MOCVD—A Linchpin in the Proper Integration of GaN-on-Si into RF Apps **p23**

These 3 VNA-Based Methods Produce Accurate Impedance Measurements **p28**

Designing and Evaluating a Low-Cost, Plastic-Packaged Power Amplifier for 28-GHz 5G **p36**

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Semi Process Diversity Delivers 5G SMALL CELLS

Designs based on Si LDMOS, GaN, and SiGe help devices meet power-amplification demands **p42**

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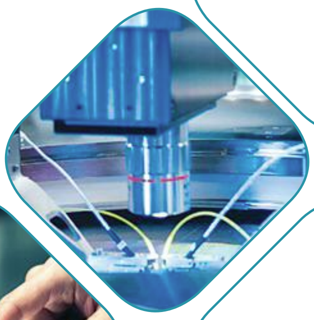

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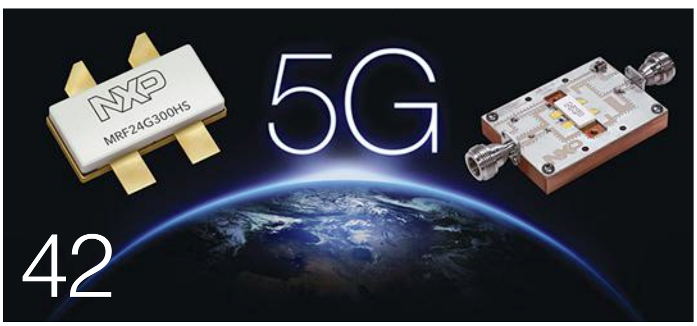

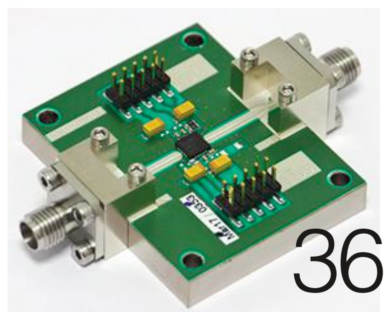

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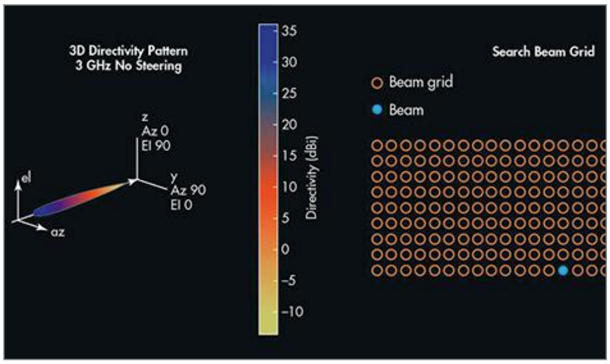


Closing the Loop in Multifunction Phased-Array Modeling

As outlined in the latest "Algorithms to Antenna" blog, resource management and task scheduling are just two of the concepts employed with system models that support closed-loop simulation in a multifunctional phased-array radar system.

https://www.mwrf.com/systems/algorithms-antenna-closing-loop-multifunction-phased-array-modeling

GPSDO vs. Atomic Clock: What's Better for Your Satellite Application?

Different timing options are available for satellite applications, such as GPS Disciplined Oscillators and atomic clocks—it all depends on the orbit.

https://www.mwrf.com/components/gpsdo-vs-atomic-clock-what-s-better-your-satellite-application

First to 5G: Who Will Win?

While carriers are scrambling to be first in the 5G race, determining a clear winner is no simple matter. National Instruments' Sarah Yost explains why.

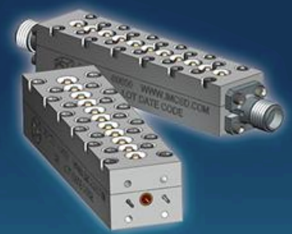
https://www.mwrf.com/systems/first-5g-who-will-win

A Modern Approach to Satcom System Design

With this model-based design platform, engineers are equipped with the tools to design and analyze systems that meet satellite-communication mission requirements.

https://www.mwrf.com/software/modern-approach-satcom-system-design

Ultra-High-Q SMT Waveguide Filter for 5G



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excluding connectors

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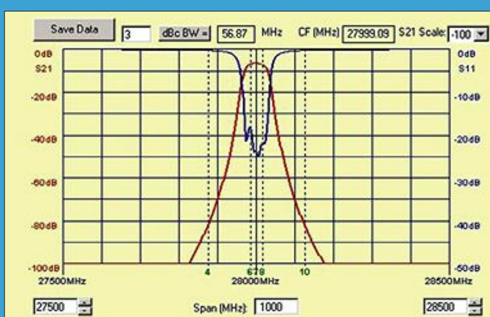
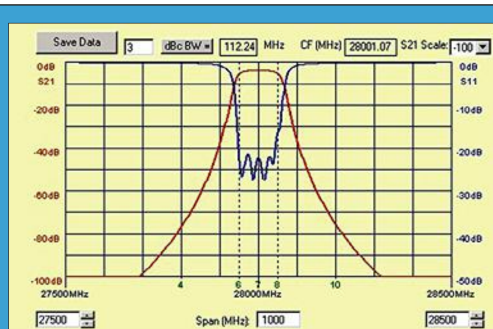
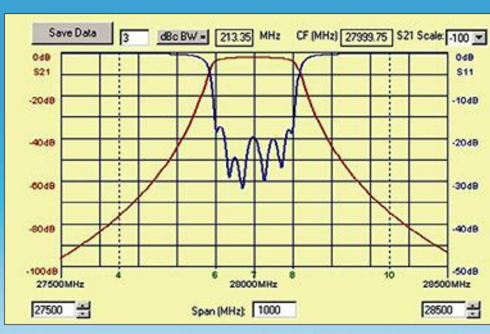


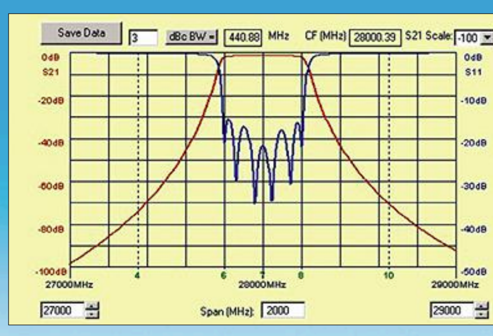
50 MHz



100 MHz



200 MHz



400 MHz

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Editorial

CHRIS DeMARTINO | Editor
chris.demartino@informa.com

The Race to 5G… and 6G?

As carriers reveal their 5G plans, some in the industry are already looking ahead to 6G.

WHILE WALKING the show floor at IMS 2019, one of the central and most obvious themes was 5G. With all the talk over the last several years, it almost feels like 5G is becoming old news. One consensus from the show is that it's now time for 5G to turn into a reality. And it's certainly becoming real, with carriers already announcing that 5G is live in some markets. (On that front, T-Mobile recently disclosed the launch of its 5G network in six U.S. cities: Atlanta, Cleveland, Dallas, Las Vegas, Los Angeles, and New York City.) It's no surprise that each of the carriers wants to win the 5G race.

In the RF/microwave industry, companies are also doing whatever it takes to get a piece of the 5G pie. This applies to suppliers of test-and-measurement equipment, which are aiming to provide the latest and greatest and test solutions, as well as design software companies striving to offer the needed simulation tools. Of course, components suppliers are eager to get in on the 5G action, too.

As every reader knows, higher millimeter-wave (mmWave) frequencies are an essential aspect of 5G. Speaking of higher frequencies, Ted Rappaport of NYU WIRELESS along with others recently published a paper titled, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond." That's right—while everyone is talking about 5G, NYU WIRELESS is actually looking ahead to 6G. Will terahertz frequencies enable future 6G wireless communication systems? It's interesting to think about, but something that we probably won't know for quite some time.

In the meantime, it will be interesting to see how 5G ultimately comes together. As Sarah Yost, senior solutions marketing manager, SDR, at National Instruments (NI) *(www.ni.com)*, recently wrote concerning 5G, "This is an exciting year for 5G as consumers are just starting to take advantage, but it's just the beginning of being able to realize and harness 5G's potential. When LTE was first being deployed, no one could imagine how the services it enabled, such as Uber, would change our world forever. It's exciting to speculate about how 5G is going to change the world and even more thrilling to watch as it starts to unfold."

So, while some are already pondering 6G, let's first see what 5G has in store for us. mw

Microwaves&RF **JULY 2019**

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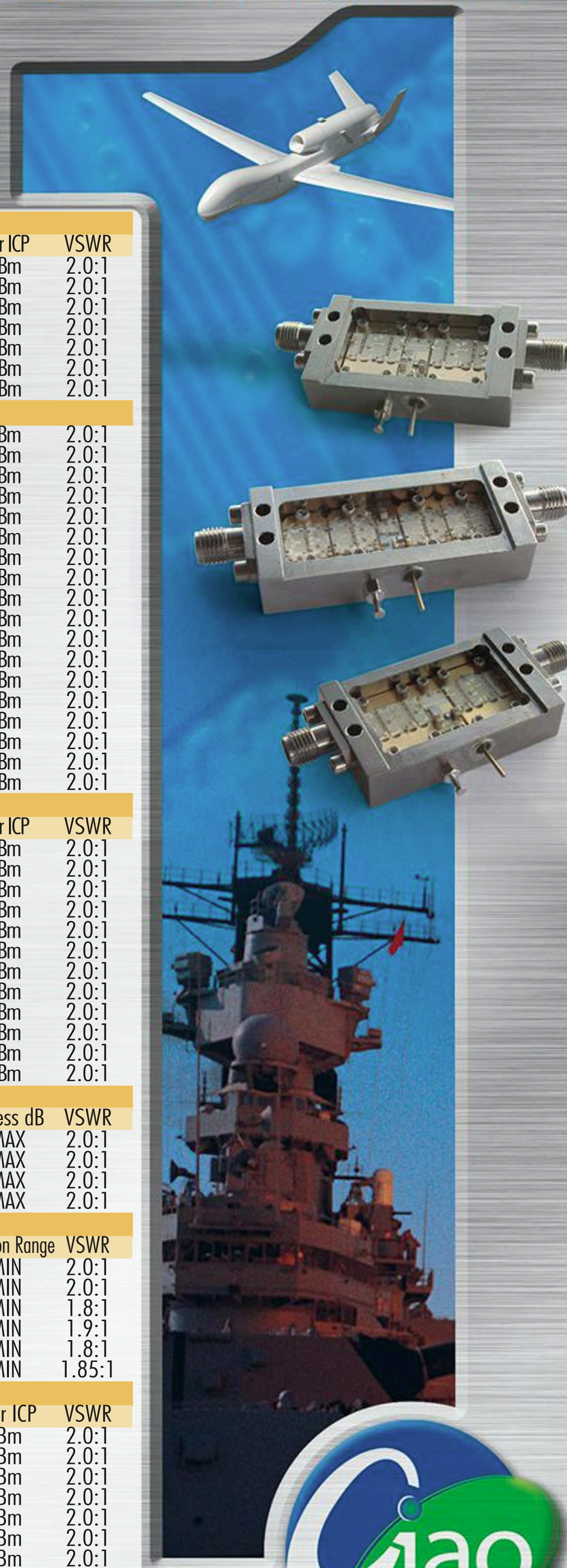

OCTAVE BAND LOW NOISE AMPLIFIERS

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

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

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

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

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

LIMITING AMPLIFIERS

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

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

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

LOW FREQUENCY AMPLIFIERS

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

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News

JOINING UP WITH the Right Connections at IMS

1. The MWX004 cables can perform at frequencies as high as 145 GHz.

2. Offering performance to 67 GHz, the MWX161 cables maintain phase stability versus bending and temperature.

Those in attendance at IMS 2019 likely could not help but observe some of the latest interconnect solutions being exhibited at the event. Although checking out the latest interconnect products may seem less captivating than seeing a demo of some fancy test system or learning about the advanced features of today's simulation software tools, interconnect products are critical aspects of the microwave world that cannot be ignored.

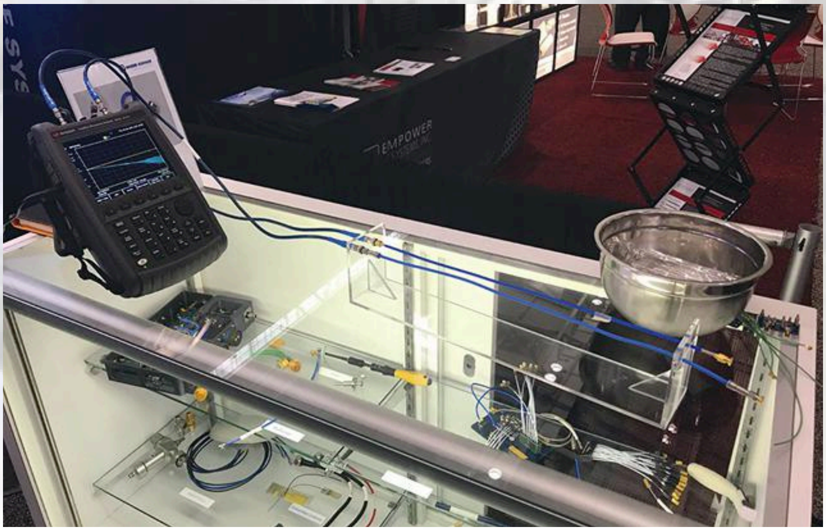
Among the companies showcasing interconnects was Junkosha *(www.junkosha.co.jp/english)*. The company displayed an assortment of products, including its new MWX004 flexible cables *(Fig. 1)*. With the MWX004 cables, customers have two options to choose from: a 130- or 145-GHz version. The 130-GHz cable is built with 1.0-mm enhanced connectors, while the 145-GHz variant comes with 0.8-mm connectors. Junkosha asserts that the MWX004 cables will enable radar applications, as well as future connected- and autonomous-vehicle applications.

Other products spotlighted by Junkosha were its MWX161 cable assemblies, which offer performance up to 67 GHz *(Fig. 2)*. Junkosha states that these cable assemblies maintain superior phase stability versus both bending and temperature. According to the company, the MWX161 cable assemblies are well-suited for multiport vector network analyzers (VNAs).

Not to be outdone, HUBER+SUHNER *(www.hubersuhner.com)* also

showcased new interconnect solutions at IMS 2019. The company conducted a live demo of its CT phase-invariant family to illustrate the product's phase stability *(Fig. 3)*. This demo was configured so that phase measurements of both a CT cable assembly and a different cable could be viewed. After spraying both cables with cold spray, the phase measurement of the CT cable assembly remained unchanged. However, the phase measurement of the other cable changed considerably.

HUBER+SUHNER also highlighted its self-locking SMP-SL connector, which can be described as a flight-ready, push-on connector that offers performance to 40 GHz *(Fig. 4)*. According to the company, the SMP-SL connector makes it possible for customers to reduce installation times while retaining both the robustness of a threaded connector and the small form factor of a standard SMP connector. Furthermore, SMP-SL connectors can only be de-mated with a dedicated removal tool (supplied by HUBER+SUHNER), thereby eliminating the risk of unintentional de-mating. ■



3. This demo at IMS 2019 was conducted so that visitors could see the phase stability of a CT cable assembly versus that of a different cable.

