructure applications.

RF SOI PRIMER & ADVANTAGES

SOI technology involves fabricating silicon semiconductor devices in a layered silicon insulator-silicon-substrate. This approach improves performance by reducing parasitic capacitance within the device and to the substrate. SOI technology enjoys higher isolation, linearity, transit frequency and lower loss passive devices compared to silicon. SOI technology uses a process similar to bulk CMOS, benefiting from larger wafer sizes and well-established fabrication verticals. Despite using a silicon process, SOI transistors are not susceptible to latch-up like silicon transistors.

Stacking also increases the power handling capability of SOI technology. Transistor stacking increases the maximum voltage a process can handle by "floating" a series of transistors, each with a limited maximum voltage handling capability. Ideally, the maximum voltage of a stack of transistors would be the maximum voltage of each transistor times the number of stacked transistors, allowing virtually any maximum voltage. However, the parasitic capacitance to the substrate (Csub) with stacked transistors degrades the overall power handling of the stack. The higher the Csub, relative to the gate-drain capacitance (Cgd) and the gate-source capacitance (Cgs), the more the stacking performance degrades. Fortunately, the very low Csub of SOI technology enables very efficient stacking compared to other technologies.

SOI OPPORTUNITIES IN SUB-6 GHZ 5G BASE STATIONS

Figure 8 shows the typical performance requirements of an RRH base station in a sub-6 GHz AAS base station. The lineup highlights the typical semiconductor technology for each function. Assuming a typical receiver IC input and transmitter IC output power of 0 dBm and average radiated output power at the antenna of 320 W, or 55 dBm, limits the range of preferred technologies. LDMOS devices in a Doherty amplifier topology exhibiting a peak-to-average power ratio of 10 dB are the preferred final-stage solution for the amplifier. The peak output power of the PA will be at least 65 dBm and the gain of this stage is likely to be relatively low to support the high power level. Multiple gain stages are used to produce the required output power since each stage will have limited gain. Given the cascade requirements, the transmit (Tx) gain block is the only candidate for SOI technology. In this analysis, GaAs amplifiers support the driver stages to the output PA. A coupler at the PA output provides feedback for the digital predistortion (DPD) circuitry that enhances transmitter linearity and efficiency. This topology has a circulator at the antenna port to route the Tx and receive (Rx) signals and a receiver protection circuit, typically a high-power, non-SOI PIN diode, at the receiver low-noise amplifier (LNA) input. The Rx signal chain uses GaAs LNAs and gain blocks for the noise figure (NF) performance of that technology.

While the RRH block diagram did not have many opportunities for

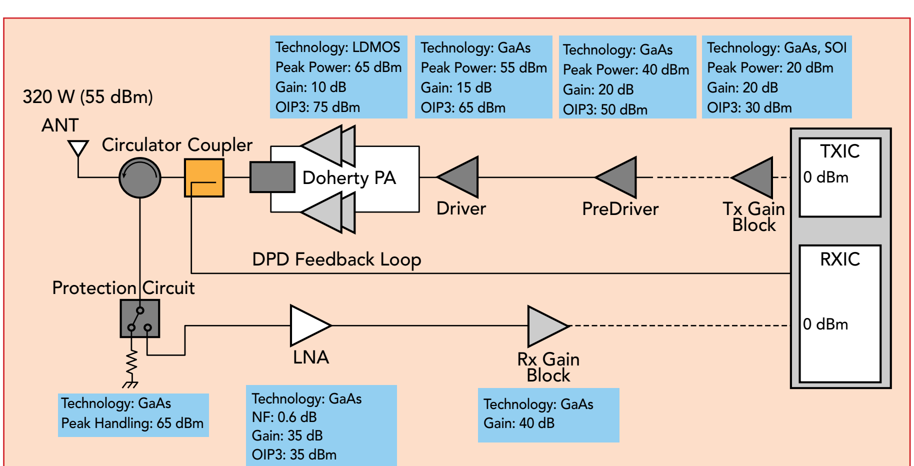


Fig. 8 **RRH RF lineup.**

SOI technology, the mMIMO AAS lineup shown in ***Figure 9*** does. The radiated power from each antenna in this example is 10 W, but the total radiated power remains the same as in the earlier example. With peak PA output power at 50 dBm, the output stage can be GaN or GaAs technology with higher gain. An SOI digital step attenuator (DSA) may be used after an SOI Tx gain block for beam adjustment. Multiple transceivers means multiple PA output couplers for DPD feedback and these couplers can feed an array of SOI SP4T switches. With lower power in each transceiver, the Rx signal chain protection circuit can be realized with SOI. A GaAs LNA is still desirable for low NF performance, but SOI can be used for the level-controlling Rx gain block and DSA at the receiver input. SOI switched-filter banks may be used at the transceiver input to enhance selectivity and output performance. SOI exhibits high power handling, high isolation and excellent linearity performance, making it

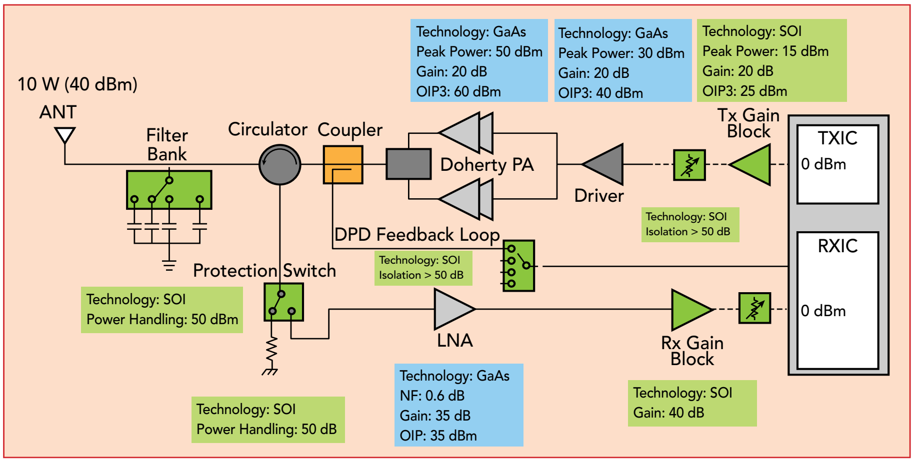
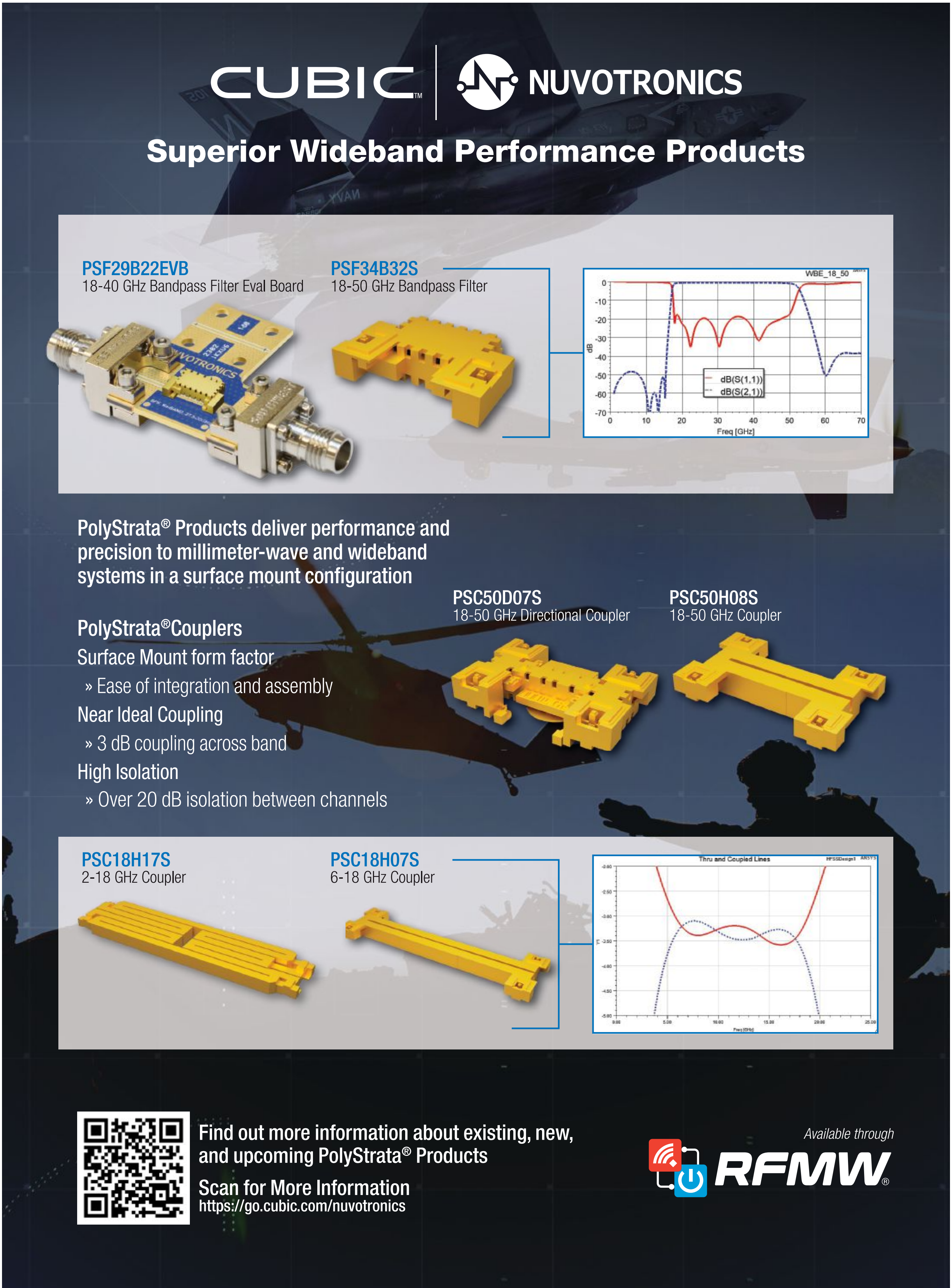


Fig. 9 **32T32R AAS base station RF lineup. *Source:* "Massive MIMO, mmWave and mmWave-Massive MIMO Communications: Performance Assessment with Beamforming Techniques" Tewelgn Kebede Engda, et al.**