4. The self-locking SMP-SL connector will work at Ka-band frequencies.

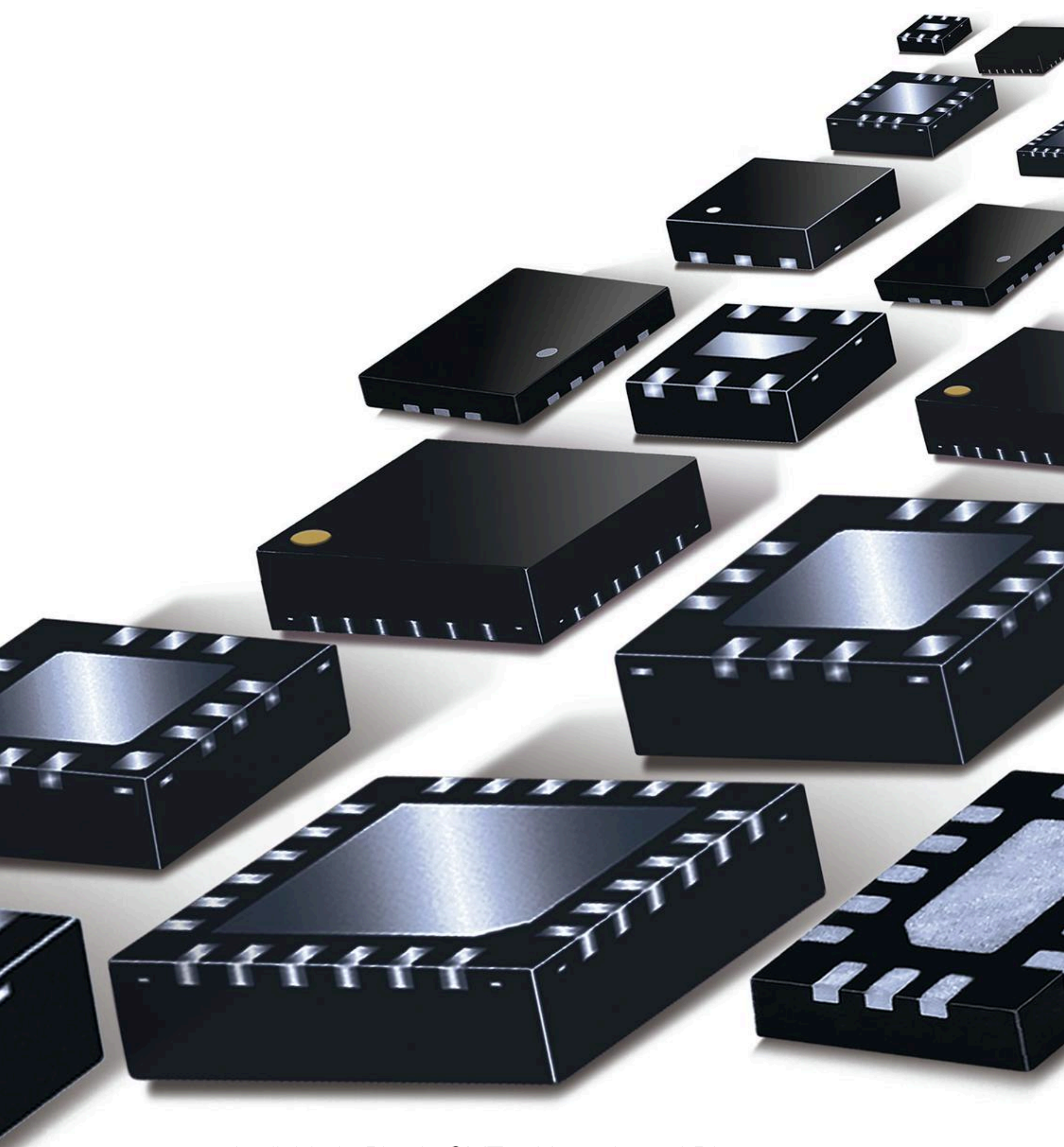
HUNTING FOR HIGH POWER at IMS 2019

HIGH-POWER TECHNOLOGY was on display throughout the IMS 2019 show floor, as companies showcased high-power solutions for applications like wireless communications, satellite communications (satcom), and radar. No doubt, gallium-nitride (GaN) technology is a key enabler in the high-power RF space, evidenced at IMS from companies like Wolfspeed (a Cree company) *(www.wolfspeed.com)*, which launched several new products in time for the event. Furthermore, just prior to IMS, Cree announced plans to invest $1 billion to expand its silicon-carbide (SiC) capacity.

One of the new products given the spotlight by Wolfspeed is the CMPA1D1E080F, an 80-W GaN monolithic-microwave-integrated-circuit (MMIC) power amplifier (PA) *(Fig. 1)*. The company maintains that this device offers benchmark performance in terms of high power for satcom applications.

Intended for the Ku-band arena, the

1. The CMPA1D1E080F is an 80-W PA targeted for Ku-band satcom applications.



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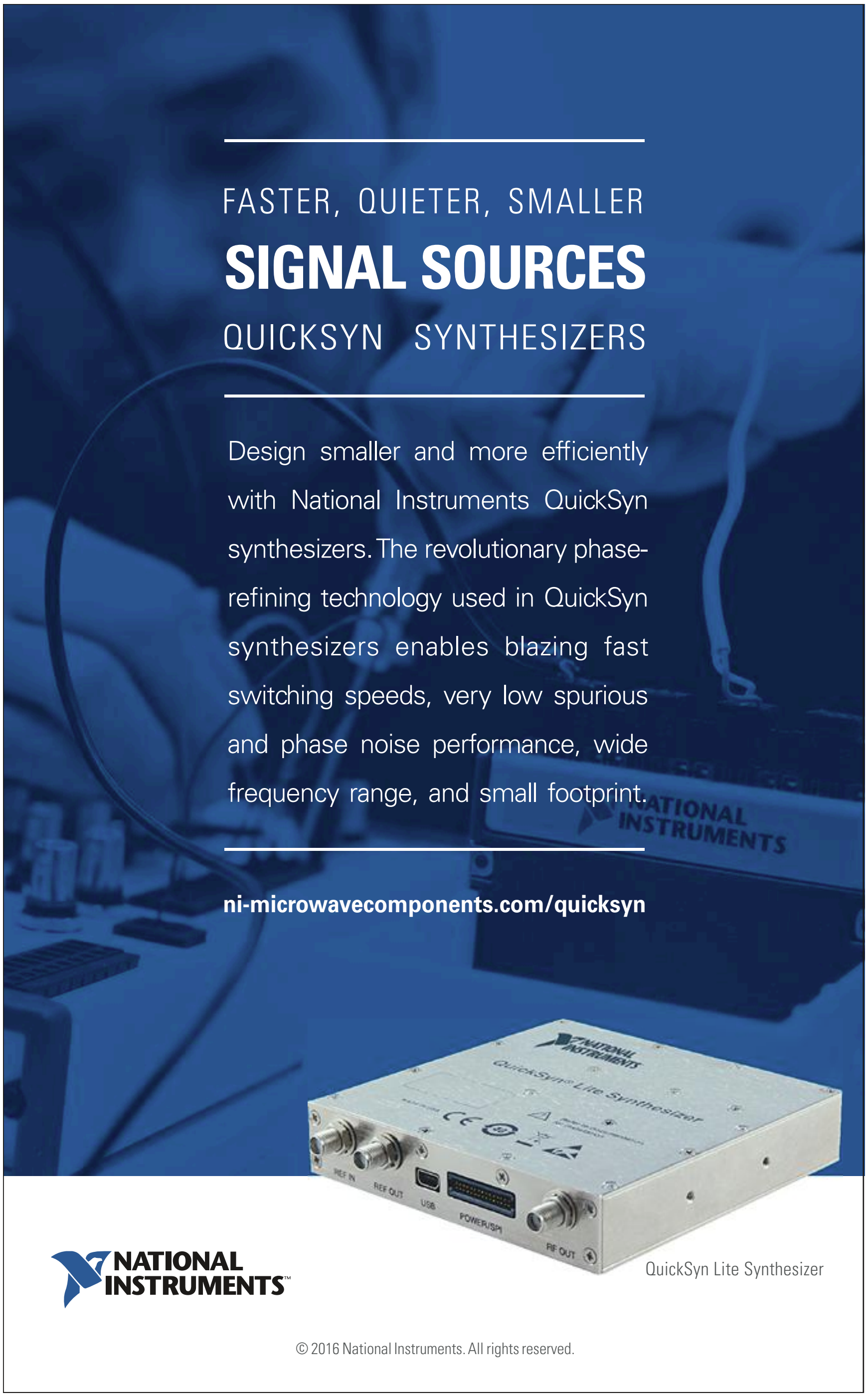
High-power technology was on display throughout the IMS 2019 show floor, as companies showcased high-power solutions for applications like wireless communications, satellite communications (satcom), and radar. No doubt, gallium-nitride (GaN) technology is a key enabler in the high-power RF space.

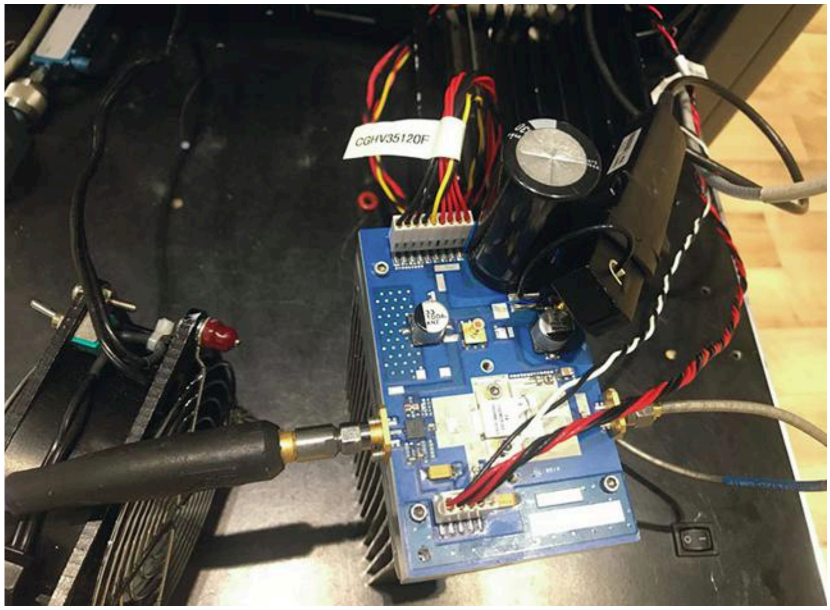


CMPA1D1E080F has an operating frequency range of 13.75 to 14.5 GHz. The device delivers over 28 dB of small-signal gain across the entire operating band. Its power-added efficiency (PAE) is greater than 17% when delivering 40 W of average output power. Furthermore, the CMPA1D1E080F comes in a 14-lead metal/ceramic flanged package that measures 17.4 × 24 mm.

2. Designed for S-band radar systems, the CGHV35120F can deliver 120 W of output power.

The company's new CGHV35120F 120-W GaN high-electron-mobility transistor (HEMT) was also front and center at IMS *(Fig. 2).* Intended for S-band radar systems, this device covers a frequency range of 3.1 to 3.5 GHz. At 3.1 GHz, the CGHV35120F achieves a power gain of 13 dB at a case temperature of +85°C. Furthermore, it was highlighted at IMS in a live demo in which the CMPA2735015S GaN MMIC was used as a driver amplifier *(Fig. 3).*

Wolfspeed unveiled another new device for radar applications: the CMPA901A035F GaN MMIC *(Fig. 4).* Under continuous-wave (CW) operating conditions at frequencies from 9 to 11 GHz, the CMPA901A035F delivers greater than 35 W of power. At 10 GHz, the



3. In this demo, the CGHV35120F device was driven by the CMPA2735015S GaN MMIC. The overall gain was over 45 dB.

Wolfspeed unveiled another new device for radar applications: the CMPA901A035F GaN MMIC *(Fig. 4)*. Under continuous-wave (CW) operating conditions at frequencies from 9 to 11 GHz, the CMPA901A035F delivers greater than 35 W of power.

device achieves a small-signal gain of 34 dB. In addition, the CMPA901A035F has a PAE of 34% when driven by a 10-GHz CW signal with an amplitude of +23 dBm.

Rounding out Wolfspeed's other latest products are the CMPA2060035F, GTRA384802FC, and GTRA374902FC. The CMPA2060035F is a 35-W GaN MMIC PA that operates from 2 to 6 GHz. It achieves 28.5 dB of small-signal gain at 4 GHz.

Then there's the GTRA384802FC thermally enhanced 400-W GaN-on-SiC HEMT. Intended for use in multi-standard cellular PA applications, the GTRA384802FC covers a frequency range of 3.6 to 3.8 GHz. The device features an asymmetrical Doherty design.

Finally, the GTRA374902FC is a thermally enhanced 450-W GaN-on-SiC HEMT that covers a frequency range of 3.6 to 3.7 GHz. Like the GTRA384802FC, it features an asymmetrical Doherty design and is intended for multi-standard cellular PA applications. ■

4. Intended for X-band radar applications, the CMPA901A035F provides more than 35 W of power under CW operating conditions.

(News continues on page 46)

CONSIDERING A CHOICE of Active Circulators

RF/MICROWAVE CIRCULATORS are usually passive components, typically based on ferrite substrate materials and often called upon to direct high-power signals in high-frequency systems. Some passive loss is to be expected, and usually such loss is one of the limiting factors in determining the power-handling capability of a passive circulator. But what if RF/microwave circulators were designed as active components?

Circulators allow the simultaneous transmission and reception of high-frequency signals at different frequencies, a key capability in enabling the high-volume use of radio waves in a growing number of wireless communications applications, including in 5G wireless cellular networks. Researchers from Hong Kong have investigated the development of active circulators that will allow the flow of RF/microwave energy only in one direction in support of many different wireless radio architectures, including in software-defined-radio (SDR) systems for coverage of many different frequency bands with a single radio.

The researchers examined different active circulator design approaches, including three-way circulators in which signals flow from an input port to two output ports and quasi-circulators, where signals flow from an input port to one of two output ports but are isolated from the other port, as required when connecting an antenna to a transmitter and receiver. Much attention is given to active quasi-circulator designs, along with several wideband and tunable circuit configurations. A combined wideband tunable quasi-circulator was developed that provides high isolation between ports while also operating over a large bandwidth.

Each active circulator design approach had strengths and weaknesses, with the most wideband configurations lacking enough isolation and tunable active circulators providing high isolation but lacking bandwidth. The researchers explored the use of a distributed-element circuit approach based on a commercial GaAs FET active device to achieve an active quasi-circulator with bandwidth of 0.8 to 2.2 GHz. The component employed a self-equalization technique to achieve minimum isolation of 20 dB between ports.

For tunable quasi-circulators, varactor diodes were used as tuning elements, with the capacitance of the varactor diodes also optimized to achieve high isolation between the desired ports. The sizes of distributed quasi-circulator designers were minimized by replacing quarter-wave transmission lines where possible by electronically tunable microwave impedance transformers.

A combination wideband tunable quasi-circulator, designed with the same GaAs FETs as in the distributed circulator, achieves minimum isolation between ports of 15 dB over a frequency range of 0.8 to 2.2 GHz with isolation of better than 40 dB at a center frequency of 1.5 GHz. The insertion loss is low, typically about 1.5 dB at midband. As these researchers showed through their work, active quasi-circulators offer many advantages compared to traditional, passive circulators, including compactness, light weight, and compatibility with monolithic-microwave integrated-circuit (MMIC) technology.

See "The Challenges of Active Circulators," *IEEE Microwave Magazine*, July 2019, pp. 55-66.

WHEN 5G ISN'T ENOUGH, It Will Be Time for 6G

WIRELESS COMMUNICATIONS TECHNOLOGY and devices have become such an important part of daily lifestyles that the entire RF/microwave industry was abuzz at the recent 2019 IEEE International Microwave Symposium (IMS) about the prospects of mass-producing mmWave components at 24 GHz and higher for 5G cellular wireless networks. The concept for 5G is simple: When bandwidth is gone at lower frequencies, reach into the mmWave frequency range for the bandwidth needed for fast wireless data rates over shorter distances.

But what happens when the 5G bandwidth is all gone? Some visitors on the 2019 IMS exhibition show floor of the Boston Convention Center had already begun to ask about 6G wireless networks.

For an RF/microwave industry that prides itself on its forward-looking vision, it should not be surprising that attention is now being given to the possibilities for 6G technology. NYU Wireless, for one, which had a great deal to do with exploring the real-world possibilities of 5G technology, is focusing research on the sub-THz radio spectrum that will be applied to 6G telecommunications.

For example, Ted Rappaport, the founding director of NYU Wireless at NYU Tandon, and team members published a report in *IEEE Access* on the potential for 6G technology and beyond. The 27-page invited paper, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," addresses some of the work to be done in a 2025 through 2030 timeframe. Applications are projected for commercial, industrial, and military users for a variety of systems, including positioning and line-of-sight (LOS) communications.

However, success will depend on development of advanced circuit materials and precision manufacturing techniques to maintain the machine tolerances needed in support of THz frequencies. Some frequency bands, such as 550 and 760 GHz, may be problematic because of the high atmospheric attenuation compared to other frequency bands, so THz frequency bands must be carefully chosen for optimum results. Still, as the white paper explains, if the large bandwidths provided by 5G frequencies have been exhausted by those future timeframes, much promise remains in the frequency bands beyond 100 GHz.

DREW HANSER | VP of Technology, Veeco Instruments
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Solving GaN-on-Si Integration Challenges in RF Applications

Leveraging the latest metal organic chemical vapor deposition technology, gallium-nitride-on-silicon is poised to meet the high-frequency demands of 5G and other platforms.

Gallium-nitride (GaN) market forecasts were pushed out in recent years because of integration and reliability issues. However, they are now experiencing a significant uptick due to continuing development and maturation of GaN device technology.