TABLE 1: ADVANTAGES OF BEAMFORMING TECHNIQUES

Features	***Beamforming Types***		
	Analog Beamforming	***Digital Precoding***	***Hybrid Precoding***
Number of Streams	Single stream	Multi-stream	Multi-stream
Number of Users	Single user	Multi-user	Multi-user
Signal Control Capability	Phase control only	Phase and amplitude control	Phase and amplitude control
Degree of Freedom	Least	Highest	Intermediate
Implementation	Phase shifters	ADC/DAC, mixer	Phase shifter, ADC/DAC and mixer
Hardware	Least	Highest	Intermediate
Energy Consumption	Least	Highest	Intermediate
Cost	Least	Highest	Intermediate
Complexity	Least	Highest	Intermediate
Performance	Least	Optimal	Near optimal


CUBIC
NUVOTRONICS
Superior Wideband Performance Products
PSF29B22EVB
18-40 GHz Bandpass Filter Eval Board
PSF34B32S
18-50 GHz Bandpass Filter
WBE_18_50
dB(S(1,1))
dB(S(2,1))
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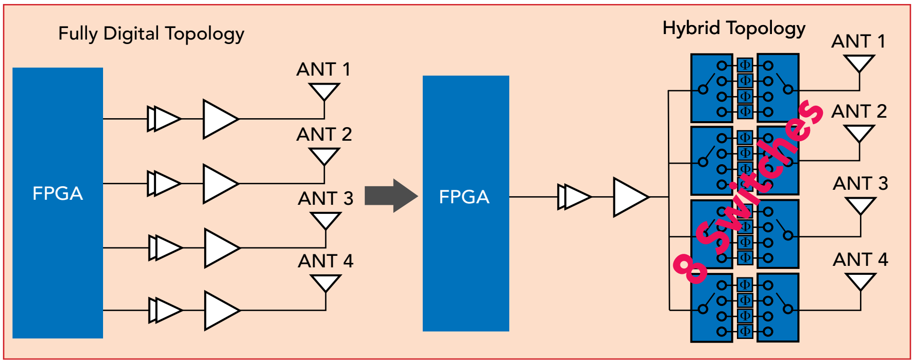

Fig. 10 Comparison of digital and hybrid beamformer topologies.

particularly well-suited for switching applications. Unlike the RRH example, mMIMO AAS base station configurations will present many RFFE SOI opportunities and these are shown in green in Figure 9.

SOI OPPORTUNITIES FOR 5G BEAMFORMERS

Beamforming is essential for high gain and directivity in mMIMO antenna arrays. The three primary beamforming techniques are analog, digital and hybrid. A digital beamformer processes each RF stream in digital blocks, with a dedicated conversion block per line. An analog beamformer processes a single stream in the baseband, with beamforming accomplished with attenuators and phase shifters at the antenna elements. A hybrid beamformer groups antenna elements into blocks and assigns a digital stream to each block. In this scheme, each element has an analog phase shifter and attenuator. Each beamforming topology has advantages and trade-offs as shown in ***Table 1***.

A digital beamformer offers the highest degree of flexibility, data throughput and coverage since each RF transceiver has a dedicated stream that is processed simultaneously. This requires an enormous amount of processing and a dedicated RF connection to each antenna element. An analog beamformer has the least complexity and power consumption, but it sacrifices flexibility and capability. A hybrid beamformer represents a compromise between the flexibility and performance of a digital beamformer and the simplicity and lower power consumption of an analog beamformer. ***Figure 10*** compares a digital beamformer with a hybrid beamformer, with both having four RF lines. The hybrid beamformer in this example has one digital data stream that is distributed to the antenna elements through four phase shifters and eight switches. This architecture consumes roughly one-quarter the power of an equivalent digital beamformer. The hybrid solution is likely to be smaller, weigh less and have a lower cost than a digital beamforming solution. The disadvantage of this approach is only one independent data stream versus four streams in the digital beamformer.

CONCLUSION

5G mMIMO base station deployment is ramping up and operators and equipment manufacturers are moving away from the legacy components and designs of earlier cellular telecommunication generations. New mMIMO architectures require dramatically different components than legacy base stations and this necessitates an evolution of the wireless technology. The new base stations have many more RF lines, with each line requiring lower RF transmit power. As 5G mMIMO system requirements evolve, OEMs and RF component vendors will collaborate to develop and optimize performance to achieve better power efficiency, size, weight and cost. These efforts will likely require greater levels of integration and fit nicely with the advantages of SOI technologies, setting the stage for an increase in the market share for SOI-based components in wireless base station applications. ■

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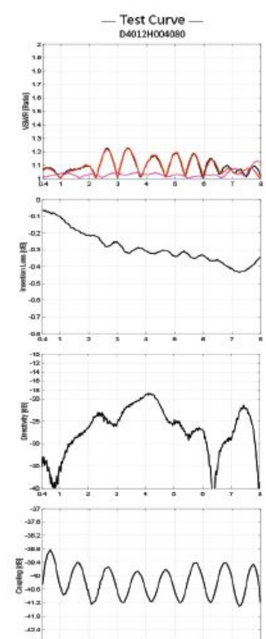
P/N	CW Power Max.(W)	Nominal Coupling (dB)	Main Line VSWR	Coupling VSWR	Insertion Loss*	Coupling	Flatness	Directivity Min.(dB)
			Max.(:1)		Max.(dB)			
0.4-8GHz Directional Coupler								
D3002H004080	120	30	1.3	1.3	0.8	30±1.0	±0.8	18
D4002H004080	120	40	1.3	1.3	0.8	40±1.0	±0.8	18
D3005H004080	250	30	1.4	1.4	0.7	30±0.9	±1.3	14
D4005H004080	250	40	1.4	1.4	0.7	40±1.0	±1.4	14
D3008H004080	400	30	1.4	1.4	0.7	30±0.9	±1.3	14
D4008H004080	400	40	1.4	1.4	0.7	40±1.0	±1.4	14
D3012H004080	600	30	1.4	1.4	0.7	30±0.9	±1.3	14
D4012H004080	600	40	1.4	1.4	0.7	40±1.0	±1.4	14
0.4-8GHz Dual-Directional Coupler								
D3002HB004080	120	30	1.3	1.3	0.8	30±1.0	±1.0	18
D4002HB004080	120	40	1.3	1.3	0.8	40±1.0	±1.0	18
D3005HB004080	250	30	1.4	1.4	0.7	30±0.9	±1.5	14
D4005HB004080	250	40	1.4	1.4	0.7	40±1.0	±1.6	14
D3008HB004080	400	30	1.4	1.4	0.7	30±0.9	±1.5	14
D4008HB004080	400	40	1.4	1.4	0.7	40±1.0	±1.6	14
D3012HB004080	600	30	1.4	1.4	0.7	30±0.9	±1.5	14
D4012HB004080	600	40	1.4	1.4	0.7	40±1.0	±1.6	14

*Theoretical I.L. Included



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INVITED PAPER

The Importance of Crystal Oscillators With Low Phase Noise

Julian Emmerich and Harald Rudolph
KVG Quartz Crystal Technology GmbH, Neckarbischofsheim, Germany

In most areas of our daily lives, data collection and processing, along with large parts of the critical infrastructure have been digitized. Common to all of these efforts is the need for highly accurate reference clocks. Often, crystal oscillators of various designs are used as frequency-determining components. These devices range from simple, unregulated crystal oscillators (XO/VCXOs) to temperature-compensated oscillators (TCXOs) and heated crystal oscillators (OCXOs). One of the most important quality criteria for high performance is the frequency stability of the quartz oscillators. Frequency stability on short time scales can be described by the three quantities: phase noise, jitter and short-term stability. A comprehensive compilation of these three measurement quantities and their interrelationships was published in the January 2023 issue of *Microwave Journal*.

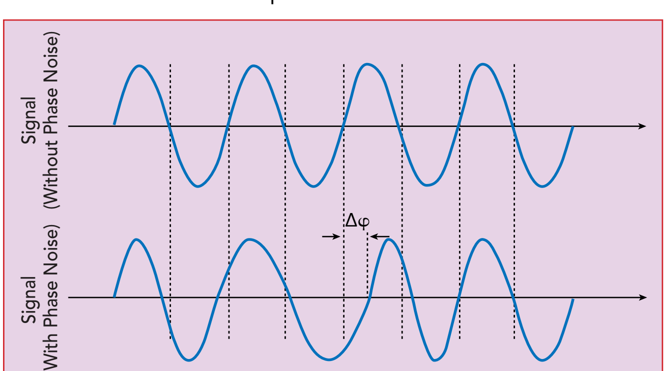

Fig. 1 **Random, time-dependent phase error (Δφ) in the sinusoidal signal.**

After a short overview of important terms, this article will address the applications of high precision quartz oscillators. Case studies from the fields of measurement technology, data transmission, navigation, radar technology and the processing of audio signals will be considered in detail. In addition to the necessity of extremely low phase noise, the effects of poor phase noise performance are explained for the individual areas.

PHASE NOISE BASICS

Noise effects in electrical circuits are a ubiquitous phenomenon that can be attributed to various physical causes. The noise near the carrier is largely determined by the quality of the oscillator crystal, which acts as a narrowband filter in the range of the resonant frequency in the oscillator circuit. ***Figure 1*** shows the short-term frequency instabilities that show up in the time domain as a deviation of the zero crossings (phase position) of the actual signal waveform compared to the ideal sinusoid. A modulation of the amplitude is not shown in this figure.