With these improvements, the RF industry's need for high frequency, efficiency, and linearity within smaller form factors will no doubt create additional opportunities for GaN moving forward. 5G applications will transform cellular communications, creating new opportunities for wireless carriers and service providers. For military applications, GaN devices bring advantages in size, weight, power, and overall system cost (SWaP-C) for a multitude of platforms.

Veeco's Propel Power GaN MOCVD system, which features a single-wafer reactor platform, is capable of processing six- and eight-inch wafers.

WHY GaN?

GaN has the potential to overcome and outperform the limitations of materials such as silicon (Si), silicon carbide (SiC), gallium arsenide (GaAs), and indium phosphide (InP) in RF and power applications. Looking at the materials properties of GaN, it becomes apparent why GaN overcomes the physical limitations of other materials:

- *Wide bandgap (3.4 eV):* High-voltage operation, high critical electric field
- *High electron velocity (2×10^7 cm/s):* High switching speed
- *High temperature capability:* >150°C junction temperature

In the 5G arena, the high-speed network will offer greater than 10-Gb/s transmission speeds for mobile broadband (phones/tablets/laptops) and ultra-fast low latency for Internet of Things (IoT) applications (vehicle-to-everything, or V2X, communications). GaN is replacing Si in specific wireless applications (i.e., 4G/LTE base-station power amplifiers), and it will significantly impact next-generation 5G deployment because power amplifiers for all transmission cells in the network (macro, micro, pico, femto/home routers) will benefit from GaN advantages. Military applications, such as jammers, communications, and radar, benefit from improved bandwidth, efficiency, and power at higher operating frequencies.

GaN CHALLENGES

The inherent materials advantages of GaN came with associated manufacturing challenges, including the cost and optimization of epitaxy and the optimization of device processing and packaging. Other issues include charge trapping and current collapse, which are being actively resolved by Veeco *(www.veeco.com)* scientists independently as well as in collaboration with leading device companies and research institutes worldwide.

GaN-on-silicon (GaN-on-Si) is emerging as a front-runner in device performance and cost, as comparable or superior performance has been demonstrated relative to GaN-on-silicon-carbide (GaN-on-SiC). In addition, the overall cost structure, manufacturability, and supply-chain ecosystem provide advantages in producibility. The GaN-on-Si approach offers wafer sizes starting at 150 mm up to 300 mm, greatly improving the potential for reduced device cost through scaling.

GaN-on-Si technology starts with, and is enabled by, a state-of-the-art manufacturing approach for epitaxy using metal organic chemical vapor deposition (MOCVD). When the goal is to create a highly repeatable manufacturing process on large substrates that achieves high final device yield, batch systems no longer offer sufficient control compared to a single-wafer process approach.

Such a goal can be achieved by leveraging Veeco's Propel MOCVD system, a single-wafer reactor (SWR) that provides superior film-deposition control *(see figure on page 23)*. Thanks to the SWR's capability to control the epitaxy process, it's possible to meet tighter specifications (within wafer, wafer-to-wafer, run-to-run, and tool-to-tool) on larger substrate sizes in the following areas:

- Uniformity (thickness, composition, doping)
- Repeatability
- Particle defectivity

- Strain and wafer curvature control
- Interface abruptness

These epitaxial performance areas are needed to make significant inroads into GaN RF applications. Next-generation production systems using silicon substrates need to be adaptable to a wider process window and offer the highest throughput combined with the lowest cost of ownership. First, the epitaxy layers must be deposited with excellent uniformity across the wafer for both thickness and composition control to effectively incorporate buffer layers and super lattice structures.

Control of the stress in the wafer is also extremely important to achieve the desired material quality, buffer isolation, and RF loss on the silicon substrate. In addition, customers demand accurate dopant control with sharp interfaces across the wafer to optimize the device properties. There must be excellent uniformity and repeatability to effectively incorporate dopants such as carbon and iron to optimize doping levels across multiple runs. This becomes more challenging with larger substrate sizes, which is what Veeco's Propel MOCVD system is designed and optimized to deliver the required performance.

NEED FOR 200- AND 300-mm GaN INNOVATION

Another important factor to consider is the demand for 200-mm GaN-on-Si. Cost is a major factor for the RF industry, and migration from 150-mm Si wafers to 200-mm Si will reduce the cost per die. But more importantly, the eight-inch fab infrastructure uniquely provides capabilities that are now critical as the industry is poised to ramp up mainstream adoption.

The ultimate goal for using GaN-on-Si is to scale to 300 mm, thereby reducing epitaxy cost per unit area, as well as the downstream processing cost, by leveraging the industry's 300-mm infrastructure. Veeco has shipped a full-production 300-mm system, demonstrating process performance on 300-mm silicon wafers and data that proves scaling to be successful with results equal to or better than 200-mm wafers.

In summary, Veeco has developed the state-of-the-art in MOCVD technology for GaN-on-Si and is ready to support production ramps. By leveraging these epitaxial process improvements, large-area Si substrates, and unique advantages of single-wafer reactor processing, GaN will continue to advance RF system capabilities and applications. mw

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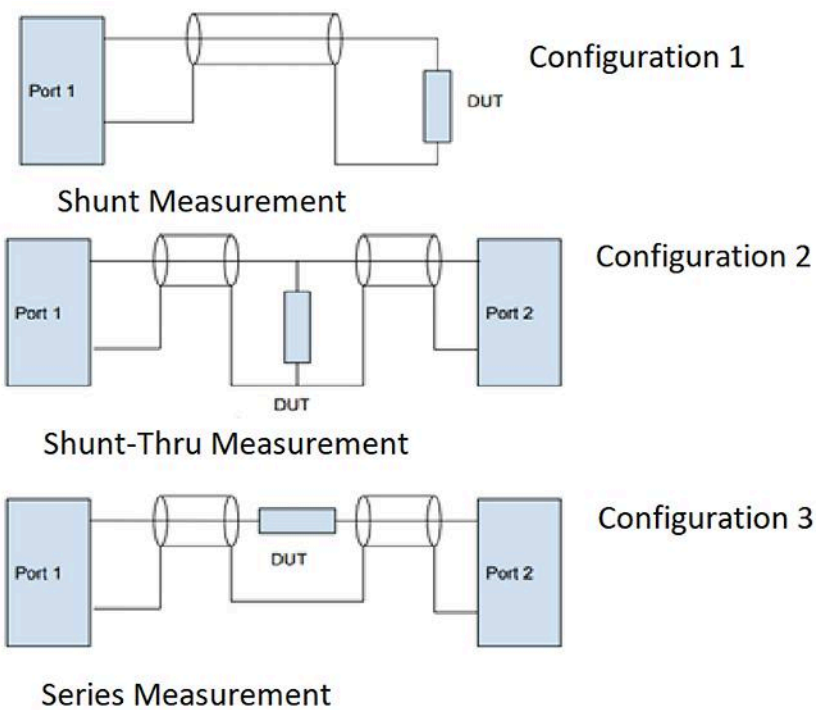
Make Accurate Impedance Measurements Using a VNA

Three different methods can be applied to accurately measure passive components with a vector network analyzer.

A vector network analyzer (VNA) is a very useful test instrument for characterizing RF circuits and amplifiers. But what about measurements of simple passive components? What's the best way to characterize a chip capacitor or an inductor—or even a resistor?

In the past, without giving it much thought, this author has measured chip capacitors by grounding one end. After doing a careful port extension to the end of a homemade probe, the cap would be measured with the Smith chart mode engaged and read off the value from an R + jX marker. As it turns out, this method is only appropriate for a narrow range of component impedances and this measurement probably had significant error.



1. Shown are the shunt, shunt-thru, and series configurations for impedance measurements.

Three measurement configurations exist for impedance measurements: shunt, shunt-thru, and series *(Fig. 1)*.

For the three measurement configurations, we want to understand the uncertainties of the measurements. This is normally done by using the Jacobian operator on the variables, which affects the outcome. In this case, there's only one variable, either S11 for configuration one, or S21 for configurations two and three. The Jacobian will require the partial derivatives of the impedance, Z, with respect to the measured reflection coefficient. Here are the needed derivatives for the three configurations:

CONFIGURATION 1: SHUNT MEASUREMENT

By definition:

$$S11 = \frac{Z - Z0}{Z + Z0}$$

Solving for Z:

$$Z = \frac{Z0(1 + S11)}{1 - S11}$$

We want to know the sensitivity of Z with respect to changes in S11, so we'll need the derivative:

$$\frac{dz}{dS11} = \frac{2Z0}{(1-S11)^2} \qquad (1)$$

CONFIGURATION 2: SHUNT-THRU MEASUREMENT

Moving on to the second configuration of *Figure 1*, the shunt-thru measurement, we have:

$$S21 = \frac{2Z}{Z0+2Z}$$

Rearranging to solve for Z, we get:

$$Z = \frac{Z0*S21}{2(1-S21)}$$

And then taking the derivative to find the sensitivity of Z with respect to changes in S21:

$$\frac{dZ}{dS21} = \frac{Z0}{2(1-S21)^2} \qquad (2)$$

CONFIGURATION 3: SERIES MEASUREMENT

Finally, for the series configuration, we need to find S21, which in this case is:

$$S21 = \frac{2Z0}{2Z0+Z}$$

Solving for Z once again gives:

$$z = \frac{2(Z0-S21)}{S21}$$

And the derivative needed for sensitivity is:

$$\frac{dz}{dS21} = \frac{-2Z0}{S21^2} \qquad (3)$$

Note that the negative sign here is irrelevant, since we will only be interested in the magnitude.

IMPEDANCE ACCURACY FOR CONFIGURATION 1: SHUNT MEASUREMENT

We want to find the error dispersion (variance) on the impedance, Z, for each of these cases. For configuration 1, the measurement involves S11. The specification sheet for the VNA gives a maximum error on S11 magnitude ($\Delta S11_{max}$). To compute statistics, we take this to be the 3σ value of a normally distributed function (99.7% confidence interval). We'll use this to calculate ΔZ_{max}, which will be a 3σ value for the expected change of impedance.

The dispersion on S11 is then:

$$D_{\Delta S11} = \frac{|\Delta S11_{max}|^2}{9}$$

(the "3" divisor is squared) (4)

In general, errors are propagated forward using the Jacobian differential operator. Thus:

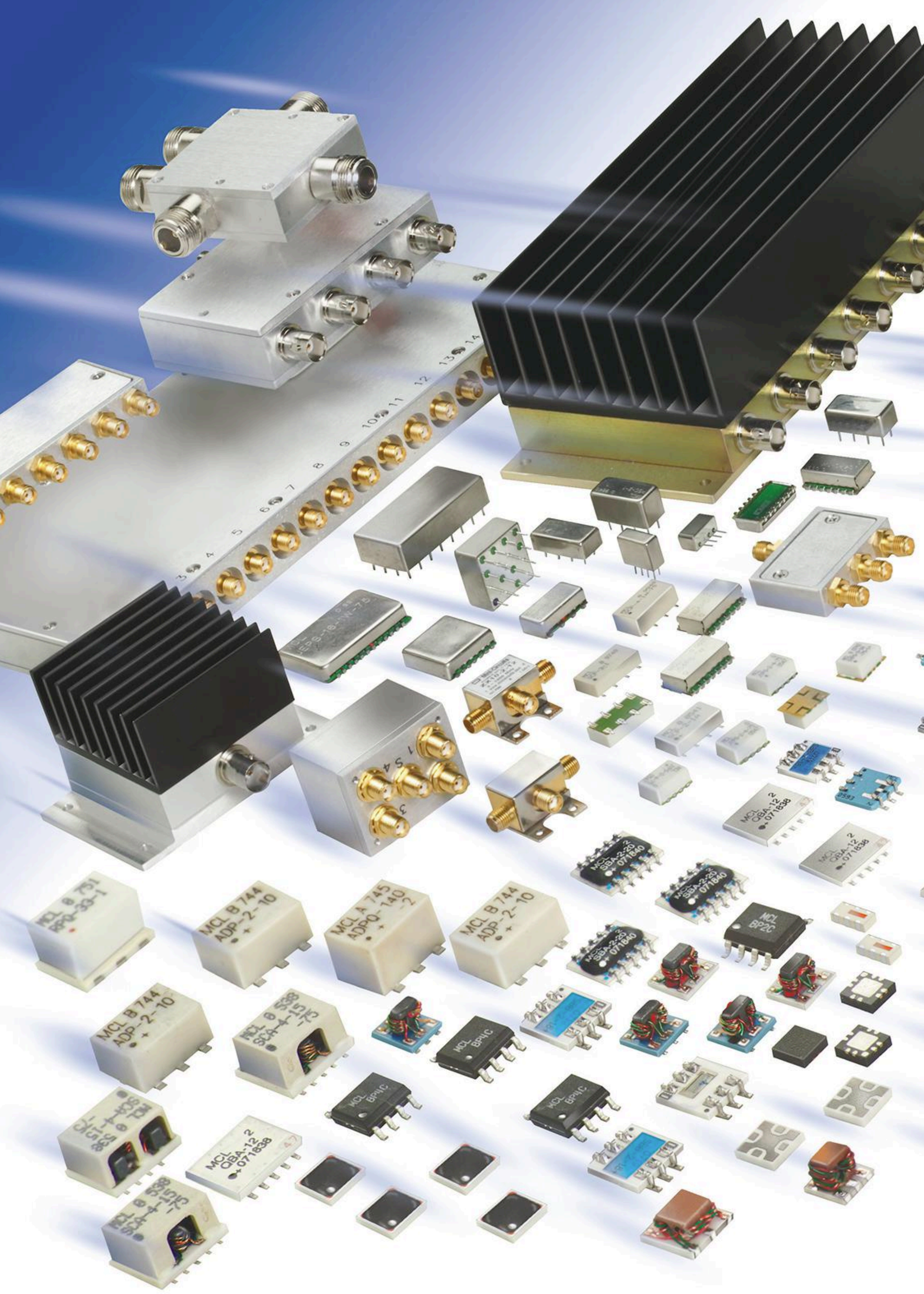
$$D_Z = J * D_{\Delta S11} * J^*$$

(from Ridler and Salter reference) (5)

For a single independent variable, this simplifies to the dispersion (variance) on S11 multiplied by the square of the partial derivative. It's important to introduce Equation 5, though, since it's central to calculating uncertainties where multiple variables are involved with non-zero covariance. In this simple case, one variable is the square of Equation 1. Multiplying by the dispersion on S11 gives:

2. The S5065 VNA has a measurement frequency range of 9 kHz to 6.5 GHz.

3. Here, impedance error is shown for the shunt, shunt-thru, and series configurations.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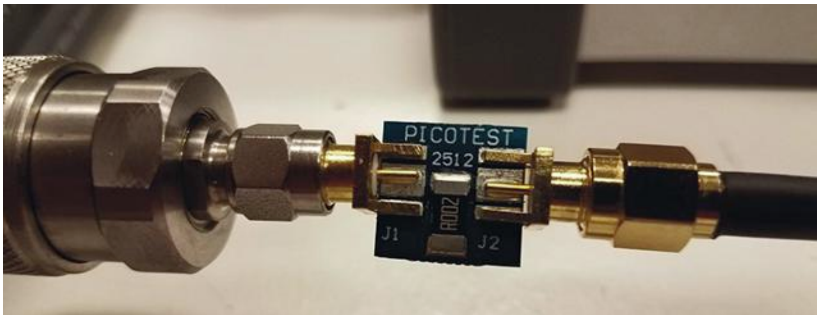
ADP-2-10
MCL A 745
ADPQ-14O
-2
MCL
QBA-12
071838
MCL
BP4C
MCL
BP2C
SBA-2-20
071840

$$D_Z = \frac{|\Delta S11_{max}|^2}{9} * [\frac{2Z0}{(1-S11)^2}]^2$$

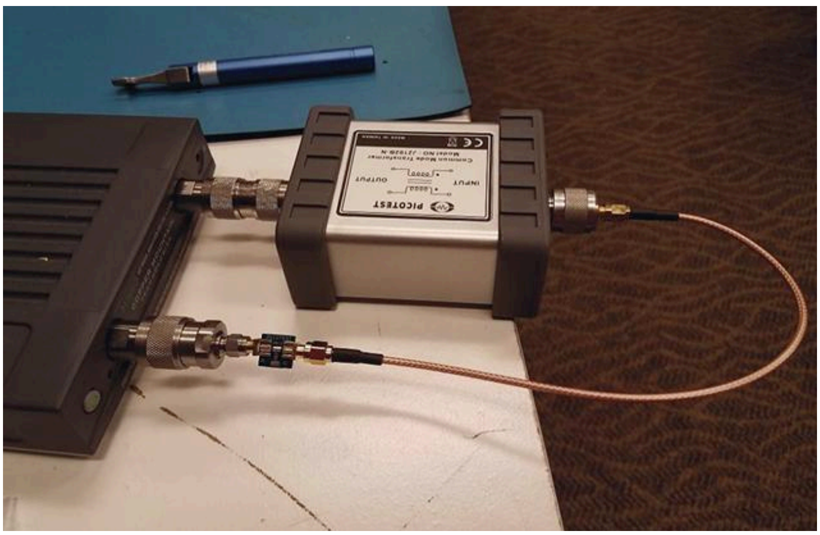
$$= \frac{4Z0^2 * |\Delta S11_{max}|^2}{9 * |1-S11|^4}$$