The most important parameters describing phase fluctuations are the phase noise, L(f), the jitter, ΔT(Δf) and the short time stability, $\sqrt{\sigma_y^2(\tau)}$. ***Figure 2*** shows the phase noise plots of a good TCXO and a very good ultra-low phase noise (ULPN) OCXO from KVG Quartz Crystal Technology. "Good" 10 MHz

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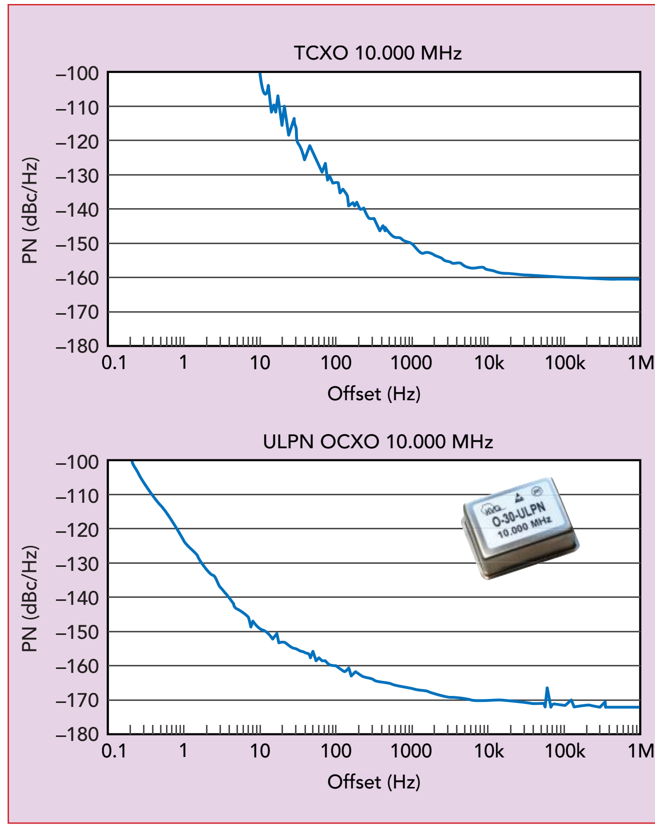
The short-term stability, mostly expressed in the form of the "Allan Variance" or "Allan Deviation" (ADEV), is much better for good OCXOs than for good TCXOs. "Good" 10 MHz TCXOs have an ADEV in the range of 2×10^{-10} to 2×10^{-11} for a τ of 1 sec. "Good" 10 MHz OCXOs have an ADEV of 2×10^{-12} to 2×10^{-13}, which is about two decades better.

MEASUREMENT TECHNOLOGY APPLICATIONS

Especially in the high frequency range, measurement technology relies on the fact that a signal to be measured is converted to a different and usually lower frequency by mixing with another signal. Low frequency signals are generally easier to analyze and fixed frequency filters and amplifiers can be used to measure the device. The signal to be measured is mixed down to the required frequency range using a local oscillator inside the device.

Figure 3a shows the basic principle of signal mixing in simplified form. In the mixer element, the input signal f_{in} is mixed with the signal of a local oscillator f_{LO}, forming a superposition of the difference signal, $|f_{LO}-f_{in}|$ and the sum signal, $f_{in}+f_{LO}$. If the local oscillator has a phase noise that cannot be neglected, this noise characteristic



▲ Fig. 2 **Phase noise diagrams for a KVG Quartz Crystal Technology TCXO and an ultra-low phase noise OCXO.**

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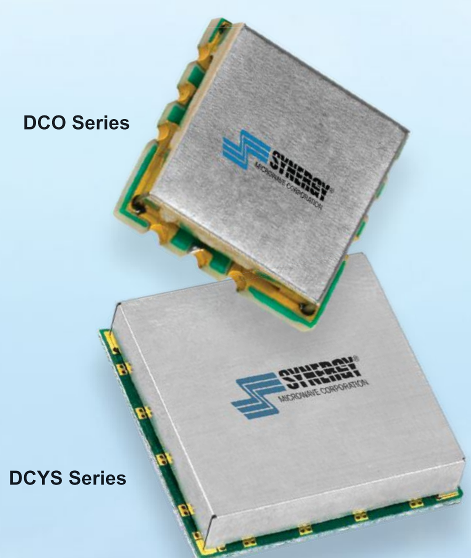
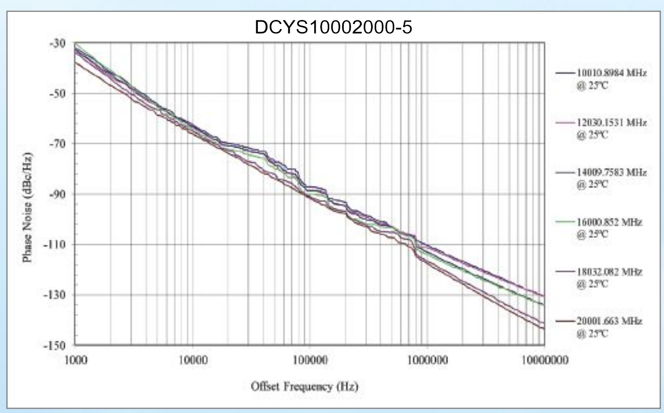
Model Number	Frequency	Phase Noise @ 10 kHz offset	Phase Noise @ 100 kHz offset	Tuning Voltage	Output Power
	(GHz)	(dBc/Hz)	(dBc/Hz)	(V)	(dBm Min.)
DCO100200-5	1 - 2	-95	-117	0.5 - 24	+1
DCYS100200-12	1 - 2	-105	-125	0.5 - 28	+4
DCO200400-5	2 - 4	-90	-110	0.5 - 18	-2
DCYS200400P-5	2 - 4	-93	-115	0.5 - 18	0
DCO300600-5	3 - 6	-78	-104	0.3 - 16	-3
DCYS300600P-5	3 - 6	-78	-109	0.1 - 16	+2
DCO400800-5	4 - 8	-75	-98	0.3 - 15	-4
DCO5001000-5	5 - 10	-70	-95	0.3 - 18	-4
DCYS6001200-5	6 -12	-70	-94	0.5 - 15	+2
DCYS8001600-5	8 - 16	-68	-93	0.5 - 15	-1
DCYS10002000-5	10 - 20	-53	-79	0.5 - 15	-4





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- *> Small Size Surface Mount Package*
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is also imposed on the mixed signals. As shown in ***Figure 3b***, two input signals close to each other are to be analyzed. If the local oscillator signal has a large noise contribution, the smaller input signal disappears almost completely after mixing with the noise of the spectrally broadened stronger signal.

High performance measuring instruments are also used to determine the phase noise of an external signal source. The simplest measurement method is to use a spectrum analyzer since it is a standard measurement device in most electronic laboratories. As long as the phase noise of the spectrum analyzer's internal oscillator is significantly lower than the signal to be measured, a measurement can be performed relatively easily. If the internal oscillator has a comparable or worse noise characteristic than the test object, the effects of signal mixing described above mean that the measurement results are limited by the phase noise of the internal oscillator and may be biased. Only internal reference oscillators with extremely low phase noise must be used in high performance measurement equipment.

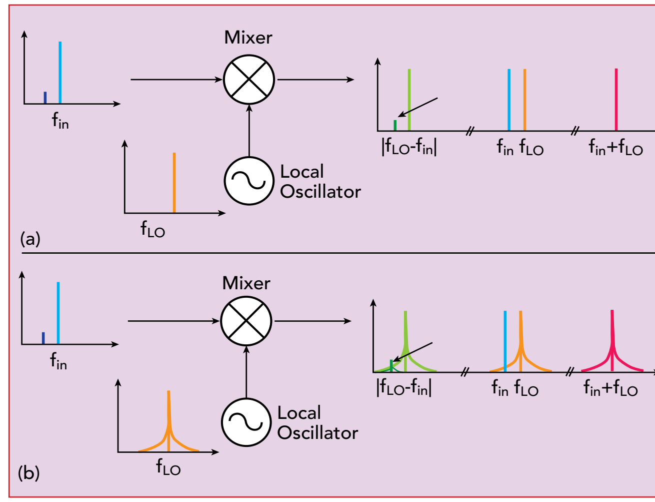


Fig. 3 **(a) Principle of signal mixing in a network analyzer. (b) Effects of mixing an input signal with a noisy LO signal.** ***Source:*** **Revised with permission from Rohde & Schwarz.**

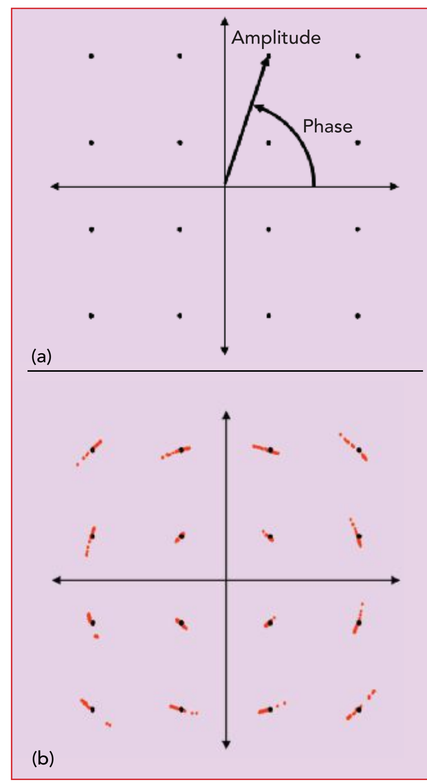


Fig. 4 **(a) 16-QAM constellation diagram. (b) Blurring of constellation diagram from phase noise.** ***Source:*** **Revised with permission from Rohde & Schwarz.**

DIGITAL COMMUNICATIONS APPLICATIONS

Analog data transmission has traditionally used amplitude modulation or frequency/phase modulation. Digital data transmission requires far more sophisticated modulation methods to maximize error-free data transmission over the available bandwidth. Current modulation methods for the transmission of digital, discrete signals use a combination of amplitude and phase modulation, with the two degrees of freedom increasing the data transmission rate. Examples of this are amplitude phase shift keying (APSK) or quadrature amplitude modulation (QAM).

Figure 4a shows a constellation diagram for a carrier with 16-QAM modulation. The chart shows 16 different states, with each being described by a unique pair of values consisting of amplitude and a phase angle relative to the coordinate origin. In this modulation variant, phase noise causes a rotation of the


SM4234
SM4477

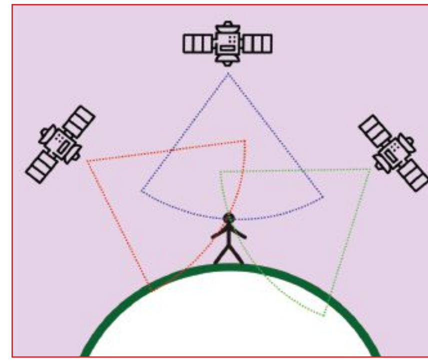
entire constellation diagram, with higher values of phase noise causing a larger rotation of the points. This is seen in ***Figure 4b*** as a blurring of the exact states of Figure 4a. If this rotation is severe enough, states can be misidentified, leading to bit errors and higher bit error rates. The bit error rate can be reduced by using stable oscillators. Digital communications networks requiring the highest performance will use rubidium or cesium standards or global navigation satellite systems (GNSS)-locked OCXOs. If slightly less performance is acceptable, OCXOs with extremely low phase noise is the likely choice.

NAVIGATION APPLICATIONS

A variety of GNSS are used to determine positions on land and in the atmosphere. Well-known examples of these systems are the Global Positioning System (GPS) in the U.S. and the Galileo system in the E.U. Both systems are available for military and civilian use, although the civilian systems have lower accuracy.

The position is determined by measuring the signal propagation time of a high frequency signal from the satellites to the corresponding receiver. Comparing the transit time differences from at least three satellites allows the exact horizontal position to be calculated. Velocity data is calculated from the frequency shift caused by the Doppler effect of the satellite moving relative to the receiver. This technique requires extremely accurate clocks in the satellites and the GNSS receivers for precise time/frequency measurement. In the satellites, this is realized via cesium/rubidium atomic clocks (GPS) or via hydrogen maser clocks (Galileo), which are regularly calibrated via ground stations distributed worldwide.

Portable GNSS receivers must also incorporate extremely accurate clocks with excellent short-term stability/phase noise. If the receiver clock matches the reference clocks of the satellites exactly, the position can be determined with only three satellite signals. This concept is shown in ***Figure 5***. In practice, the data from at least four satellites are required to compensate for the time offset caused by the poor long-term stability of the receiver clocks.



▲ Fig. 5 **Determining position using a GNSS system.**

The resolution accuracy of a GNSS receiver is directly related to the noise performance of its internal time reference. Portable receivers for the mass market usually contain only simple XOs or TCXOs for generating the reference frequency, which can result in resolution accuracies in the range of several tens of meters. Professional GNSS receivers work with highly stable OCXOs, which can reduce the error in determining the position to a few centimeters due to the high short-term stability of these OCXOs.

RADAR TECHNOLOGY APPLICATIONS

Depending on the particular area of application, signals with frequencies up to 300 GHz are required for location and speed determination using radar technology. In current systems, the signal is generated by a voltage-controlled oscillator (VCO), which usually has poor frequency stability. To stabilize the signal, the VCO is connected to an extremely stable reference oscillator via a phase-locked loop (PLL). The overall performance of the system, especially the phase noise, is largely determined by the selection of the reference oscillator. In this case, the preference is to design this oscillator as an ultra-low phase noise OCXO.

Using a PLL ensures that the phase noise close to the carrier is determined by the noise of the reference oscillator. Above a certain frequency offset, which is determined by the loop bandwidth of the PLL, the phase noise of the high frequency oscillator dominates. This effect is shown in ***Figure 6***, where up to an offset frequency of 100 kHz the

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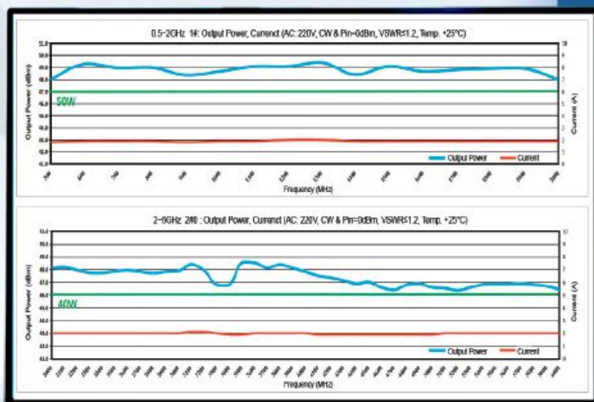

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phase noise is significantly reduced by the use of the reference oscillator, compared to the free-running VCO.

Using the Doppler effect, radar technology can determine the velocity of a moving object from the frequency shift. In a simplified model of a CW radar, a signal of fixed frequency is emitted in the direction of the object to be measured. The electromagnetic wave is reflected by the measured object and travels back to the receiver of the radar unit. Depending on the target's motion relative to the receiver, the frequency of the received signal changes. ***Figure 7a*** shows the basic Doppler effect concept.

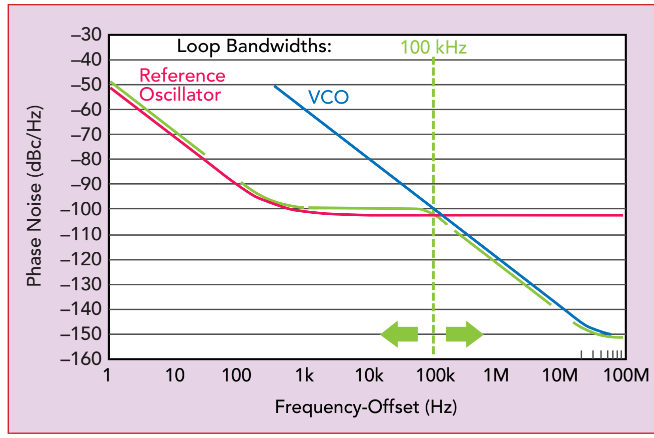


Fig. 6 **Phase noise improvement using a reference oscillator. *Source:* Revised with permission from Rohde & Schwarz.**

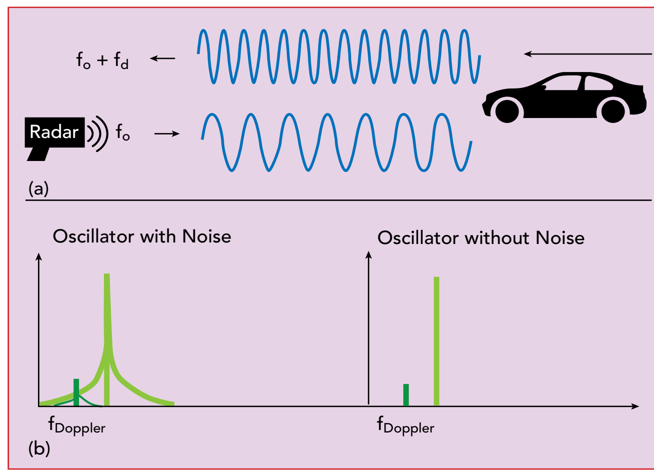


Fig. 7 **(a) A radar signal experiences a frequency shift from a moving object. (b) A noisy carrier signal can mask the Doppler-shifted reflected signal.**

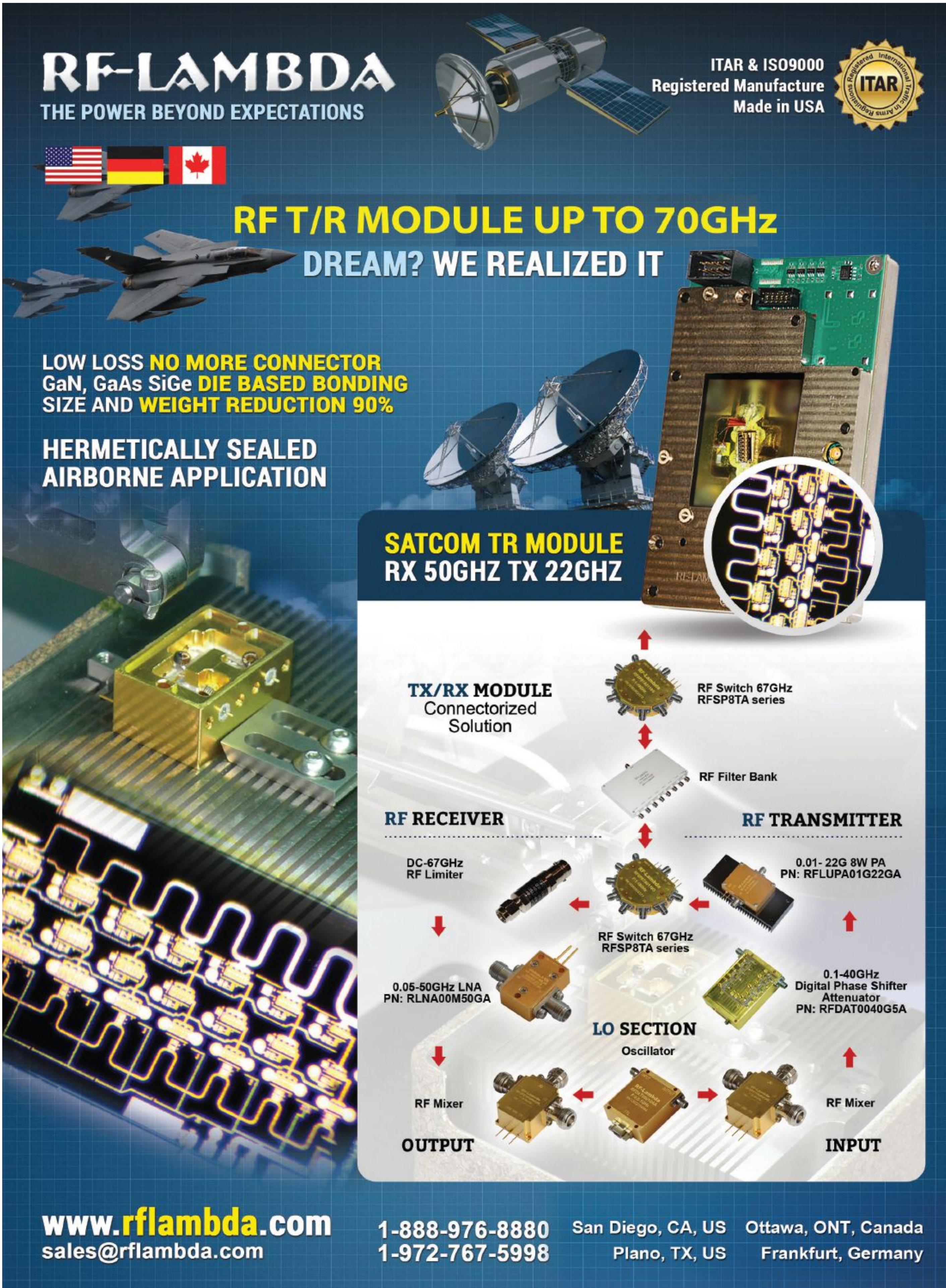
An issue arises if the resulting frequency difference is so small at low velocities that it cannot be measured relative to a noisy carrier frequency as shown in ***Figure 7b***. A frequency source with lower phase noise allows for a more accurate velocity determination. For a radar source with a carrier frequency of 1 GHz, an object moving at a speed of 1 km/h produces a Doppler shift of about 1.9 Hz.