Assuming ΔZ_{max} is $3\sigma = 3 * \sqrt{D_Z}$ (99.7% confidence interval again) or:

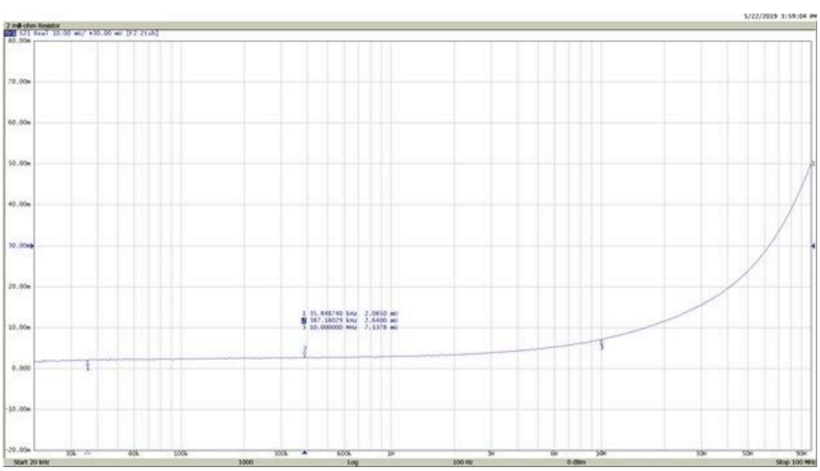
$$\Delta Z_{max} = \frac{2Z0 * |\Delta S11_{max}|}{|1-S11|^2} \qquad (6)$$



4. This 2-mΩ resistor was measured by the S5065 VNA.



5. Included in the test setup was the J2102B-N common-mode transformer.



6. The resistor measurement revealed a value of 2.085 mΩ at 35 kHz.

The Copper Mountain Technologies *(www.coppermountaintech.com)* S5065 VNA can measure from 9 kHz to 6.5 GHz, making it ideal for evaluating power plane impedances and measuring inductors and capacitors that might be used in RF designs *(Fig. 2)*. The reflection accuracy (S11) of this device is specified to be ±0.4 dB for measurements from –15 to 0 dB.

Assuming that the datasheet spec of 0.4 dB for S11 accuracy is a 3σ spec, one sigma would be 0.13 dB, or 0.0154 in linear terms. Then:

$$\Delta S11_{max} = 3 * 0.0154 * S11 = 0.0464 * S11$$

(3σ S11 in linear form)

Then:

$$\Delta Z_{max} = \frac{Z0 * 0.0928 * S11}{|1-S11|^2}$$

$$\text{for } S11 = \frac{Z-Z0}{Z+Z0}$$

And now ΔZ_{max} may be evaluated as a function of Z. The measurement error of Z as a function of Z is less than 10% from about 2.5 to 250 Ω. Below and above that range, this measurement method will exhibit very high errors.

IMPEDANCE ACCURACY FOR CONFIGURATION 2: SHUNT-THRU MEASUREMENT

Using Equation 5 again:

$$D_Z = \frac{|\Delta S21_{max}|^2}{9} * [\frac{Z0}{2*(1-S21)^2}]^2$$

$$= \frac{Z0^2 * |\Delta S21_{max}|^2}{36 * |1-S21|^4}$$

Using Equation 2 and following the same logic we arrive at:

$$\Delta Z_{max} = \frac{Z0 * |\Delta S21_{max}|}{2 * |1-S21|^2}$$

Here, $\Delta S21_{max}$ is the maximum expected error on S21, which will come from the datasheet. Copper Mountain Technologies' S5065 VNA has specified accuracy on S21 of ±0.2 dB for S21 values of –60 to 0 dB over most of the frequency range, or 0.0228 in linear terms.

Again, assuming $\Delta S21_{max}$ is a 3-sigma value and squaring to get variance, $D_{\Delta S21}$.

$$D_{\Delta S21} = \frac{|\Delta S21max|^2}{9}$$

For a 3σ ΔZ_{max}, it's $3\sigma = 3 * \sqrt{D_Z}$ (99.7% confidence interval again) or:

$$\Delta Zmax = \frac{Z0 * |\Delta S21_{max}|}{2 * |1 - S21|^2}$$

Assuming that $\Delta S21_{max}$ is 0.2 dB on any S21 value, then in linear terms, the delta is 0.0228 * S21. So, we can plot:

$$\Delta Zmax = \frac{Z0 * 0.0114 * S21}{|1 - S21|^2}$$

and

$$S21 = \frac{2Z}{Z0 + 2Z}$$

IMPEDANCE ACCURACY FOR CONFIGURATION 3: SERIES MEASUREMENT

From Equation 5:

$$D_Z = \frac{|\Delta S21_{max}|^2}{9} * \left[\frac{-2Z0}{S21^2}\right]^2 = \frac{4Z0^2 * |\Delta S21_{max}|^2}{9 * |S21|^4}$$

Assuming ΔZ_{max} is $3\sigma = 3 * \sqrt{D_Z}$ (99.7% confidence interval again) or:

$$\Delta Z_{max} = \frac{2Z0 * |\Delta S21_{max}|}{|S21|^2}$$

Using the same value for $\Delta S21_{max} = 0.0228$ from above:

$$\Delta Z_{max} = \frac{Z0 * 0.0228 * S21}{|S21|^2} \text{ and } S21 = \frac{2Z0}{2Z0 + Z}$$

Figure 3 shows the percent error on the measurement of impedance using the three different methods and using the datasheet values from the S5065 VNA for $\Delta S11_{max}$ and $\Delta S21_{max}$.

The shunt error doesn't actually go to zero. The error on the very low reflection would round off the point to about 1%. What's important is the relationship between the three curves. The shunt measurement is best for impedances from 20 to about 80 Ω, while the other two methods work best below and above that range.

As an example, a 2-mΩ resistor was measured with the S5065 VNA, which can measure from 9 kHz to 6.5 GHz using the shunt-thru method *(Fig. 4)*. The test setup includes

Picotest's *(www.picotest.com)* common-mode transformer (model J2102B-N) *(Fig. 5)*.

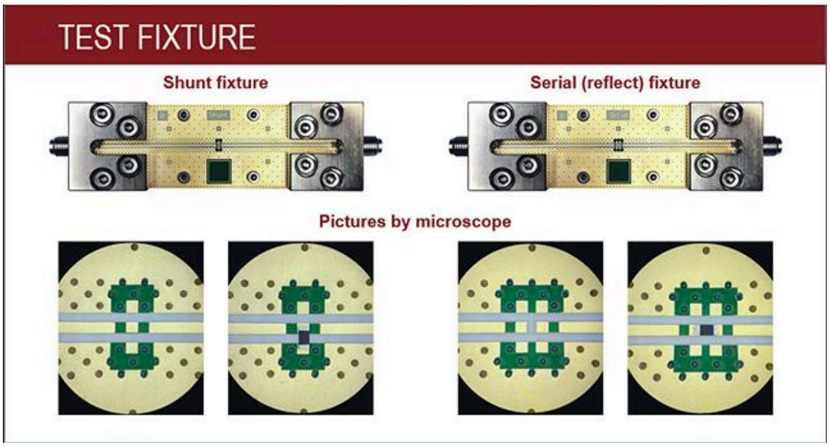
The common-mode transformer is needed to remove the resistance of the cable shield from the measurement. Because this is a shunt measurement, the return is through the system ground and it's important to deal with the parasitic ground resistance to get a good measurement of a low impedance. The transformer does this and maintains a good 50-Ω match up to about 300 MHz. *Figure 6* shows the measurement results.

The measurement looks very solid and shows 2.085 mΩ at 35 kHz. As the frequency increases, the lead inductance becomes apparent and the impedance rises quickly. This might seem unlikely, but since the resistance is so small, it doesn't take much lead inductance to cause this to occur. In this case, it's about 80 pH.

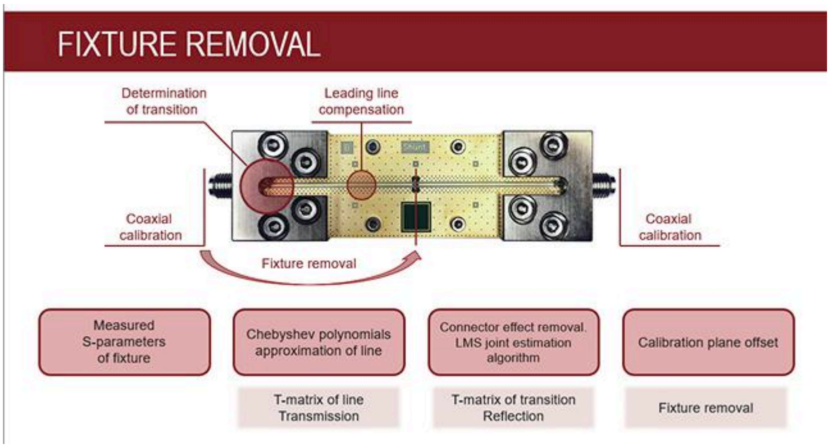
Clearly, if one was depending on this resistor to be 2 mΩ at 100 MHz, there would be a problem.

This same measurement setup may be used to easily evaluate the capacitance, self-resonance, and equivalent series resistance (ESR) of capacitors, as well as the inductance, resistance, and self-resonance of inductors. To facilitate these measurements, Copper Mountain Technologies offers fixturing *(Fig. 7)*.

Calibration is accomplished through regular cable calibration followed by fixture removal *(Figs. 8 and 9)*.



7. Shown are various test fixtures from Copper Mountain Technologies.



8. Fixture calibration is depicted here.

9. Different forms of the measurement test stand can be used.

CONCLUSION

It's important to understand how to make impedance measurements with a VNA to achieve the best accuracy. Hopefully, the exploration of the three methods in this article has made it clear how to accomplish this task. Thanks to Steven Sandler at Picotest for supplying the common-mode transformer and the many test coupons, including the 2-mΩ shunt used here. mw

REFERENCES

A.A. Savin, V.G. Guba, O.N. Bykova, *Measurement of Electronic Component Impedance Using a Vector Network Analyzer,* UDC 621.317.33.

Steven Sandler, "Power Integrity Measurements with CMT VNAs and Picotest Accessories," 2018, https://coppermountaintech.com/power-integrity-measurements-with-cmt-vnas-and-picotest-accessories/

Nick M. Ridler and Martin J Salter, Centre for Electromagnetic and Time Metrology, *Propagating S-parameter uncertainties to other measurement quantities.*

STUART GLYNN, LIAM DEVLIN, ANDY DEARN, GRAHAM PEARSON | Plextek RFI
www.plextekrfi.com

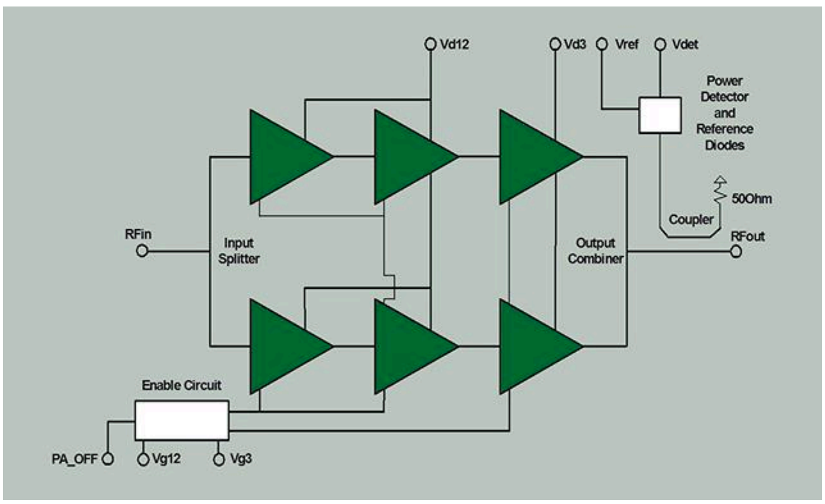
The Design of a Plastic-Packaged PA for 28-GHz 5G

Engineers put a low-cost, 4- × 4-mm, plastic-packaged power amplifier intended for 28-GHz 5G applications through a series of simulations to see how it "measures" up.

Following years of research from the industry's key players, it's widely expected that the first millimeter-wave (mmWave) 5G systems will soon be rolled out. A focus of this research has geared toward the power amplifier (PA), which poses a number of technical challenges.

In addition to having adequate gain and output power capability, a PA for mmWave 5G must linearly amplify waveforms with very high peak-to-average ratios—and do it with a high degree of efficiency. This is particularly important as 5G terminals are expected to adopt a phased-array or switched-antenna topology, requiring the use of multiple PAs. Such architectures also demand that the PA be compact, low cost, and easy to control and monitor.

This article describes the design and evaluation of a surface-mount-technology (SMT) packaged PA for the 28-GHz 5G band (27.5 to 28.35 GHz), which successfully addresses these technical challenges. The part was developed by Plextek RFI *(www.plextekrfi.com)* and fabricated on WIN Semiconductor's *(www.winfoundry.com)* PE-15 process, which is a 4-V, 0.15-µm enhancement-mode gallium-arsenide (GaAs) P-HEMT process. It's conveniently housed in a compact and low-cost 4- × 4-mm plastic overmolded SMT-compatible QFN package. It offers good performance across a frequency range of 27 to 29 GHz, thereby readily encompassing the full 28-GHz 5G band.



1. The integrated power-amplifier IC features two three-stage PAs.

28-GHZ 5G PA ARCHITECTURE

Figure 1 depicts the block diagram of the PA integrated circuit (IC). It consists of two equal three-stage PAs that are joined at the input by an in-phase power splitter and at the output by an in-phase power combiner. Located after the power combiner is a compact directional coupler used for power-detection purposes. The coupled signal is rectified by a forward-biased detector diode, which has a temperature-compensated characteristic thanks to an identical and equally forward-biased reference diode. The temperature-compensated detector output is given by "Vref – Vdet," which can be readily monitored by an analog-to-digital converter (ADC).

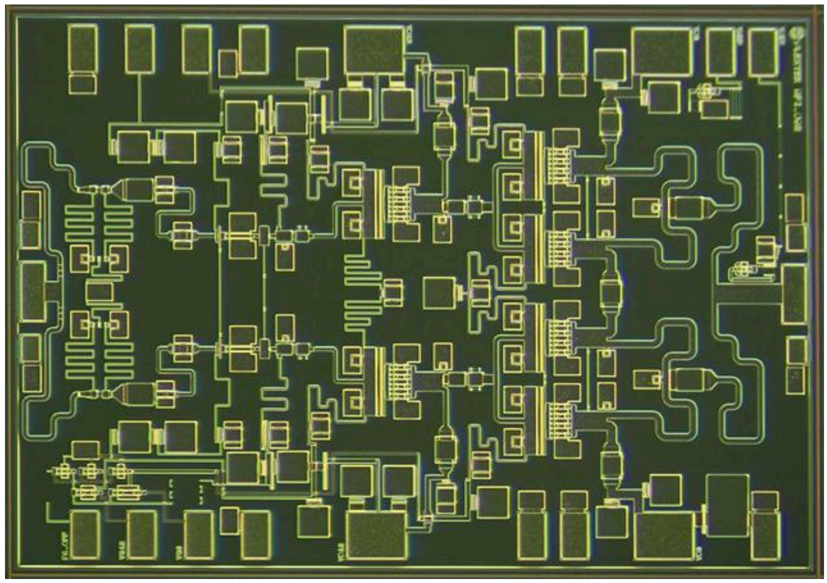
Also included is a fast-switching enable circuit, which is controlled by the logic signal "PA_OFF." This can be used to rapidly power up and power down the PA such that it draws just 0.1 mA of current when not in use, thus maximizing overall system efficiency. In power-down mode, "PA_OFF" is set to +2.5 V; in normal operation, it's set to 0 V.

During operation, the PA is typically backed-off from compression to preserve modulation fidelity of the transmitted signal. With this in mind, the design approach adopted involved optimizing the PA's performance when operating at 7-dB back-off from 1-dB compression (P1dB). A deep Class AB bias scheme was utilized so that the power-added efficiency (PAE) could be optimized at this operating point.