AUDIO PROCESSING APPLICATIONS

Sound is a time-dependent, analog mixture of acoustic waves of different frequencies. Audio signals are degraded during analog processing because of noise in components like cables or analog amplifiers. Digital processing of audio signals overcomes some of these limitations. In this process, the analog signal is converted to a digital signal by an analog-to-digital converter (ADC) before it is digitally processed and converted back to an analog signal by a digital-to-analog converter (DAC). After this conversion, the analog signal is routed to an audio source, like a loudspeaker.

The conversion to the digital audio signal in the ADC takes place at a digital clock rate called the sample frequency f_S, which is usually 44.1 or 48 kHz. According to the Nyquist theorem, these sample frequencies are suitable for digitizing analog signals up to 22.05 or 24 kHz. The sample frequency is usually provided by an internal oscillator called the master clock, which typically oscillates at a multiple of the sample frequency.

The challenge in digitization, especially in the playback of audio signals, is to use a master clock that is as accurate as possible with the lowest possible phase noise. ***Figure 8*** illus-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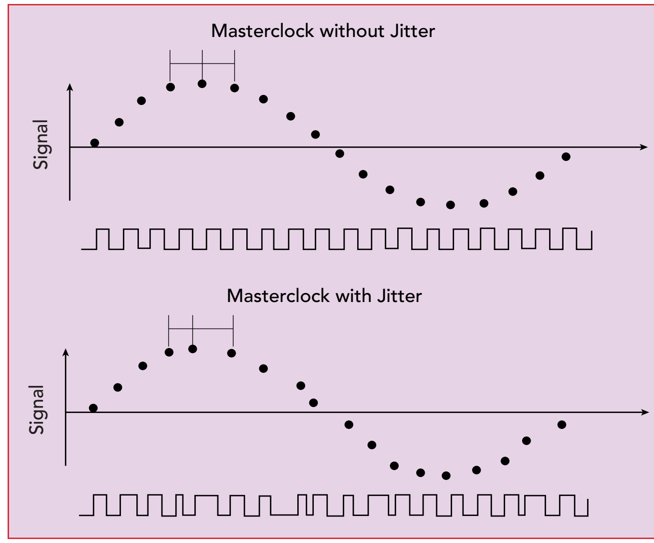

Fig. 8 **Effects of master clock jitter on signal sampling.**

trates the problem of a noisy master clock. During digitization, an accurate master clock ensures exactly equidistant sampling of the analog signal in the ADC, which ensures a faithful reproduction of the input signal at the output. If the master clock is not exactly periodic, this jitter influences the signal sampling. When the sampled signal is converted in the DAC, the result is a distorted output signal that does not faithfully reproduce the input signal and this affects the sound quality at the output.

Low-cost consumer products tend to use low-cost oscillators as the master clock. These oscillators typically have high values for jitter and the sound quality suffers. Professional high performance playback devices for digitally recorded music rely on crystal oscillators with extremely low phase noise to perfect the sound experience in conjunction with high-quality amplifiers and speaker systems.

CONCLUSION

High precision frequency sources, such as quartz oscillators with extremely low noise characteristics have become the undisputed standard for electronics in the 21st century. Measurement, data transmission, navigation and audio applications all place the highest demands on the signal sources. While all these applications rely on high performance signal sources, the most important parameters may be different. In telecommunications, the jitter value is important because it can be used to derive the bit error rate during data transmission. In metrology, phase noise is important with oscillators often characterized by a phase noise curve. Depending on the application, near-carrier or far-carrier phase noise may be more relevant, so phase noise values are specified at different distances from the carrier signal. Navigation applications benefit greatly from extremely stable reference clocks. If uncontrolled deviations in the time reference occur at the GNSS receiver, the accuracy of the position determination can deteriorate by one to two orders of magnitude. These and other examples show the importance of highly stable oscillators in a wide variety of applications. ■

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Using Drones to Verify Antenna Performance

QuadSAT
Odense N, Denmark

Satellite communication plays a key role in meeting the relentless demand for connectivity in society. Our industry is seeing a game-changing deployment of infrastructure on the ground and in space, driving the need to maximize the use of the finite radio spectrum. The more efficient we are, the more users will benefit.

QuadSAT has developed a technology to ensure efficient and reliable use of the radio spectrum, allowing satellite operators to deliver more services to more customers while maintaining high quality and availability. This development results from a new method of testing and verifying satellite ground station antennas and RF equipment using drones. By pairing a drone-mounted RF payload with unique pre- and post-flight software, ground station and user terminal satellite antennas can be tested throughout their lifecycle.

The technology was initially offered as a service, which made it possible to bring solutions and perform verification missions for satellite companies. This also provided the opportunity to test the capabilities in operational environments, allowing QuadSAT to hone the product, which is now available both as a product to customers with high testing demands or service providers and as a service for those users where that is preferable. The goal of this product evolution is to make testing more accurate, accessible and cost-effective for global users.

DRONE-BASED ANTENNA TESTING

Using drones for antenna testing and measurement introduces new capabilities and removes a large amount of complexity normally

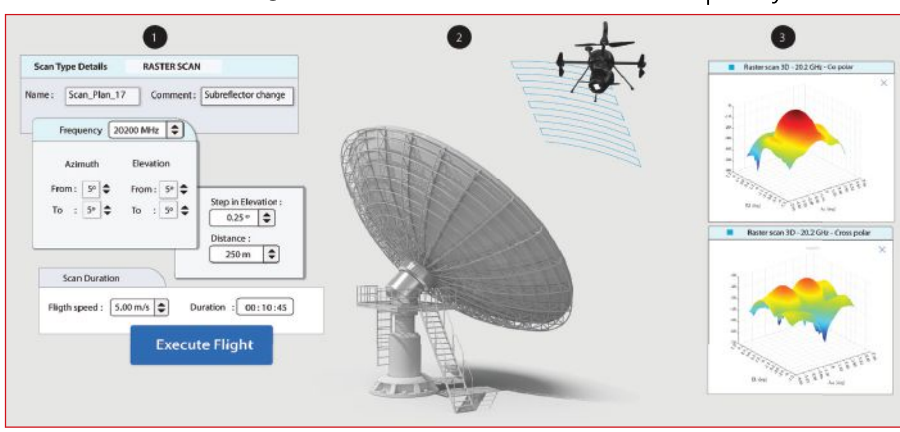

Fig. 1 Raster scan process diagram.

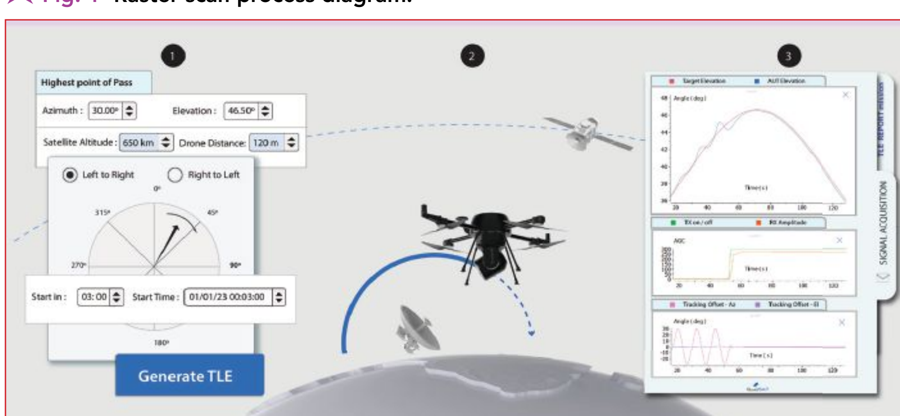

Fig. 2 Antenna tracking verification process diagram.

associated with this testing. The measurement system can be taken to the site while ensuring a level of accuracy comparable to traditional measurement methods. These tests are fully automated, flexible and location-independent. The system already supports a wide range of measurements critical for ground station equipment, with more features and capabilities in development.

Raster Scans

Measuring the radiation pattern is a fundamental feature of the system and this capability has been used on nearly all our missions. Determining an antenna's performance requires knowledge of the radiation pattern. Without this knowledge, comparing performance between antennas and identifying issues becomes very difficult.

Raster scans are a way of measuring the radiation diagram on a 3D plane and compared to a single cut it provides much more information about the antenna properties. Their application includes:

- Capturing the radiation diagram of the antenna and painting a clear picture of the main beam and sidelobes
- Determining the state of the antenna performance, i.e., checking for problems with focus, misalignment or manufacturing tolerances
- Measuring and calibrating the pointing mechanism of the antenna
- Tracking changes in the antenna diagram between equipment modifications.

To perform the measurement, the operator plans a flight path for the drone by specifying the width of measurement in azimuth and elevation, as well as the granularity of the measurement lines. The drone flies autonomously on the path and maintains constant pointing and polarization alignment with the antenna under test (AUT). The result is generated by merging the measured amplitude levels with the computed angular position of the drone compared to the AUT. The data points are interpolated and presented in a heatmap or 3D diagram. This process takes around 15 minutes of flight time, with the result generated almost immediately. These results then enable users to:

- Apply contours and determine the 3 dB beamwidth
- Compute beam center
- Verify levels against regulatory masks
- Compare results between measurements
- Extrapolate cuts for regions of interest.

Figure 1 shows an excerpt of the graphical user interface, a representation of the drone flight path, along with a sample output for a representative raster scan for a co-polar and cross-polar measurement. QuadSAT has performed measurements at frequencies from C-Band to Ka-Band for antenna sizes ranging from 40 cm to 17 m and distances from 50 m to 12 km.

Antenna Tracking Verification

Since medium earth orbit (MEO) and low earth orbit (LEO) satellites move relative to Earth, antennas must be able to accurately track the satellite. The rise of new MEO and LEO constellations introduces unknown complexities and being able to quickly evaluate and verify antennas and algorithms can prove to be mission-critical. Identifying potential system issues promptly can help avoid costly delays.

The drone introduces the possibility of simulating satellite passes in real-time, from any direction and at any peak angle. This enables the user to holistically test and verify the tracking and pointing performance of LEO/MEO ground segment antennas, gateways and user terminals. The system can perform make-before-break and handover procedures, along with simulating multiple-beam tracking. It can also simulate real-life scenarios of loss and re-acquisition, launch and early operations or tracking with minimum power levels, sudden changes in frequency, amplitude, modulation type, trajectory, etc. and provide results as well as key performance indicators useful in evaluating the state of the system under test.

To activate this capability, the user locks a precise measurement reference system where the test will be performed. The passes are generated on demand based on peak azimuth and elevation and desired orbital parameters of the satellite. The output, in either TLE or ECEF format, is uploaded into the antenna and the angles and received signal levels are recorded during the pass. A single flight can contain up to four passes and the full-duplex functionality enables the drone to fully simulate a satellite transponder by receiving and storing I/Q data, as well as replaying or transmitting a modulated carrier back to the system under test. The data can be used to perform a calculation of tracking offsets as well as an assessment of the link quality and system reaction in various simulated events. A diagram of this process is shown in ***Figure 2***.

Other Measurements

Besides the measurement techniques described, several other measurements are possible. These include wide radiation cuts, absolute gain, cross-polarization discrimination and axial ratio, as well as environment reflectivity analysis and holistic pointing offset assessment. QuadSAT is constantly upgrading the feature list, working in close cooperation with customers to provide the best solutions.

SUMMARY

QuadSAT has developed this technology to make it cost-effective to test ground station antennas throughout their lifecycle of prototyping, qualification, factory acceptance testing, site acceptance testing, calibration and troubleshooting post-deployment. By expanding the service delivery approach to include licensing partners globally, any user can get antenna measurements cost-effectively and responsively, avoiding months of waiting time.

QuadSAT
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One Box Solution for FR1 Base Station, Small Cell and RF Component Test

Rohde & Schwarz
Munich, Germany

Rohde & Schwarz has introduced the new R&S PVT360A performance vector tester to address high speed, high-throughput testing of all forms of 5G frequency range 1 (FR1) base stations, along with RF component characterization and production testing. The compact single-box instrument provides excellent signal generation performance and analysis capabilities in a small footprint. The R&S PVT360A supports demanding test requirements where minimal error vector magnitude (EVM) is required while accommodating high test throughput. The optional second generator and analyzer support multiport tests, true MIMO testing or simply double the test capacity.

Fig. 1 **Graphical user interface of the PVT360A.**

VSG/VSA SINGLE-BOX TESTER

The R&S PVT360A performance vector tester meets the increasingly demanding requirements for 5G New Radio (NR) FR1 base station and small cell tests, which have resulted from the evolution of the original 3GPP Release 15 specification to Releases 16 and 17. ***Figure 1*** shows an analysis of a 5G NR signal using the R&S VSE signal analysis software. The instrument's 400 MHz to 8 GHz frequency range covers all 5G FR1 requirements, along with unlicensed frequency bands up to 7.125 GHz in the U.S. The 500 MHz maximum signal bandwidth far exceeds the 5G FR1 maximum of 100 MHz, supporting out-of-band and adjacent channel leakage ratio measurements.

For maximum test throughput, two independent signal generators and analyzers enable fast parallel measurements, with each channel supporting eight parallel full-duplex test ports. For each channel, the output test signal can be broadcast to all eight ports. Input ports are switched in less than 10 microseconds for sequential analysis of either parallel or multiport devices. Transmit-

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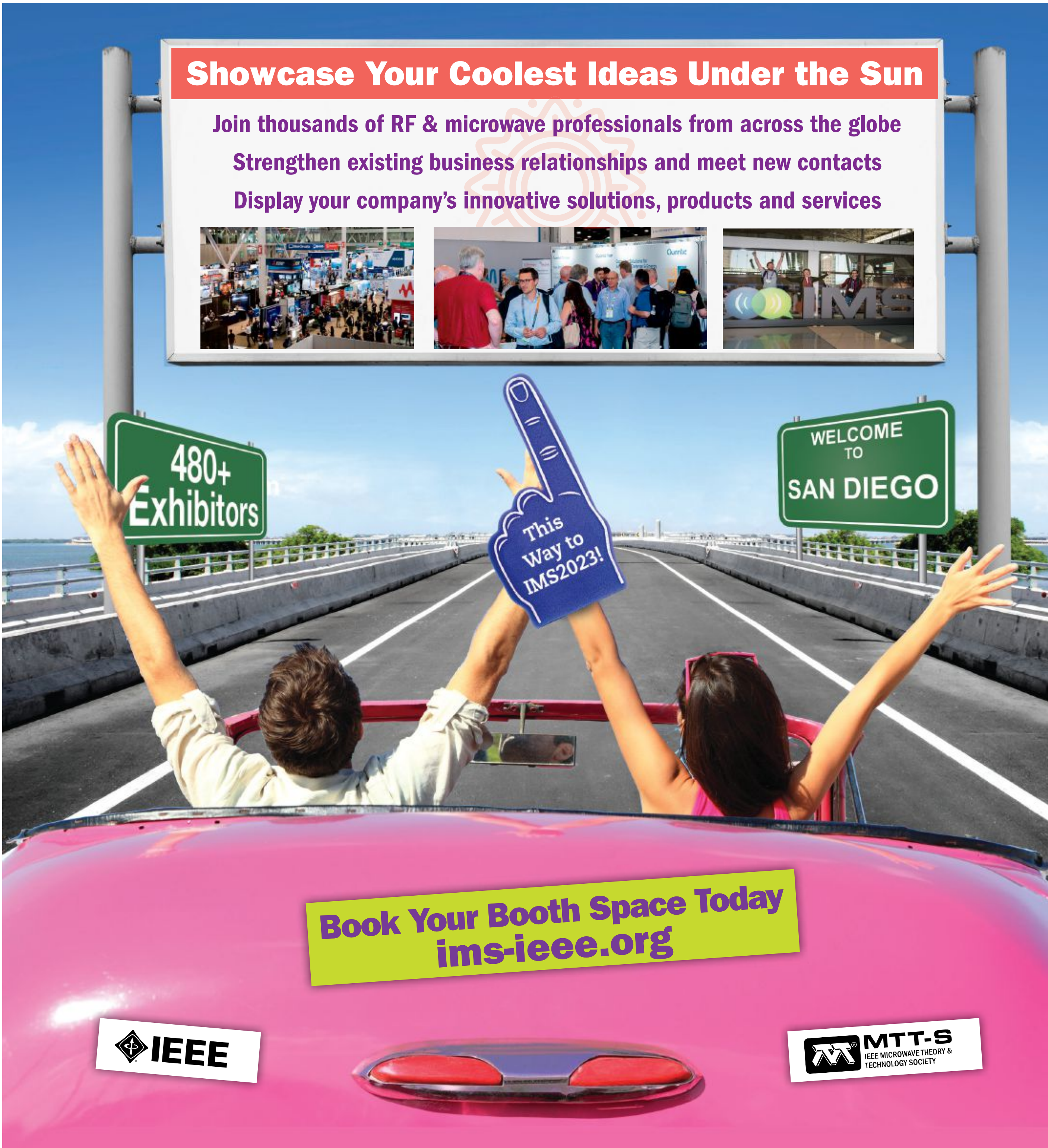

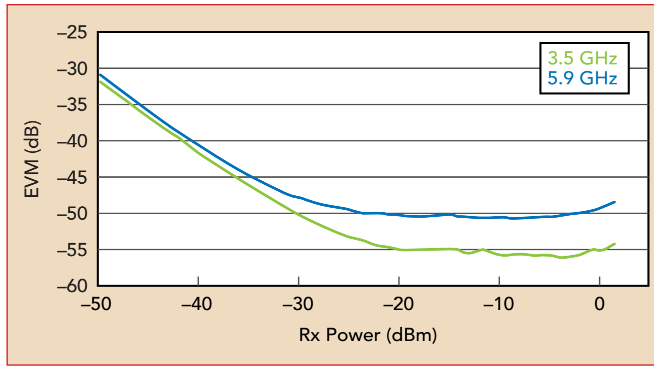

▲ Fig. 2 Measured EVM of a 5G NR downlink TM 3.1 100 MHz signal.

▲ Fig. 3 R&S PVT360A in a component test setup.

ter and receiver tests can be carried out in parallel and the R&S PVT360A optimizes test sequences to minimize idle time between result processing. With the second channel installed, users can run true MIMO 2×2 tests with the signal paths tested in parallel, not sequentially. The optional smart channel mode divides the R&S PVT360A into a maximum of eight separate virtual instruments. Each of these virtual instruments has an independent VISA address and a separate tab in the GUI, allowing different measurements on each channel. The generator and analyzer are shared across the virtual instruments, with optimized resource scheduling for all calculations and processing.

BASE STATION AND SMALL CELL TEST

For most production test requirements, standard-compliant waveforms for 5G NR release 15, 16 and 17 support all typical base station transmitter and receiver tests such as EVM, output power or frequency error. The R&S PVT360A achieves EVM results as shown in ***Figure 2***. The measurements can be operated fully in parallel for up to two transmitter tests. If a higher number of devices under test or ports are connected, the tests run in quasi-parallel with automated scheduling of resources. Multi-component carriers can be tested and the optional two pairs of vector signal generators and analyzers enable real MIMO measurements. The graphical representation of the measurement results gives a comprehensive overview of the signal characteristics. The second signal generator benefits users performing receiver tests. Wanted and interfering signals for in-band blocking and in-channel selectivity tests can be generated, as required, in one box.

COMPONENT TEST AND IN-DEPTH CHARACTERIZATION

For active component testing as shown in ***Figure***

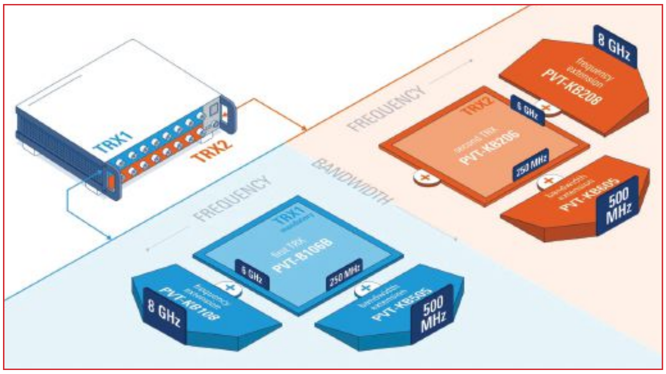

Fig. 4 Keycode options for hardware extensions.