The design commenced by selecting the optimum transistor size for the output stage, followed by load-pull simulation trials to assess the optimum impedances for best linearity and PAE at back-off at different quiescent bias conditions. The tradeoff in gain, linearity, and PAE was then evaluated and the optimum bias condition determined.

Optimum transistor sizes for the driver and pre-driver stages were selected as the design of the complete three-stage PA progressed. Again, careful tradeoffs were considered. Larger transistor sizes improve the overall linearity but reduce the PAE. With the size and bias of all transistors selected, the detailed design of the matching and biasing circuitry could proceed.

The layout was considered from an early stage of the design process to ensure that a practical implementation was possible without incurring unacceptable parasitics. A common gate bias line was used for stages one and two (applied at pin PA_Vg12). A separate bias line was used for stage three (PA_Vg3). This allowed for the possibility of separately optimizing the two voltages for potential linearity or PAE improvements to the PA. The drain supplies were similarly applied through two separate pins. However, these were connected on the printed circuit board (PCB) used to evaluate the packaged parts. The +4-V drain supply is applied at "PA_Vd12" and "PA_Vd3."



2. The size of the PA die is a mere 2.85 × 1.99 mm.

To ensure good RF performance, careful electromagnetic (EM) simulation was essential. A step-by-step approach was adopted, adding each part of the circuit to the EM simulation one at a time, with the rest of the circuit still being simulated using process-design-kit (PDK) models. As the IC was destined for packaging in an overmolded plastic package, the EM simulation also needed to account for the presence of the molding compound atop the IC.

Figure 2 is a photograph of the PA die. The engineering die size measures just 2.85 × 1.99 mm, but this can be reduced to 2.85 × 1.85 mm for mass production. Its pad/pin positions are similar to those shown in the block diagram *(Fig. 1, again)*, although it incorporates a number of GND pads to make it fully RF-on-wafer (RFOW) testable. RFOW test also requires that the drain voltages are applied at each side. When assembled in a package, however, the drain bias only needs to be applied on one side.

The IC was designed to be packaged in a low-cost plastic overmolded 4- × 4-mm QFN. In addition, to account for the effects of the molding compound, the RF transition from IC to PCB needed to be carefully optimized. A custom leadframe was designed to facilitate this operation, and the RF ports of the package are all implemented as ground-signal-ground interfaces.

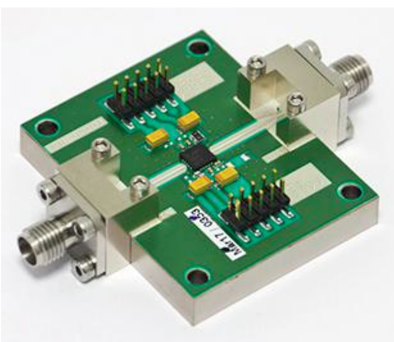
MEASURED AND SIMULATED PERFORMANCE

Prior to packaging, several of the die were tested RFOW, which confirmed that the first pass design had been successful (the RFOW results are not presented here). All measurements were made on a packaged assembled IC mounted on a representative evaluation PCB.

The evaluation PCB was designed using a low-cost laminate PCB material suitable for volume mass production. Samples of the packaged PAs were assembled onto the evaluation PCBs. All of the measured performance is

The evaluation PCB was designed using a low-cost laminate PCB material suitable for volume mass production.

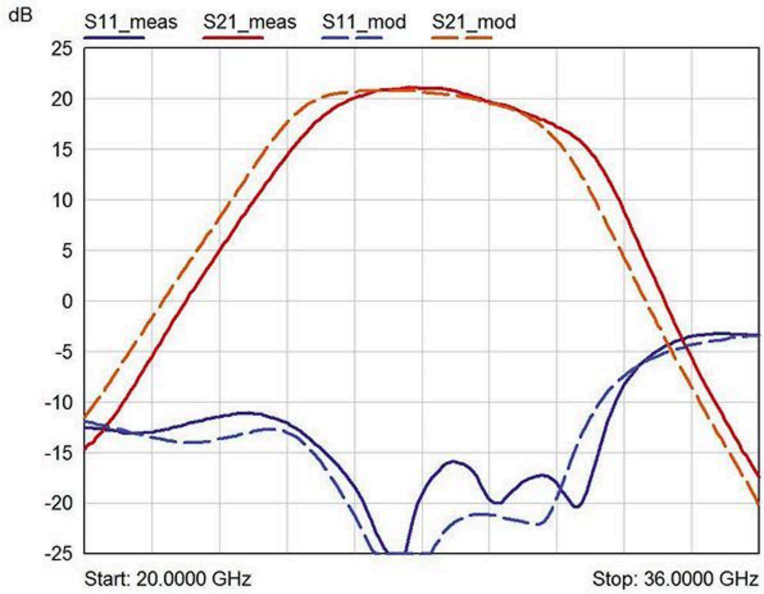
calibrated to the package pins on the evaluation PCB and includes the effects of the IC-to-PCB transition. A thru-reflect-line (TRL) calibration tile was designed to allow for calibration of the measured performance to the reference planes of the package. *Figure 3* shows a photograph of one of the evaluation PCBs.



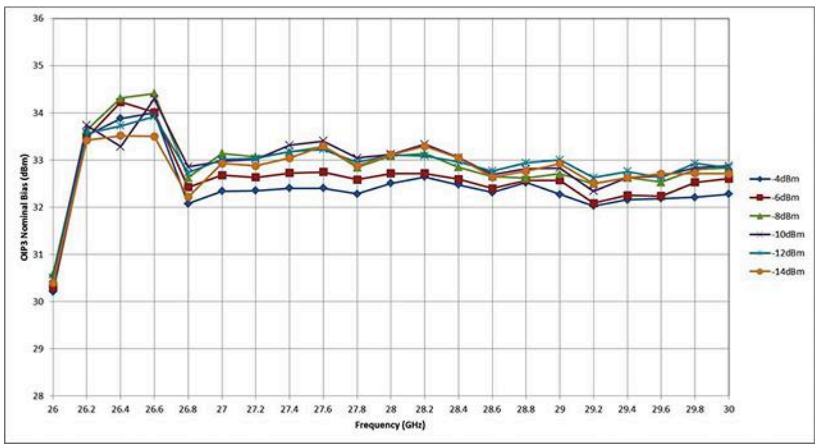
3. Here, the PA is housed on an evaluation board.

All of the measured results presented correspond to the packaged PA monolithic microwave integrated circuit (MMIC) mounted on the PCB. The measurements are referenced to the RF pads of the package. Throughout the evaluation, a commercially available multichannel digital-to-analog converter (DAC) and ADC IC was used to control and monitor the PA. Conveniently, the PA does not require any negative voltages, since it was designed on an enhancement-mode process.

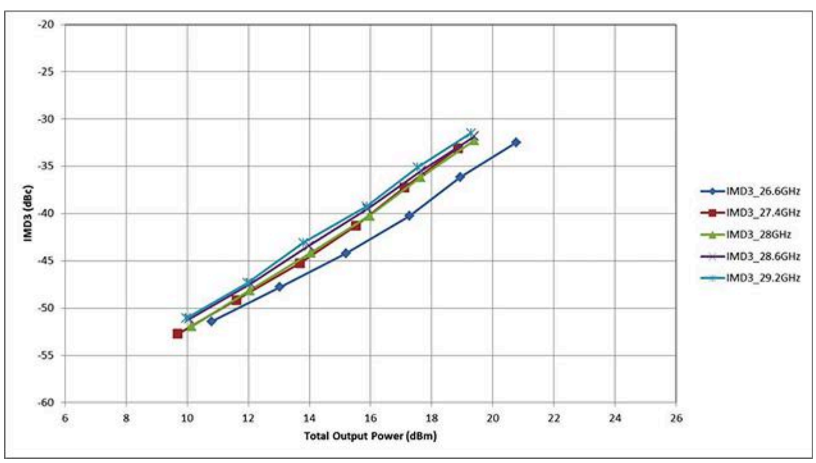
Figure 4 compares the measured-to-simulated S-parameters of a typical PA.



4. Measured and simulated PA S-parameters are plotted.



5. Shown is measured OIP3 versus frequency for different input tone levels.



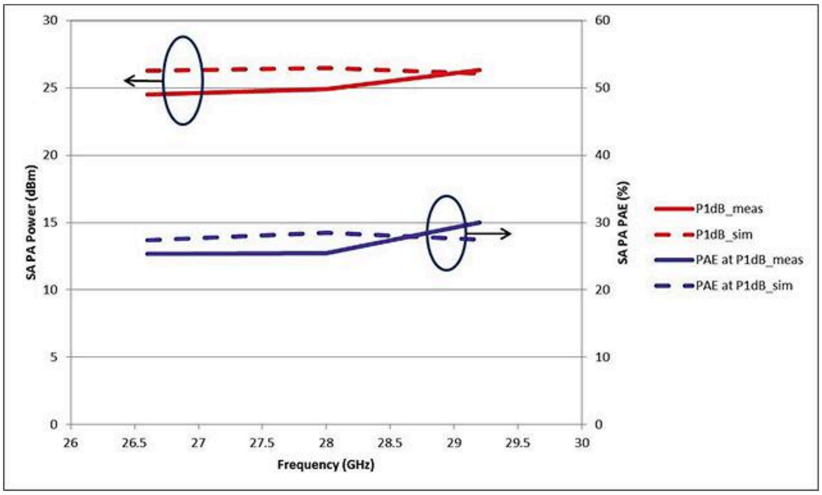
6. Measured IMD3 versus output power is given at five different frequencies.

The PA MMIC described here will potentially play a vital role in 28-GHz 5G systems. The part, which has been shown to address all of the requirements for integration into mmWave phased-array or beam-switched terminals, offers excellent linearity and efficiency. The key performance specifications were met, ensuring that the part is highly suitable for mmWave 5G applications.

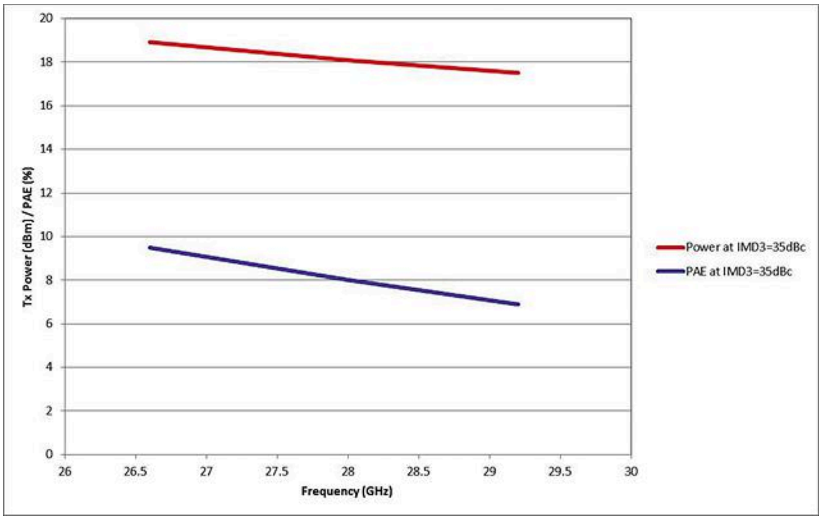
The solid traces represent the measured data, while the dashed traces depict simulated results. The PA is biased to around 180 mA total quiescent current from +4 V. Small-signal gain (S21) is above 20 dB from 27 to 29 GHz. The input return loss (S11) is better than 16 dB across the band. The output is matched for best PAE at back-off rather than best S22, but the measured S22 (not shown) is 8 dB or better across the band.

To reflect the wide channel bandwidths anticipated in 5G systems, the output-referred third-order intercept point (OIP3) of the PA was evaluated with a tone spacing of 100 MHz. The measured OIP3 of a typical PA is plotted in *Figure 5*, with the wanted output tone powers ranging from +7 to +17 dBm per tone. One can see that the OIP3 is around +32.5 dBm across the 5G band and shows very little variation with tone power over a 10-dB dynamic range. The data was rearranged to plot IMD3 versus total output power *(Fig. 6)*. This indicates that at an operating point of around +18 dBm, the corresponding IMD3 is –35 dBc. This key target performance parameter—among others—was successfully met.

To provide a figure of merit for comparative purposes, the output-referred P1dB and PAE were also measured, although 5G systems will require linear amplification to preserve modulation fidelity. The measured performance is plotted in *Figure 7* using solid traces, revealing a P1dB around +25 dBm. The corresponding PAE is around 25.5%, rising to 30% at the top of the band. *Figure 7* also shows the simulated P1dB and corresponding PAE (dashed traces), which are in good agreement with the measured data.



7. In terms of measured and simulated P1dB and PAE versus frequency, a measured P1dB of about +25 dBm was achieved.



8. This is the measured power and PAE operating at about 7-dB back-off.

As mentioned above, the PA is designed for optimum performance (OIP3 and PAE) when operated at around 7-dB back-off from P1dB, or more specifically, with the third-order intermodulation products (IMD3) at a level below −35 dBc relative to the wanted products during a two-tone test with 100-MHz tone spacing. This operating point is close to that envisaged in the 5G system for which the PA was designed.

Figure 8 shows a plot of the measured-to-simulated PAE and total RF output power when operating at an IMD3 point of −35 dBc. The measured PAE is 8%, which is a good result and largely due to the PA being designed to operate in deep Class AB. The total RF output power is around +18 dBm, which equates to an OIP3 level of +32.5 dBm.

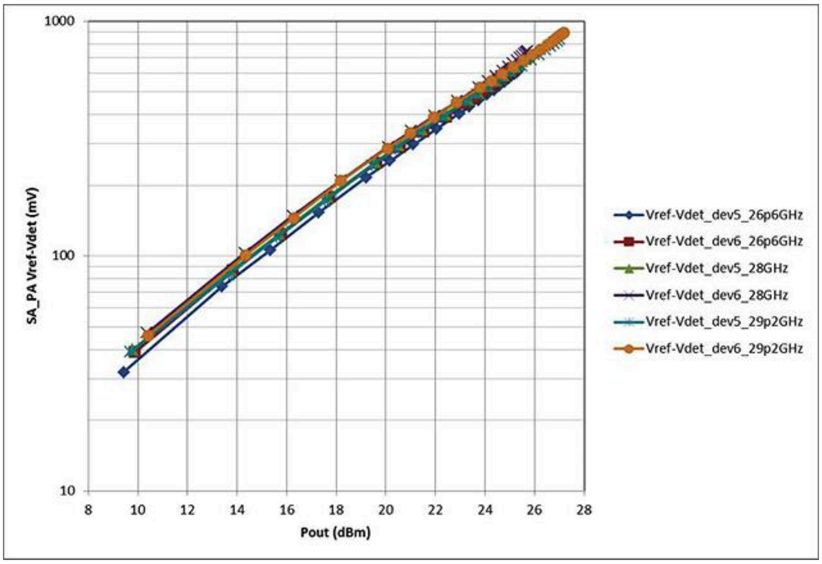
A dc voltage that enables monitoring of the RF output power is provided by the on-chip transmit (Tx) power-detector characteristic. In *Figure 9,* the temperature-compensated detector output "Vref-Vdet" is plotted in mV on a logarithmic scale against output power in dBm for two devices each measured at three frequencies over a 17-dB dynamic range. On this scale, the characteristics are very similar—and linear—which simplifies power monitoring.

The PA's performance was also evaluated using a real wideband 5G signal. The selected test signal was an OFDM waveform of 400-MHz bandwidth with 120-kHz subcarrier spacing using 64-QAM modulation. The waveform has a high peak-to-average ratio of 11.71 dB. The error vector magnitude (EVM) against input power at 28 GHz when the PA is transmitting this signal *(Fig. 10)* indicates that the PA has a high degree of linearity. At an operating point of +18 dBm average output power, the input power is −3 dBm and the EVM is less than 4%. The corresponding PAE at this operating point is 8%.