3, the R&S PVT360A provides signal generation and analysis capabilities for both cellular and WLAN standards. When testing components with modulated signals, their characteristics can be validated under realistic conditions. Good EVM performance of the R&S PVT360A signal generator provides high precision test signals that create minimal measurement uncertainty in component characterization applications, providing developers with the highest possible performance. If additional signals are required, customized waveforms may be created using WinIQSIM2, a PC-based waveform creation program. For additional analysis, the R&S VSE vector signal explorer PC-based signal analyzer software can be utilized.

Measurements performed during the characterization phase can be stripped down and carried out on the box for fast production testing of key parameters. The results can then be correlated with more extensive tests performed during the characterization phase. The hardware-accelerated list mode provides outstanding measurement speed and automation options in production.

ENHANCED TESTING IN PRODUCTION ENVIRONMENTS

Designed for remote operation, the R&S PVT360A performance vector tester offers automated capabilities for easy integration into testbeds. Preconfigured test routines consistent with 3GPP requirements simplify the test process. The intuitive web user interface gives an overview of all signal generation and measurement parameters and capabilities for manual configuration.

To cover the full range of requirements in the extremely price-sensitive production test market with a single instrument, the R&S PVT360A option concept uses a single generator and analyzer to support eight test ports with frequencies ranging from 400 MHz to 6 GHz and a bandwidth of 250 MHz. In the complete twin-channel configuration, each port has a frequency range of 400 MHz to 8 GHz with a 500 MHz bandwidth. As illustrated in ***Figure 4***, all extensions are by keycode and they can be installed instantly. The new R&S PVT360A performance vector tester is now available from Rohde & Schwarz.

VENDOR**VIEW**

Rohde & Schwarz
Munich, Germany
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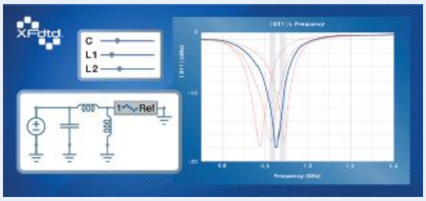

XFdtd® Software Update Introduces Tuning Functionality for Comprehensive Matching Network Design

The latest version of XFdtd® 3D Electromagnetic Simulation Software introduces matching network tuning, which enables users to easily adjust component values to meet design goals and understand the behavior of a circuit. The tuning functionality is part of a new analysis workbench in XFdtd's schematic editor, broadening the software's toolset for comprehensive matching network design. The workbench's intuitive sliders enable rapid manipulation of inductor and capacitor values to reveal the impact of various combinations in real time. This immediacy makes additional analysis effortless while resulting in a more thorough understanding of how the circuit will behave. Intermediate states may be saved without changing the base schematic; final states can then be added to a new operating mode or committed to the schematic permanently.

In addition to simplifying the process of identifying a favorable match that meets or exceeds performance requirements, the tuning functionality is valuable for analyzing the matching network's sensitivity to component tolerance. Use cases include fixed band matching for devices that use a single band as well as tunable matching for devices that must switch between bands.

VENDORVIEW

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VNA Provides Component Analysis up to 26.5 GHz

The continuous growth of radio and cellular networks means increases in data traffic and data rates, driving the need for high performance measurement technology. Analyzing and verifying components and the network are important tasks during the development phase. High frequency vector network analyzers (VNAs) are the key measuring device for this work.

The SNA5000A Series VNAs can analyze 2-port devices up to 26.5 GHz and 4-port devices up to 8.5 GHz. All single-ended and differential S-parameter measurements are available by pressing a button. The 125 dB dynamic range allows, for example, a precise analysis of the stopband of a filter without losing sight of the passband. The flexible multi-window function combined with a 12-in. touchscreen enables a concise representation of all results on one screen. Bias tee inputs simplify the setup to characterize devices that need DC-bias voltage.

The SNA500A series also includes multiple options for key applications. An optional scalar mixer measurement (SMM) mode makes analyzing frequency conversion devices like mixers easy and fast. The analyzer series offers enhanced time-domain analysis as an option to further increase this flexibility. This mode allows an eye diagram to be displayed and it supports jitter performance measurements. This option makes the analyzer well-suited for cable and connector performance characterization measurements. The SNA5000A series can also be equipped with a spectrum analysis mode, which can be used in parallel on every port. The advanced and intuitive user interface and versatile capabilities make the SNA5000A a great choice for every bench while its solid RF performance, ease of use and convenient size make it great for everyday RF testing.

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Infineon Kicks Off Smart Power Fab in Dresden

Infineon is starting construction of its new plant for analog/mixed-signal technologies and power semiconductors. After extensive analysis, Infineon decided on the Dresden site, with completion set for 2026.

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Poster: How High Precision GNSS Enables New Automotive Applications

This poster shows the different types of error sources and explains how high precision GNSS calculates and transmits error correction data to vehicles, enabling new automotive applications for GNSS.

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Reflective Switch Gates G-Band Signals

VENDORVIEW

Model SKS-1442243035-0505-R1-M is a single pole, single throw (SPST) reflective switch that operates from 140 to 220 GHz. The switch exhibits insertion loss of 3 dB in the ON state with typical isolation of 35 dB in the OFF state. In-line WR-05 waveguide ports have UG-387/U-M anti-cocking flanges. An SMA connector accepts the TTL-level control signal. The switching speed is 100 ns. Bias voltages of +1 and -2 V are required. The switch measures 1.0 × 1.0 × 0.75 in.

Eravant
www.eravant.com

S-Band Diplexer

VENDORVIEW

Exceed Microwave's custom designed S-Band diplexer provides high isolation of > 120 dB with low insertion loss of < 0.3 dB. It uses dual mode resonators for low insertion loss and sharp near-band rejection. The transmit channel is designed to handle 10 kW minimum. Custom designed filters and other passive RF/microwave components are available.

Exceed Microwave
www.exceedmicrowave.com

Common Mode Choke Inductors

Vanguard Electronics, under the iNRCORE family of brands, announced its new XTCMN5 Series common mode choke inductors. The XTCMN5 Series is designed to operate in extreme environments and work in frequency ranges from 100 to 600 KHz+, making them ideal parts for GaN-based power supplies as well as traditional switching supplies. These parts feature a compact low profile, ideal for automatic placement as well as demands of high shock and vibration. Different electrical values and termination finishes are available.

iNRCORE
www.inrcore.com

mmWave Controlled Components

General Microwave offers a wide range of mmWave products operating in the 18 to 40 GHz frequency range including catalog attenuators, switches and phase shifters as well as integrated microwave assemblies. If it is a standard catalog unit or a highly customized mmWave product designed specifically for high performance, General Microwave can provide products to support your requirements.

Kratos/General Microwave Corp.
wwwkratosmed.com

USB SP4T Switch

VENDORVIEW

Mini-Circuits' model USB-1SP4T-A673 single pole, four throw (SP4T) absorptive switch steers 0.1 to 67 GHz with 2 ms switching speed. Typical insertion loss is 5.8 dB to 40 GHz and 9.8 dB to 67 GHz. Isolation between ports is typically 35 dB to 60 GHz and 30 dB to 67 GHz. Featuring USB port, 1.85-mm female connectors and integrated microcontroller, the switch measures just 4.874 × 0.984 in. (123.8 × 25.0 mm) and can handle as much as +22 dBm input power.

Mini-Circuits
www.minicircuits.com

New Bias Tees

VENDORVIEW

Pasternack has introduced an innovative series of bias tees addressing a variety of applications, including test and measurement, research and development, optical communications, satcom and more. Pasternack's expanded bias tee offering includes various design configurations that cover a broad range of frequencies from 12 KHz to 40 GHz, high DC current and voltage handling up to 7 amps and 100 V, and high port isolation of 30 dB typical. A variety of coaxial packaged configurations are available.

Pasternack
www.pasternack.com

Switch Filter Banks

Switch filter banks are readily customized for filters centered between 0.5 and 18 GHz, with bandwidth from 1 to 100 percent. Digital control can be configured to use TTL or COMS logic with inputs provided through a variety of methods including a micro-D connector or hermetic pins. Typical design considerations include minimizing package size, switching speed, video leakage, phase noise, impulse response, high power and high isolation. Our modules are packaged in a rugged housing with hermetical seals and internal potting in order to provide high-reliability in difficult environments. Applications include military radio, radar, SIGINT, electronic warfare and satcom.

Q Microwave
www.qmicrowave.com

High-Power, High Directivity Directional Couplers

RLC Electronics' high-power, high directivity directional couplers offer accurate coupling (± 1.0 dB), low insertion loss (0.1 to 0.35 dB maximum) and > 35 dB directivity in both directions. These high-power couplers are offered with 500 to 1000 W average power handling up to 18 GHz, as well as 100 W versions up to 40 GHz. Couplers are provided in both single- and dual-directional construction, typically over a two octave bandwidth or less. RLC can utilize SC or 7/16 connectors on the main line, should this be needed to meet customer designs.

RLC Electronics
www.rlcelectronics.com

AT Series of RF Chip Attenuators from DC to 20 GHz

VENDORVIEW

RF chip attenuators are components used in communication systems to reduce the strength of a signal passing through it. They play a crucial role in protecting systems from receiving a signal with a power level that is too high to process. The range being introduced from Smiths Interconnect is significant because it offers a high frequency of DC to 20 GHz which is required for use in key commercial and space applications.

Smiths Interconnect
www.smithsinterconnect.com

CABLES & CONNECTORS

High Voltage 10 kV/20 kV Connectors and Adapters

VENDORVIEW

Fairview Microwave released a series of 10 kV and 20 kV connectors and adapters. They are suitable for a wide range of uses, including imaging inspection, test and measurement, medical and aerospace applications. This new line of hermetically sealed 10 kV and 20 kV connectors and adapters offers decreased rates of off-gassing and diffusion. Made with rugged brass bodies and nickel plating, these high voltage connectors and adapters are resilient and long lasting.

Fairview Microwave
www.fairviewmicrowave.com

Multipin Hermetic Connectors

SHP SPECIAL HERMETIC PRODUCTS INC.
Hi-Rel By Design
ISO 9001:2015 Certified

SHP manufactures a select group of both RF and rectangular multipin hermetic connectors for various military and commercial temperature environments. These competitively priced connectors are unique in that they are specifically designed and optimized for high-reliability in specific packaging materials. The result is significant savings by elimination of the common failure modes associated with the "one size."