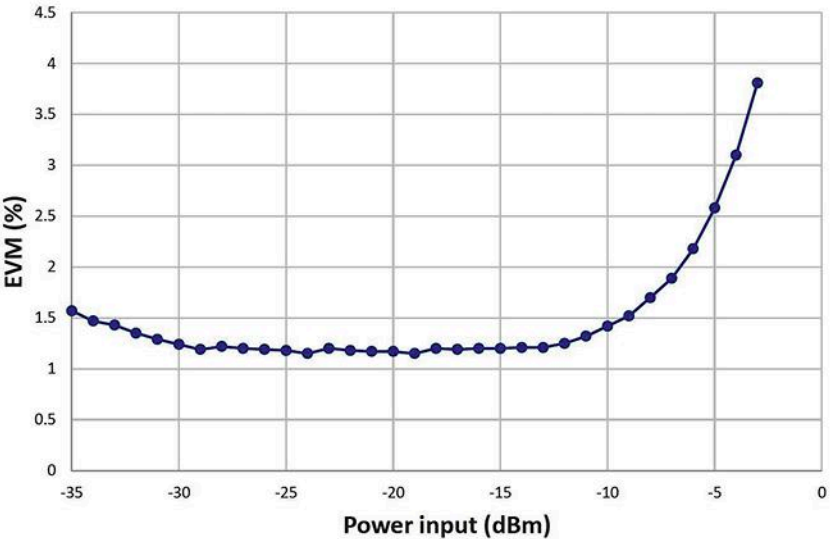
SUMMARY AND CONCLUSIONS

The PA MMIC described here will potentially play a vital role in 28-GHz 5G systems. The part, which has been shown to address all of the requirements for integration into mmWave phased-array or beam-switched terminals, offers excellent linearity and efficiency. The key performance specifications were met, ensuring that the part is highly suitable for mmWave 5G applications.

The IC also includes useful features, such as a Tx power detector and an enable circuit. Realized on a state-of-the-art 0.15-μm enhancement-mode GaAs P-HEMT process, the part is extremely easy to control and monitor using widely available multichannel ADC and DAC ICs. In addition, the part is conveniently housed in a compact and low-cost 4- × 4-mm plastic overmolded QFN SMT package. At an operating point of +18 dBm, the PA has a PAE of 8% and achieves an EVM of less than 4% for a 400-MHz-wide 5G waveform with a high peak to average ratio of 11.7 dB. mw



9. On-chip power-detector outputs of two PAs were measured.



10. This is the EVM versus PA input power at 28 GHz. The conditions included OFDM waveform, 400-MHz bandwidth, and 64 QAM.

JACK BROWNE | Technical Contributor

Sizing Up Semiconductors for 5G Small Cells

Armed with several semiconductor technologies, NXP is readying for the requirements of 5G infrastructure systems with discrete devices and compact modules.

Wireless technology is a large part of modern communications, requiring more bandwidth for growing numbers of users and functions. Much of the promise of 5G wireless cellular networks hinges on optimum use of available bandwidth, especially at millimeter-wave (mmWave) frequencies.

Effective radio networks will require efficient power amplification and NXP Semiconductors *(www.nxp.com)* has recognized that a single semiconductor technology may not be enough for 5G. The semiconductor innovator is developing discrete and integrated device solutions for 5G based on three different in-house technologies: silicon (Si) LDMOS, gallium-nitride (GaN), and silicon-germanium (SiGe) processes. In addition to transistors and amplifiers, the firm has developed integrated multiple-input, multiple-output (MIMO) integrated antenna modules as part of efforts to reduce the size and costs of future wireless cellular base stations.

NXP is perhaps best known as a global supplier of high-power Si LDMOS transistors and amplifiers, widely used as the active analog power devices in cellular communications infrastructure equipment, such as base-station transmitters. With an LDMOS device lineup that includes transistors running on supplies from +7.5 to +65 V dc and delivering RF/microwave output power levels from 1 to 1800 W at frequencies from 1 MHz to 5 GHz, NXP has supported the various generations of wireless cellular equipment in addition to applications in aerospace, broadcast, medical, and military systems.

This is hardly a "single semiconductor process" supplier, though—it draws from expertise in multiple semiconductor processes. At the recent 2019 IEEE International Microwave Symposium (IMS) in Boston, Mass., the firm's representatives displayed packaged devices currently serving 3G and 4G Long Term Evolution (LTE) wireless systems—devices that are also expected to assist the expansion of remote radio heads (RRHs) in 5G systems. In keeping with NXP's approach of matching the semiconductor technology to the application, the devices on display were based on both Si LDMOS and GaN technologies.

One Si LDMOS device, model A3T21H456W23S, was not new for that exhibition, although its performance is noteworthy. The device, a member of the company's Airfast product line, can produce healthy continuous-wave (CW) and peak output power levels from a compact flange package. The N-channel enhancement-mode LDMOS transistor runs on +30 V dc (with quiescent current of 800 mA) and is capable of 87 W CW output power and 562 W peak output power from 2110 to 2200 MHz.

Perhaps what is surprising about the asymmetrical Doherty device is the package: an air-cavity plastic package capable of safely dissipating excess heat for reliable and long transistor operating life. The RoHS-compliant (lead-free) device can withstand high output VSWR (load-mismatch) conditions and is well-suited for applications requiring wide instantaneous bandwidth.

The power transistor features a wide negative-gate-source-voltage range for improved Class C operation and high efficiency; typical drain efficiency is 49.5%. Typical power gain is 14.8 dB at 2110 MHz when tested in a Doherty fixture, with gain rising to 15.3 dB at

2140 MHz. And typical peak-to-average power ratio (PAR) at both frequencies is 8 dB.

The plastic-packaged transistor achieves a typical 3-dB compression point of +56.8 dBm when evaluated with a single-carrier wideband-code-division-multiple-access (W-CDMA) test signal, with typical adjacent-channel power ratio (ACPR) of −30.3 dBc. For many small-cell base-station applications, this transistor will provide the final-stage output power in a multiple-stage amplifier configuration.

GIVE IT THE GaN

To show what it could do in GaN at higher frequencies, the firm also displayed its +48-V dc A3G26H200W17S GaN power transistor for use at 2496 to 2690 MHz. The GaN transistor delivers 30 W CW power and 200 W peak output power over that frequency range. It's also an asymmetrical Doherty device like the A3T21H456W23S, but unlike the LDMOS device, is supplied in an air-cavity ceramic package rather than a plastic package.

The GaN power transistor, which is well-suited for final-stage amplification in small cells, features 56% typical power-added efficiency. It delivers 14.3 dB power gain at 2496 MHz with 13.8 dB power gain at 2690 MHz. The typical PAR at 2496 MHz is 8.2 dB with a typical ACPR of −30 dBc. The typical PAR at 2690 MHz is 7.6 dB with typical ACPR of −36.1 dBc.

As with the lower-frequency LDMOS device, this GaN transistor can function as part of a small-cell, base-station amplification lineup completed by other NXP transistors based on different semiconductor process technologies. For example, the GaN device would serve as the final stage in an amplification lineup that would include a MMG3014N pre-driver device and a A2125D025N driver stage.

In keeping with using different semiconductor technologies for different functions, the MMG3014N is a broadband amplifier based on an indium-gallium-arsenide (InGaP) heterojunction-bipolar-transistor (HBT) semiconductor process. It's also supplied in a plastic package—an SOT-89 surface-mount housing—but this is a small-signal device meant to boost low-level signals prior to power amplification by larger, higher-power semiconductors. The amplifier provides generous gain over a range of 40 to 4000 MHz, with 19.5-dB small-signal gain at 900 MHz.

The driver stage in the three-device cellular amplification lineup, the model A2125D025N, returns to Si LDMOS technology for higher power over a broad frequency range, 2100 to 2900 MHz. It's an integrated circuit (IC) with multiple transistor stages and on-chip impedance matching (to 50 Ω) that runs on supplies of +26 to +32 V dc. Supplied in a multipin plastic package, the IC is capable of 31.7-dB typical power gain or more across the full frequency range, with PAE of 19% or more across that frequency range. The typical CW output power at 1-dB compression is 24 W.

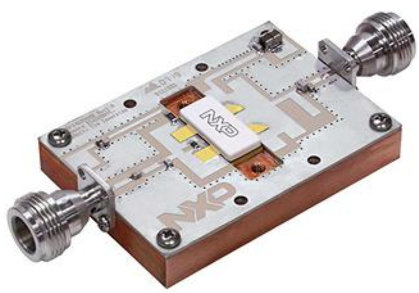
TERMINATING TUBES

In addition to supporting a wide range of traditional applications with its various semiconductor technologies, NXP introduced a GaN-on-silicon-carbide (GaN-on-SiC) power device at the IMS exhibition. It's the company's first such semiconductor device for RF energy applications in the industrial-scientific-medical (ISM) band from 2400 to 2500 MHz.

Designed as a solid-state replacement for high-power magnetron vacuum tubes in such applications as heating and welding systems at 2450 MHz, the MRF-24G300HS *(Fig. 1)* leverages its extremely high efficiency and the high conductivity of SiC to provide high CW output power levels within such a small package. The transistor has a nominal operating temperature range of 0 to +55°C. It's available as model MRF24G300H in an air-cavity ceramic package with mounting flanges and as model MRF-24G300HS in a package without mounting flanges.

When tested in a MRF24G300HS reference circuit *(Fig. 2)* with drain voltage of +48 V dc and gate-source voltage of −5 V dc, and soldered to a heatsink for good thermal flow, the transistor offers typical measured power gain of 15.3 dB at 2400 MHz and 14.9 dB at 2500 MHz

1. Model MRF24G300HS is a high-power GaN-on-SiC transistor developed for CW and long-pulse application from 2400 to 2500 MHz, and as a solid-state replacement for magnetrons at 2.45 GHz in heating and welding systems. *(Courtesy of NXP Semiconductors)*



2. This reference circuit was used to characterize a high-power GaN-on-SiC transistor meant as a solid-state replacement for magnetrons in ISM RF energy applications at 2400 to 2500 MHz. *(Courtesy of NXP Semiconductors)*

MRF24G300H GAN-ON-SIC TRANSISTOR AT A GLANCE*				
Frequency (MHz)	Input power (W)	Output power (W)	Power gain (dB)	Power-added efficiency (%)
2400	10	336	15.3	70.4
2450	10	332	15.2	73.0
2500	10	307	14.9	74.4
*in a model MRF24G300HS reference circuit at +48 V dc drain voltage and – 5 V dc drain-source voltage				

(see table above). Such high-power gain transforms a 10-W CW input signal at 2400 MHz to a 336-W CW output signal and a 10-W CW input signal at 2500 MHz to a 307-W CW output signal.

Typical power-added efficiency (PAE) for the device is 70.4% or better across the full 100-MHz bandwidth, reaching more than 74% at 2500 MHz. It can be used in single-ended or push-pull amplifier configurations and has been characterized for CW operation as well as with short and long (as long as several seconds) pulses.

In addition to its ability to produce high power in much smaller footprints than magnetrons, power transistors such as the model MRF24G300HS promise longer operating lifetimes than tubes with much more flexibility than magnetrons. That's due to bias control, which makes it possible to dynamically adjust the power, frequency, and phase of the output signal energy of the transistor for optimum heating/welding results.

The high-power density of GaN semiconductor materials makes them well-equipped for RF energy applications, even compared to Si LDMOS technology: The 73% drain efficiency measured for the MRF24G300HS transistor at 2.45 GHz is five percentage points higher in PAE than the most advanced Si LDMOS devices at the same frequency. In addition, the GaN-on-SiC transistor exhibits its high output impedance compared to LDMOS devices, to enable broadband impedance matching compared to LDMOS devices, The MRF24G300HS also features simplified gate biasing to remove some of the mystery from starting the power-up sequence for GaN transistors.

HANDLING HIGHER FREQUENCIES

These LDMOS and GaN devices will provide usable transmit power levels within frequency bands currently used for 3G and 4G systems as well as some lower-frequency bands of 5G from about 600 MHz to 6 GHz. But what about handling the 5G signals reaching into mmWave frequency bands, such as from 26 to 29 GHz and 37 to 40 GHz?

NXP is exploring the use of massive multiple-input, multiple-output (mMIMO) active-antenna arrays for use in RRHs of 5G small cells utilizing multifunction (such as switching and amplification) multichip modules (MCMs) in miniature surface-mount packages, including packages measuring 10 × 6 mm and 4 × 3 mm. The MCMs are based on the firm's various semiconductor technologies, such as Si LDMOS and GaN. In addition, the modules include matching to 50 Ω to simplify integration in mMIMO antenna systems.

These antenna systems are being developed with 16 to 64 transmit and receive paths/antenna elements in a single active antenna constructed with antenna elements, filters, switches, antenna modules, and impedance matching under cloud-based automated control. Such mMIMO antenna systems have already been applied in time-division-multiple-access (TDMA) formats and are expected to move to frequency-division-multiple-access (FDMA) configurations with the design and construction of 5G infrastructure equipment.

In quest of semiconductor solutions at 5G mmWave frequencies, such as 26 through 40 GHz, NXP refers to its silicon-germanium (SiGe) semiconductor technology as a "sweet spot" for low cost and power consumption compared to other semiconductor technologies. The semiconductor technology has long held the promise of low-noise, high-gain capabilities in heterojunction bipolar transistors (HBTs) for microwave and mmWave frequencies while producing discrete devices and ICs on low-cost silicon semiconductor substrates. If 5G grows as expected, SiGe semiconductor process technology could reach high mass-production numbers in devices for predriver, driver, and output stages in potentially millions of RRHs and small cells. mw

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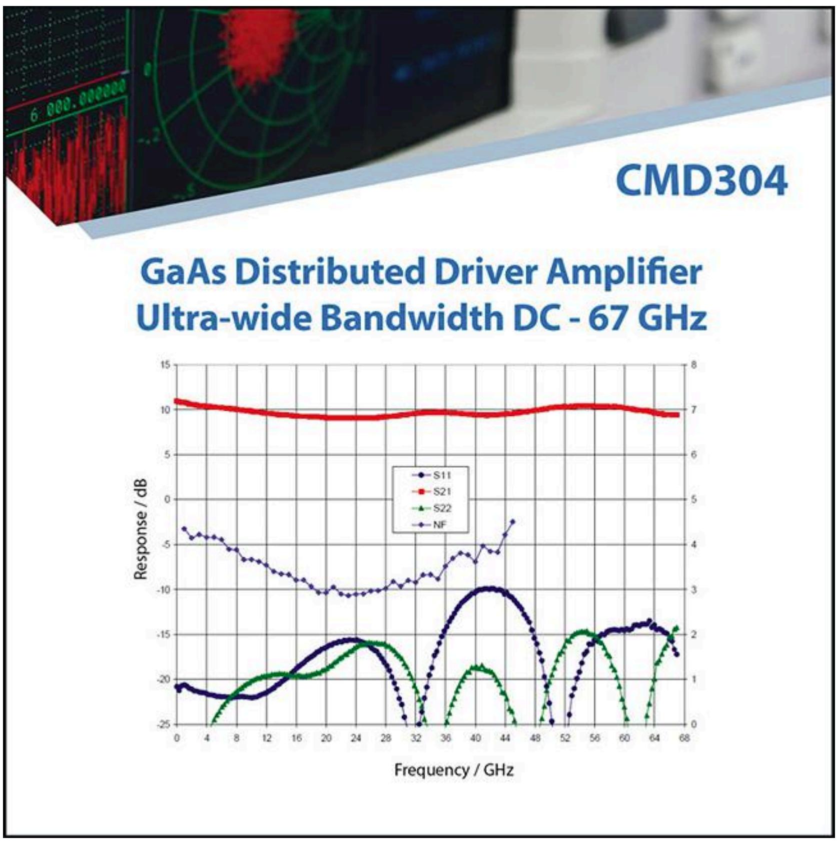
SMALLER MMIC PLAYERS SHINE at IMS

WHEN WALKING THE SHOW FLOOR at IMS 2019, it was easy to spot the big names in the microwave industry with their large booths and various company representatives on hand. However, one shouldn't forget about the contributions being made by smaller companies throughout the industry. For instance, a couple of them are making a big impact in the monolithic-microwave-integrated-circuit (MMIC) space, demonstrated by several new products announced in time for IMS.

Though it might be considered a smaller firm, Custom MMIC *(www.custommmic.com)* has established itself as a major player in the MMIC arena. At IMS, the company's new CMD304 MMIC was front and center. The CMD304 is a gallium-arsenide (GaAs) distributed driver amplifier that operates from dc to 67 GHz. What's impressive about the CMD304 is its flat gain over a wide frequency range *(Fig. 1)*. At 30 GHz, the CMD304 achieves a gain of 9.5 dB, a noise figure of 3 dB, and an output 1-dB compression (P1dB) of +11 dBm.

Another relatively diminutive company that's made a name for itself in the MMIC world in recent years is Guerrilla RF *(www.guerrilla-rf.com)*. While the company didn't have a booth at IMS, several new product announcements were made in time for the show.



1. Shown are the performance plots of the CMD304 distributed driver amplifier. The amplifier maintains flat gain over a frequency range of dc to 67 GHz.