Special Hermetic Products Inc.
www.shp-seals.com

AMPLIFIERS

Exodus AMP2080D, 10 kHz - 250 MHz, 500 W

VENDORVIEW

Exodus AMP2080D is ideal for broadband EMI-Lab applications. Class A/AB linear design for all modulations and

NewProducts

industry standards. Covers 10 kHz to 250 MHz, produces 500 W minimum, 700 W typical with 57 dB minimum gain. Excellent flatness, optional monitoring parameters for forward/reflected power indication, VSWR, voltage, current and temperature sensing for superb reliability and ruggedness. Integrated in the compact 8U chassis weighing approximately 45 kg.
Exodus Advanced Communications
www.exoduscomm.com

High Linearity, High Power Amplifier
VENDORVIEW

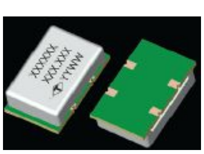
MIcable introduces the new 100 W solid-state high gain wideband power amplifier MPAR-010060S50 with the latest high-power RF GaN transistors, built-in control, monitoring and protection functions. It is designed for applications, such as 5G/LTE, Wi-Fi and other related system and EMC test. Custom designs are available.
Fujian MIcable Electronic Technology Group Co. Ltd.
www.micable.cn

High Gain, Broadband, Low Noise Amplifier

Model ABL1800-01-4525 is a high gain three stage MMIC based low noise amplifier module operating in the frequency range from 0.1 to 18.0 GHz. It offers 45 dB of linear gain and 2.5 dB typical noise figure with excellent gain flatness and input/output return loss. The unit has a built-in voltage regulator and operates with a single DC power supply voltage. The package size of the amplifier is 1.9 × 1.0 × 0.4 in.
Wenteq Microwave
www.wenteq.com

SOURCES

VLCU and VLEU VCXO



Taitien Electronics introduced a new VLCU and VLEU VCXO product series that has superior phase noise and low G-sensitivity performance. The noise floor is as low as -175 dBc/Hz and is ideal for applications like testing, optical communication, satellite, 5G base station, high-definition video broadcasting system, etc. The VLCU/VLEU series VCXO supports 50 to 150 MHz, clipped sinewave or CMOS output, 3.3 or 5 V power supply, -40°C to 85°C operation temperature and is sized at 14.0 × 9.0 × 3.6 mm.
Taitien Electronics
www.taitien.com

TEST & MEASUREMENT

Vector Network Analyzer

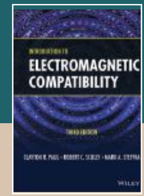
The SIGLENT SNA5000A series of vector network analyzers (VNAs) have a frequency range of 9 kHz to 8.5 GHz and 100 kHz to 26.5 GHz, which support 2/4-port scattering parameter, differential parameter and time-domain parameter measurements. The SNA5000A series of VNAs are effective instrumentation for determining the Q factor, bandwidth and insertion loss of a filter. They feature impedance conversion, movement of measurement plane, limit testing, ripple test, fixture simulation and adapter removal/insertion adjustments.
Siglent
www.siglentna.com

PCI Digitizers
VENDORVIEW

Spectrum Instrumentation launched the fastest digitizers in the 33-year company history. The cards offer a stunning combination of ultra-fast 10 GSPS sampling speed, 12-bit vertical resolution and market-leading 12.8 Gbps data streaming over the PCIe bus. The one- and two-channel cards also feature front-end circuitry with over 3 GHz bandwidth and up to 16 Gb (8 GS) of on-board memory.
Spectrum Instrumentation
www.spectrum-instrumentation.com

MICRO-ADS

Review by: Whitney Lohmeyer



Bookend

Introduction to Electromagnetic Compatibility

By Clayton R. Paul, Robert C. Scully and Mark A. Steffka

"Introduction to Electromagnetic Compatibility, Third Edition" is an ideal textbook for every university undergraduate enrolled in an EMC course, for practicing electrical engineers dealing with interference issues or for those wanting to learn more about electromagnetic compatibility to become better product designers. The authors provide a well-written, easily digestible, yet thorough reference that demystifies EMC through the explanation of fundamental theory around spectrum, transmission lines, antennas, radiation, crosstalk and shielding, along with Federal Communications Commission regulations – why they exist and how compliance tests are performed. Included in the appendix is an intro to electrical circuit analysis and lumped-circuit approximate models for transmission lines using tool kits like PSPICE or LTSPICE, which may be used for EMC analysis. Future editions of this text could introduce computational electromagnetics with techniques like MoM, FIT, FEM and tools like HFSS, CST or FEKO and contextualize their use by delineating specific modeling methods appropriate for various analyses. The text culminates with a chapter on systems-level EMC design strategies that elegantly incorporate and synthesize material presented in previous chapters. Most electronic products are designed to achieve metrics related to reliability, accuracy, cost, weight or some combination of these qualities. EMC has traditionally posed a challenge to each of these metrics, especially cost. While this book will not magically solve every EMI issue, in the words of Dr. Paul himself, "Successful EMC design of a product depends on the early and continuous application of the principles outlined in the text."

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FABS and LABS

Guerrilla RF: Making Better Networks™

Celebrating its tenth anniversary, Guerrilla RF was founded by North Carolina State University graduate Ryan Pratt. Pratt, with a degree in electrical engineering, had previous RF component experience in the North Carolina area working his way up the RFIC design and engineering management ladder at RFMD before founding and becoming director of the Skyworks design center in Greensboro, NC. Following a change in leadership at Skyworks in 2013, Pratt founded Guerrilla RF that April. Shortly thereafter, he established an office in the Nussbaum Center for Entrepreneurship, a small business incubator catering to startups in Greensboro, NC. The entrepreneurial spirit runs deep in the Pratt family as Bill Pratt, Ryan's father, was one of the co-founders of RFMD.

From these beginnings, Guerrilla RF has grown from the first hire in early 2014 to more than 70 employees worldwide. As the company has grown, so have its accomplishments. 2014 saw the first GaAs pHEMT LNA shipment, which was followed by power LNAs, driver amplifiers, gain blocks, RF switches, attenuators, mixer cores, power detectors and power amplifiers. From the early days of GaAs, Guerrilla RF has diversified its technology portfolio to include InGaP and SOI. The company has used this expanding product and process portfolio to surpass 150 million devices shipped in mid-2022. After supporting this growth with several private funding rounds, the company went public in October 2021. For the year ending December 2022, Guerrilla RF reported record revenues of $11.6 million, a 10.7 percent increase year-over-year.

As Guerrilla RF's product and technology portfolios, shipments, revenues and staff have grown, they are realizing the need to expand their physical footprint. In February 2023, the company moved into a new headquarters in Greensboro that provides 55,000 square feet total with 11,000 square feet of lab space. This is a substantial upgrade from the 10,800 square feet of office and lab space they utilized for more than nine years previously.

In an ecosystem that loves a certain amount of vagueness and ambiguity in company names, like Qorvo, Skyworks, Broadcom and Avago, "Guerrilla RF" provides a clarity of purpose. The name reflects a strategy of targeting bigger competitors in markets and applications where those companies are not focused and resourced correctly. Guerrilla RF views these areas as underserved markets and they believe addressing these areas with a portfolio of the right products will create significant business opportunities and help differentiate the company from its competitors.

While some of their broadband gain blocks operate as high as 12 GHz, most of Guerrilla RF's broad mix of control components, amplifiers, mixers and detectors are designed to operate in frequency ranges at or below 6 GHz. These products are capturing market share in various 4G/5G small cell and 5G massive MIMO antenna applications. Automotive applications are a key target area, with Guerrilla RF's products being designed into GPS/GNSS front-end applications, SDARs front-ends and V2X compensators. The company's parts are also well-represented in the growing repeater/DAS market.

Guerrilla RF made the Inc. 500 list of fastest-growing private companies twice before it went public and its trajectory of product development, revenues and expansion bode well for continuing this growth now that the company is public. The rapid growth of any company presents challenges, but Guerrilla RF looks well-positioned to address these challenges. Ryan Pratt and Guerrilla RF's senior management are acutely aware of maintaining a work-life balance and they are proud of the fact that their parking lots are mostly empty by 5:15 PM as they guide the company along the next phase of growth.

www.guerrilla-rf.com

WERLATONE
ENGINEERING EVOLVED

DIGITAL RF POWER METERS

Optimal Accuracy ✦ 40 dB Dynamic Range ✦ No Calibration Required

Simultaneously Monitor: Forward Power, Reverse Power, Load VSWR, & Temperature

ACCURACY

- Multi-Octave Solutions provide accuracy within ± 5% of a Customer Lab Standard (± 2% Typical).

CALIBRATION

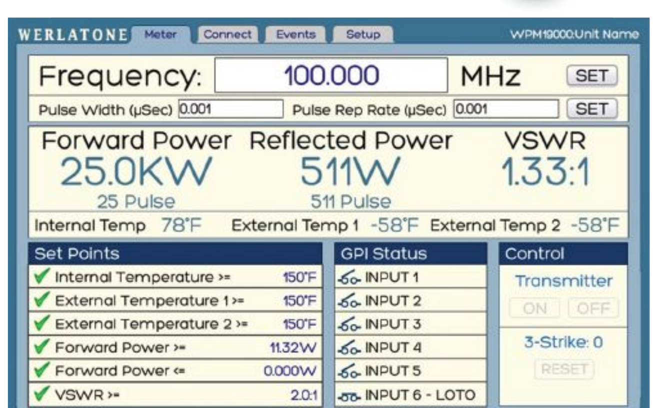
- No On-Site Calibration Required.
- Calibration Routine completed internally to each Power Sensor.
- Traceable to National Institute of Standards & Technology (NIST).

ALARMS & RELAYS

- Alarm Thresholds of Forward & Reverse Power.
- Full VSWR Monitoring/Alarm Capability.
- Full Temperature Monitoring/Alarm Capability.
- Six General Purpose Inputs & 2 Form-C Relays to External Devices

FIRMWARE

- Windows Application includes an ergonomic tab-based access system for easy setup and operation of the Power Meter.
- Multi-Window Display for access to up to five Meters on screen.
- VSWR Indication & Reflected Power on main Power Sensor display.
- MIB File available for use with SNMP software.
- LabVIEW Driver Available.



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