One announcement centered on Guerrilla RF's first two power-amplifier (PA) products that utilize indium-gallium-phosphide (InGaP) heterojunction-bipolar-transistor (HBT) technology. The GRF5504 high-efficiency PA, which covers a frequency range of 400 to 500 MHz, delivers as much as 3.5 W of saturated output power *(Fig. 2)*. With a bias voltage of +5 V, the GRF5504 provides a typical gain of 41 dB at 460 MHz. Applications for the GRF5504 include RFID and automatic meter readers.

The second new InGaP HBT PA is the GRF5509, which covers a frequency range of 700 MHz to 1 GHz. The GRF5509 can deliver 5 W of saturated output power. At 915 MHz, it achieves a typical gain of 34 dB and has a power-added efficiency (PAE) of 58% at the saturated output power level. The amplifier is intended for the 900-MHz industrial, scientific, and medical (ISM) market, as well as automatic meter readers and RFID applications.

Guerrilla RF also announced the expansion of its AEC-Q100 Class 2 qualified component portfolio to satisfy the requirements of demanding automotive applications. This disclosure comes after the company revealed two automotive-qualified products back in February: the GRF2073-W ultra-low-noise amplifier and the GRF4002-W broadband low-noise gain block.

2. The GRF5504 high-efficiency PA can deliver 3.5 W of saturated output power.

Following that development, Guerrilla RF announced that two additional products completed AEC-Q100 Class 2 qualification: the GRF2012-W broadband gain block and the GRF2501-W ultra-low-noise amplifier. The GRF2012-W offers low noise figure and good linearity over a frequency range of 700 MHz to 3.8 GHz. Specifically, at 900 MHz, the GRF2012-W achieves a noise figure of 2.7 dB and an output P1dB of +23 dBm when operating from a +5-V supply.

The GRF2501-W ultra-low-noise amplifier covers a frequency range of 4.9 to 6.0 GHz. With a bias voltage of 3.3 V, the amplifier's gain and noise figure at 5.5 GHz are 17 dB and 1 dB, respectively. The company also stated that several other products will complete AEC-Q100 Class 2 qualification before the end of the year. ■

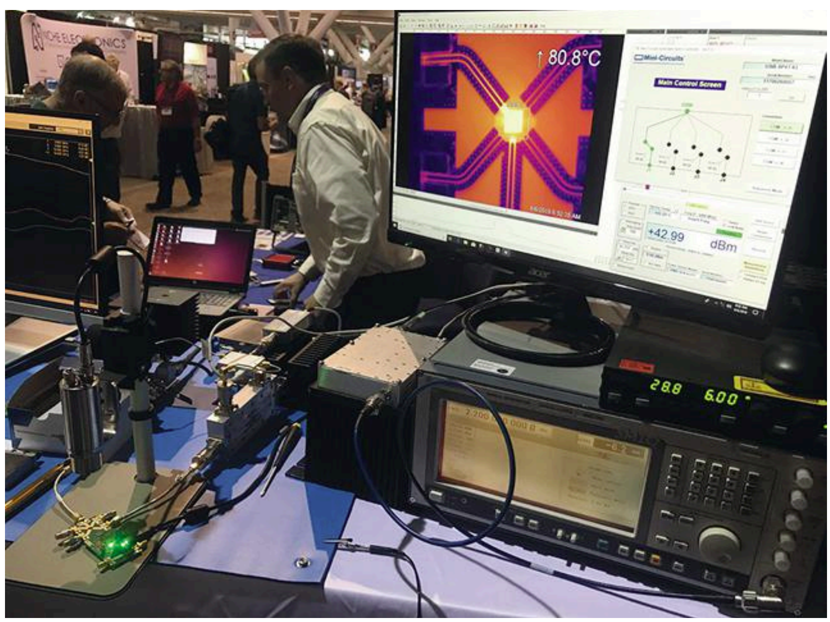
MAKING THE SWITCH PITCH at IMS 2019

SWITCHES ARE IMPORTANT COMPONENTS for applications like test-and-measurement instrumentation, among many others. Simply put, any scenario that involves signal routing requires an appropriate switching solution. Those attending the exhibition at IMS 2019 had an opportunity to get a firsthand look at some of the latest switches to hit the market.

One company making an impact in this arena is Menlo Micro *(www.menlo-micro.com)*, which recently unveiled its MM5120 and MM5130 single-pole, four-throw (SP4T) switches. The MM5130 was demo'd at IMS, giving visitors an opportunity to see the device's wideband performance and high power-handling capability in person *(Fig. 1)*.

Looking at its specifications, the MM5130 micro-mechanical SP4T switch operates from dc to 18 GHz. The device can handle 25 W of continuous-wave (CW) power along with 150 W of pulsed power. At 6 GHz, the MM5130 achieves an insertion loss of 0.2 dB. In addition, the switch's third-order input intercept point (IIP3) is in excess of +85 dBm, and it achieves 25 dB of isolation at 6 GHz.

According to Menlo Micro, the MM5130 is rated for more than 3 billion switching cycles at +85°C. The device comes in a 2.5- × 2.5-mm wafer-level chip-scale package (WLCSP). Markets for the

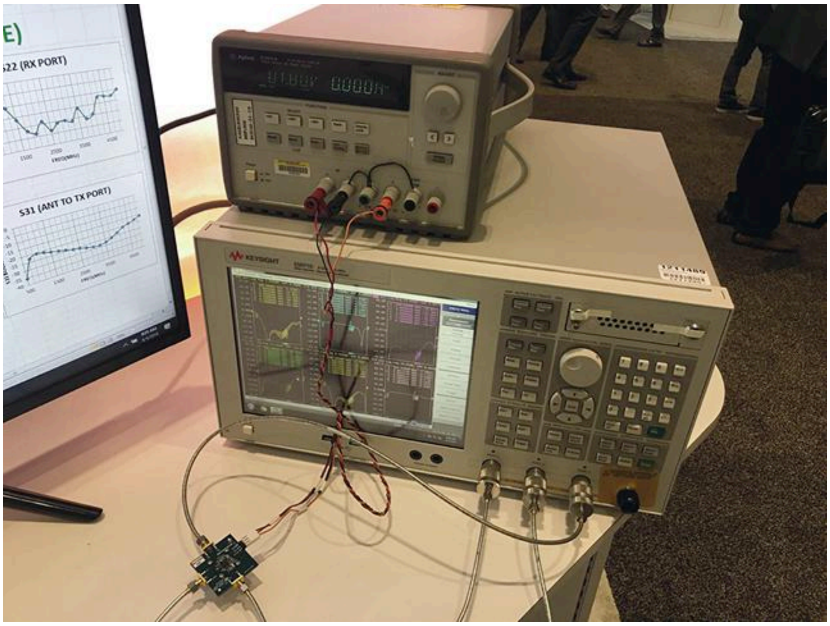


1. At IMS, Menlo Micro demonstrated how its MM5130 SP4T switch still performs when driven by a high-power signal.

MM5130 include aerospace and defense, test-and-measurement systems, and wireless infrastructure.

Menlo Micro's other new high-power SP4T micro-mechanical switch is the MM5120. This device covers a frequency range of dc to 12 GHz. At 6 GHz, the MM5120 is also rated for 25 W of continuous-wave (CW) power and 150 W of pulsed power. Furthermore, the switch achieves 0.35 dB of insertion loss at 6 GHz. The MM5120 comes in a 4.0- × 4.0-mm BGA package.

Skyworks *(www.skyworksinc.com)* also showcased its latest RF switching products at IMS. On the show floor, the company demonstrated its SKY12245-492LF 100-W single-pole, double-throw (SPDT) switch with integrated driver circuitry *(Fig. 2)*. The SKY12245-492LF covers a frequency range of 300 MHz to 3.8 GHz. It requires only a single +5-V dc supply and a control voltage that ranges from 0 to 3 V. Intended for LTE time-division-duplex (TDD) applications, the device comes in a 5.0- × 5.0-mm quad-flat no-leads (QFN) package.



2. At this live demo, visitors saw Skyworks' SKY12245-492LF SPDT switch in action.

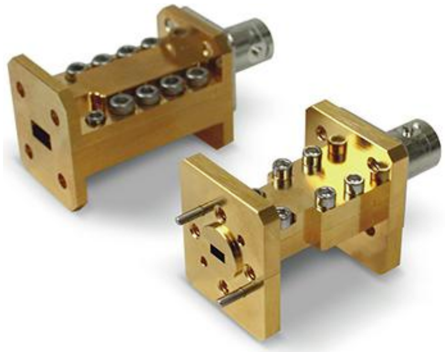
The SKY12247-492LF SPDT switch is an even newer product from Skyworks. This 100-W switch with integrated driver circuitry operates from 3.4 to 3.8 GHz. Also intended for LTE TDD applications, the SKY12247-492LF has typical transmit and receive insertion losses of 0.3 and 0.75 dB, respectively. The device also comes in a 5.0- × 5.0-mm QFN package.

COMPANY SHOWS WHY Noise is the Answer

AT IMS EACH YEAR, Wireless Telecom Group *(www.wirelesstelecomgroup.com)*, comprised of Boonton Electronics *(www.boonton.com)*, CommAgility (www.commagility.com), Microlab *(www.microlabtech.com)*, and Noisecom *(www.noisecom.com)*, always seems to have several demos on hand for visitors to see. IMS 2019 was no exception, as the company showcased a few different test solutions. One was a millimeter-wave (mmWave) noise figure test arrangement that utilized Noisecom's new NC5115A additive white Gaussian noise (AWGN) source *(Fig. 1)*. Wireless Telecom Group also demo'd an over-the-air (OTA) test system that featured Noisecom's NC1128B amplified AWGN source.

The mmWave noise figure solution employed the NC5115A AWGN source, which has a frequency range of 50 to 75 GHz and an excess noise ratio (ENR) of 15.5 dB. This setup was actually a collaboration between Wireless Telecom Group and Tektronix (www.tek.com); measurements were made with Tektronix's RSA5126B real-time signal analyzer *(Fig. 2)*. This analyzer was also used to supply +28 V to the NC5115A AWGN source.

In the setup, the NC5115A drove the device under test (DUT), which was a V-band low-noise amplifier (LNA). The DUT was followed in order by an isolator, LNA, and bandpass filter. After the filter came a mixer, which was used to downconvert to a frequency within the measurement range of the RSA5126B analyzer. Also included in the setup was a local oscillator (LO) that drove the mixer,



1. Noisecom's new NC5115A AWGN source has a frequency range of 50 to 75 GHz.

with the analyzer supplying the LO with a 10-MHz reference.

To determine the noise figure, the test system was first calibrated without the DUT. The DUT was then placed back into the setup. According to Wireless Telecom

Group, measurement uncertainty was reduced thanks to the isolator and the other LNA used in the arrangement. They allowed for a reduction in reflected power between components in the test system by reducing the noise figure of the test setup itself. With this configuration, the company notes that the overall accuracy of the noise-figure measurement is primarily determined by the accuracy of the noise-source calibration.

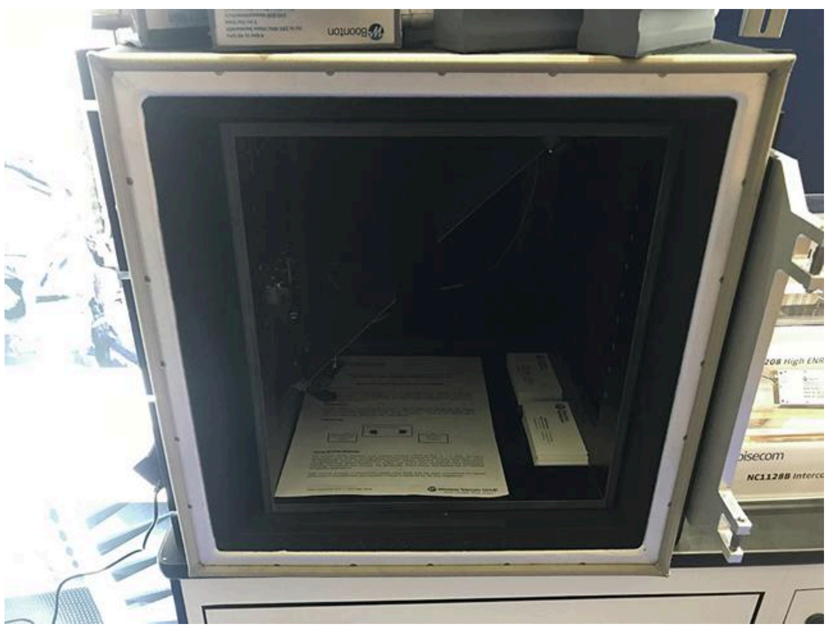
In addition to the mmWave noise figure test configuration, Wireless Telecom Group also demonstrated an OTA test system *(Fig. 3)*. The company is heavily invested in OTA testing, evidenced by the demonstration of an OTA test system at last year's IMS. This year's OTA demo utilized an NC1128B amplified noise module, which has a frequency range of 10 MHz to 10 GHz and can produce AWGN as high as 0 dBm. Wireless Telecom Group asserts that a noise source coupled together with a spectrum analyzer can replace the vector network analyzers (VNAs) used in counterpart test systems.

In this setup, the NC1128B was connected to a spectrum analyzer to obtain a normalized reading. After normalizing the spectrum analyzer, the noise source was connected to a transmitting Vivaldi antenna located inside an RF enclosure. The spectrum analyzer was connected to a receiving Vivaldi antenna that was also inside the enclosure. The results obtained allow one to determine path loss and antenna performance for the band of interest. DVTEST (www.dvtest.com) provided the enclosure and Vivaldi antennas used in the setup.

Wireless Telecom Group believes that this OTA test system implementation represents a cost-effective approach for production test systems. The company also points out other benefits, stating that "current test methodologies use fast-swept continuous-wave (CW) signals to determine the response of the system. Noise sources transmit an OFDM-like signal with high crest factors and offer broadband performance, which is important since these signals are being received and transmitted in modern communication devices."

The company also maintains that "production test systems can be subject to repeated connections, which can degrade connector performance. However, noise sources can simply be switched into the setup to determine if the performance has changed without the time-consuming calibration methods associated with VNA-based setups." ■

2. The NC5115A AWGN source was at the heart of this mmWave noise figure test setup. Tektronix's RSA5126B real-time signal analyzer was used to perform measurements.



3. Shown is the enclosure used in the OTA test solution demonstrated at IMS. Inside the enclosure are two Vivaldi antennas—one for transmitting and the other for receiving.

Software

CHRIS DeMARTINO | Editor

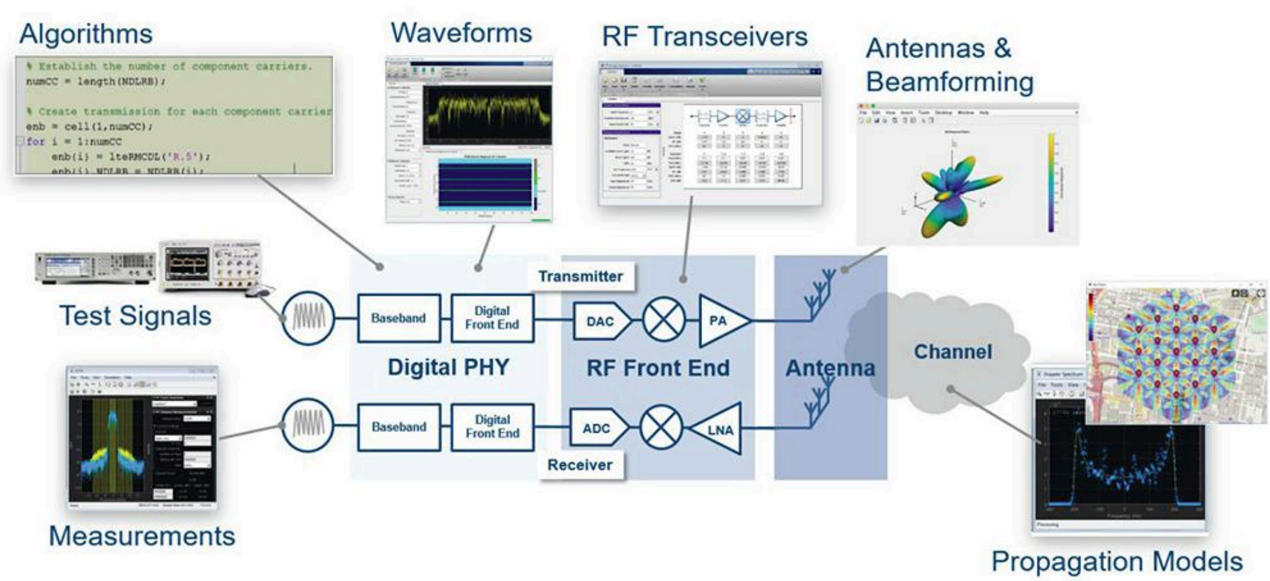
Striving to Unify Next-Generation Workflows

Development of next-gen communications systems often is fraught with obstacles, which led one company to bridge the different areas that constitute modern system design.

MathWorks *(www.mathworks.com)* believes that the complexity of today's wireless standards is creating serious challenges for engineering teams tasked with designing next-generation communications systems. Consider an environment in which multiple design teams are each working in separate disciplines like RF, antenna, analog, digital, software, and systems engineering. According to MathWorks, "designers from these varied and highly specialized engineering fields typically lack access to a single, sharable modeling platform. Instead, they resort to a patchwork of incompatible simulation and test tools that undermine team collaboration."

Furthermore, MathWorks states, "The absence of a unified workflow leaves designers unable to efficiently simulate, test, verify, and validate their designs as early as required to meet shrinking deadlines and tight budgets. Separate teams now spend as much as 70% of their time testing and validating their designs using isolated toolsets. This creates redundancies that lead to costly inefficiencies and project delays. And with new wireless standards emerging—and existing standards constantly evolving—this problem is likely to worsen."

So, how can MathWorks' tools help to overcome these issues? Ken Karnofsky, senior strategist for signal processing and communications at MathWorks, said, "Our customers are often taking advantage of many aspects of our wireless tools. We have a number of products that support various wireless standards, which is an essential part of the solution."



PRODUCT FLEXIBILITY

According to Karnofsky, different customers are using MathWorks products in different ways. "The designers who are creating the algorithms for the physical layer are using our tools at a very detailed level as a design reference. Other engineers, whether they're RF engineers or test engineers, are mostly using the waveforms available in our tools to test models of their RF or antenna designs, or they're using the waveforms in the lab once they have real hardware to be tested.

"Our quest in this market is to try to bridge those different worlds," continued Karnofsky. "Over the last several years, we've done that by enhancing our capabilities not only for the wireless standards, but also for the RF and antenna design. That allows customers to validate their designs in different parts of the system in the same environment. This is really critical in this day and age, because it's very difficult to design one component without considering the impact of the others. Once you have a validated model of the system, you can reuse the test bench and the models as a reference to produce tests that are used in the lab—either in a design validation or testing environment."

"Designers from these varied and highly specialized engineering fields typically lack access to a single, sharable modeling platform. Instead, they resort to a patchwork of incompatible simulation and test tools that undermine team collaboration."

Karnofsky also pointed out how MathWorks' tools can interface directly with test equipment, offering significant advantages. "In the testing world, you can get very sophisticated conformance testing and over-the-air (OTA) testing capability from the RF test-and-measurement vendors. But we've seen that customers are finding they can save time by applying the waveforms and tests they've done in simulations with our tools, and then just connecting directly to those instruments and reusing what they've already done in simulations. That saves time by simplifying and speeding up the comparison of the actual results in the lab with the predicted results in the model."

One way to validate some of the points brought up by Karnofsky is to highlight an actual customer use case. A Qualcomm division in the United Kingdom that develops RF front-end components for 5G systems used MATLAB to build a complete model of the transmit and receive paths. Included were fixed-point digital blocks and power-amplifier models. The team performed simulations to predict system performance measures, optimize design parameters, and automate testing over a range of waveform combinations. Furthermore, the team automatically generated C waveform libraries from the MATLAB 5G models, enabling the delivery of waveform generation to customers. mw

New Products

Programmable Attenuator Tunes Amplitude to 40 GHz

MINI-CIRCUITS' MODEL RCDAT-40G-30 is a programmable attenuator with wide bandwidth of 0.1 to 40.0 GHz. Controllable directly from a PC or over a network via USB or Ethernet, the attenuator can be programmed in 1.0-dB steps from 0 to 30 dB (Mode 1) or 0.5-dB steps from 0 to 29 dB (Mode 2). The attenuation accuracy at all frequencies is ±1 dB for attenuation to 8 dB and ±1.5 dB for attenuation through 30 dB. Insertion loss (at 0-dB attenuation) is typically 12 dB through 24 GHz and 14 dB through 40 GHz. Typical input-to-output isolation is 40 dB across the frequency range. The programmable attenuator is rated for maximum input power of +24 dBm; multiple attenuators can be connected in a master/slave configuration with independent control of each attenuator channel through the single USB or Ethernet connection of the master unit. The RoHS-compliant programmable attenuator is backed by full software support, including a user-friendly graphical-user-interface (GUI) application for MS Windows and a full API with programming details for MS Windows and Linux operating environments (in both 32- and 64-b environments).

MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500; https://www.minicircuits.com/WebStore/dashboard.html?model=RCDAT-40G-30

Linear Amp Drives 20 W to 2000 MHz

THE ZHL-20W-202-S+ FROM MINI-CIRCUITS from Mini-Circuits is a Class AB amplifier capable of 20 W saturated output power from the 20- to 2000-MHz band. It provides 53-dB typical gain with ±2-dB gain flatness across the frequency range and 10-dB typical noise figure. Typical output power is +39 dBm at 3-dB compression with +45 dBm output power at saturation; typical output third-order intercept point is +45 dBm. The RoHS-compliant amplifier exhibits typical input and output VSWRs of 2.0:1 and 3.5:1, respectively, and draws 4 A current from a +28-V dc supply. The power amplifier is unconditionally stable regardless of input and load conditions, with built-in protection against reverse polarity, overdrive, and overheating, plus output stage self-protection from damage against full-power operation into open or short load conditions. Maximum (no damage) input power ratings are +5 dBm into a 50-Ω load and −13 dBm into an open or short load. Available as model ZHL-20W-202-S+ with optional heat sink and fan attachment for cooling and as model ZHL-20W-202X-S+ without attachments, the amplifier is housed in an aluminum-alloy case measuring 4.3 × 6.7 × 1.2 in. with SMA connectors. It's rated for operating temperatures from −20 to +60°C.

MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500; https://www.minicircuits.com/WebStore/dashboard.html?model=ZHL-20W-202-S%2B

Highpass Filter Absorbs Signals Below 1650 MHz

MINI-CIRCUITS' MODEL VXHF-23+ is a unique coaxial highpass filter in which the stopband is matched to the characteristic impedance of the source—50 Ω. Stopband signals are absorbed and terminated rather than reflected to the source. This enhanced performance allows the filter to minimize reflections that can cause intermodulation and distortion and be used with sensitive components, such as broadband amplifiers. The compact filter features a passband of 2010 to 10100 MHz and a stopband of dc to 2,010 MHz, with cutoff frequency of 1,650 MHz. Typical passband insertion loss is 1.2 dB from 2,010 to 10,100 MHz with typical passband VSWR of 1.60:1 from 2,010 to 3,200 MHz and 2.0:1 from 3,200 to 10,100 MHz. The typical stopband rejection is 14 dB from dc to 1210 MHz with typical VSWR of 1.20:1 over that frequency range. The cascadable highpass filter is supplied with a male SMA input connector and a female SMA output connector. It's designed for operating temperatures from −55 to +100°C.

MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500; https://www.minicircuits.com/WebStore/dashboard.html?model=VXHF-23%2B

Crystal Oscillators Drive Automotive Circuits

SURFACE-MOUNT CRYSTAL OSCILLATORS in the HY series feature wide operating temperature ranges that are essential for automotive electronics applications. Oscillators feature 15-pF-load low-voltage-CMOS (LVCMOS) outputs from 1.25 to 50.00 MHz and come with a choice of ±50- or ±100-ppm frequency stability for an operating temperature range of −40 to +125°C. They can also be specified with frequency stability of ±25 ppm for commercial operating temperatures from −10 to +70°C or industrial operating temperatures of −40 to +85°C. Crystal oscillators with nonstandard frequency stability levels, such as ±20 or ±30 ppm, are also available. The oscillators exhibit phase noise of typically −155 dBc/Hz offset 10 kHz from the carrier and −160 dBc/Hz offset 100 kHz from the carrier. Typical RMS phase jitter is 150 fs. The crystal oscillators have worst-case aging rates of ±2 ppm/yr. for the first year with maximum startup time of 5 ms and maximum rise/fall time of 10 ns. They can be supplied in three different package sizes: 3.2 × 2.5 × 1.0 mm, 5.0 × 3.2 × 1.2 mm, and 7.0 × 5.0 × 1.4 mm, with respective supply voltages of +1.8, +2.5, and +3.3 V dc and overall current consumption of 2 to 6 mA.

MERCURY ELECTRONICS (MEC) EUROPE, Blacknell Lane Industrial Estate, Crewkerne, Somerset, TA18 7HE, UK; +44 (0) 1460 230010, Fax: +44 (0) 1460 230011, www.mecxtal-europe.com

Waveguide Antennas Span 40 to 220 GHz

A LINE OF WAVEGUIDE ANTENNAS (with 85 separate models) provides frequency coverage in bands from 40 to 220 GHz. Available in various formats, including standard gain horns, conical gain horns, wide-angle scalar feed horns, and horn lens antennas, the components are well-suited for radar, defense, test, and wireless communications applications. Waveguide sizes range from WR-5 to WR-19 with nominal gain levels from 3.5 to 25.0 dBi. The waveguide antennas are RoHS- and REACH-compliant.

FAIRVIEW MICROWAVE, 17792 Fitch, Irvine, CA 92614; (972) 649-6678, (800) 715-4396, www.fairviewmicrowave.com

Miniature Oscillators Tackle Down-Hole Drilling

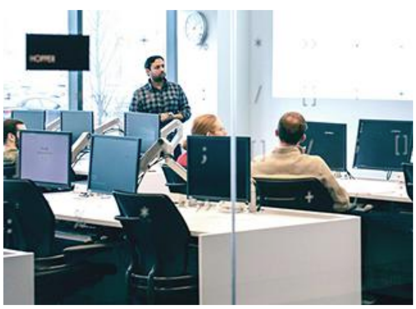
THE QTCH SERIES of miniature crystal oscillators includes sources operating from 1 to 48 MHz with low current consumption (less than 3 mA) from supply voltages of +1.8 to +5 V dc. Designed for extremely wide operating temperatures of –55 to +200°C, these crystal oscillators are well-equipped for down-hole drilling and other high-temperature operating environments. The surface-mount oscillators come in three low-profile packages: 2.5 × 3.2 mm, 3.2 × 5.0 mm, and 5.0 × 7.0 mm. The RoHS-compliant oscillators are ECCN: EAR99 classified and available with MIL-PRF-55310 screening.

Q-TECH CORP., 10150 W. Jefferson Blvd., Culver City, CA 90232; (310) 836-7900, FAX: (310) 836-2157, E-mail: sales@q-tech.com, www.q-tech.com

PLL LNB Tackles Q-Band Satcom Signals

MODEL Q1000H IS A phase-locked-loop (PLL) low-noise block downconverter (LNB) developed for satellite-communications (satcom) and other mmWave applications at Q-band frequencies from 40.5 to 41.0 GHz. Well-suited for remote sensing, terrestrial microwave communications, and radio astronomy, the LNB is a good fit for Q-band satellite terminals, fixed antennas, and radio telescopes. It has an RF range of 40.5 to 41.0 GHz with an intermediate-frequency (IF) range of 950 to 1450 MHz when working with a local oscillator (LO) at 39.55 GHz. The maximum noise figure at room temperature (+25°C) is only 3 dB. The LNB provides as much as 60-dB gain and at least 50-dB gain, with worst-case phase noise levels of –70 dBc/Hz offset 1 kHz from the carrier, –80 dBc/Hz offset 10 kHz from the carrier, and –90 dBc/Hz offset 100 kHz from the carrier. The maximum input VSWR is 2.0:1 with maximum output VSWR of 1.80:1. The Q-band LNB, which draws maximum current of 1 A from a supply of +8 to +13 V dc, delivers at least +5 dBm output power at 1-dB compression. It has an operating temperature range of –40 to +50°C and is equipped with waterproof WR-22 grooved waveguide input and 75-Ω waterproof Type F and 50-Ω waterproof Type N output connectors. The Q-band LNB measures 5.75 × 2.16 × 1.53 in. (146 × 55 × 39 mm) and weighs 700 g.

NORSAT INTERNATIONAL INC., Corporate Headquarters, 110-4020 Viking Way, Richmond, British Columbia; V6V 2L4; sales@norsat.com, www.norsat.com



Math Modeling Software Extends its Educational Reach

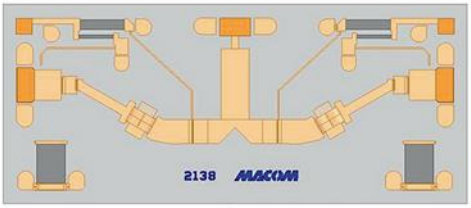
MATHWORKS IS MAKING available expanded access to the MATLAB Parallel Server in support of academic research efforts, allowing educational users with extended capabilities to take advantage of its popular MATLAB mathematical modeling software and Simulink simulation software. All researchers and students at an academic institution with a MathWorks Campus-Wide License with MATLAB Parallel Server will receive unlimited access to scale MATLAB programs and Simulink simulations to computer clusters and cloud networks. The flexible use policy also applies to visiting professors and researchers at the licensed campus. The software supplier already offers a large collection of educational tools and teaching examples for students based on its programs.

MATHWORKS, 1 Apple Hill Dr., Natick, MA 01760-2098; (508) 647-7000, FAX: (508) 647-7001, www.mathworks.com

Power Dividers Reach as High as 67 GHz

A LINE OF HIGH-FREQUENCY power dividers includes wideband two- and four-way coaxial models with bandwidths as wide as dc to 67 GHz. The power dividers, which handle as much as 20 W CW power, are equipped with SMA, 2.92-mm, 2.4-mm, and 1.85-mm connectors, depending on frequency. As an example, model PE20DV1056 is a two-way power divider with 2.4-mm connectors for use from dc to 50 GHz. Typical insertion loss is 7.8 dB or less across the wide frequency range with 14-dB typical isolation between ports. The 50-Ω power divider handles as much as 0.5 W CW input power and 5 W peak power with ±0.2-dB amplitude balance and ±3-deg. phase balancer. For even greater bandwidth, model PE20DV1057 is a two-way power divider with 1.85-mm connectors and similar performance across a frequency range of dc to 67 GHz.

PASTERNACK ENTERPRISES INC., P. O. Box 16759, Irvine, CA 92614; (949) 261-1920, FAX: (949) 261-7451, E-mail: Sales@pasternack.com, www.pasternack.com



Distributed Amplifier Gains on 40 GHz

MODEL MAAM-011275-DIE is a broadband RF/microwave distributed amplifier in chip form for applications from 30 kHz to 40 GHz. For ease of installation in high-frequency circuits, the input and output ports are both matched to a characteristic impedance of 50 Ω. The amplifier's typical broadband performance includes 15-dB gain with ±0.75-dB gain flatness across the full frequency range. The output power at 1-dB compression is +21 dBm and at 3-dB compression is +24 dBm. Typical return loss is 13 dB. The noise figure is typically 5.3 dB across the frequency range. The miniature amplifier typically draws 200 mA current from a +7-V dc supply. It's a good match for applications in communications and test-and-measurement circuits and systems.

MACOM TECHNOLOGY SOLUTIONS INC., 100 Chelmsford St., Lowell, MA 01851; (978) 656-2896, (800) 366-2266, www.macom.com

Coaxial Fixed Attenuators Handle Power to 50 W

A LINE OF HIGH-POWER fixed attenuators includes models for use from dc to 6 GHz with standard attenuation values of 3, 6, 10, 20, and 30 dB and maximum power ratings of 5, 10, and 20 W continuous-wave (CW) power. The attenuators come with SMA or Type N male or female connectors. Higher-power attenuators are also available for use from dc to 4 GHz with CW power ratings of 50 W and peak power ratings to 5 kW with fixed attenuation values as high as 60 dB with flat attenuation (±1 dB or better) across the frequency range.

ARRA INC., 15 Harold Court, Bay Shore, NY 11706; (631) 231-8400, FAX: (631) 434-1116, E-mail: sales@arra.com, www.arra.com

USB Spectrum Analyzer Captures 100 kHz to 20 GHz

THE SM200B SPECTRUM ANALYZER features an instantaneous bandwidth (IBW) of 160 MHz across a wide frequency range of 100 kHz to 20 GHz. Introduced at the recent 2019 International Microwave Symposium (IMS), the spectrum analyzer makes it possible to capture and study even agile signals over that almost-20-GHz total frequency range. The compact analyzer is controlled by a PC and software via a Universal Serial Bus (USB) connection. It provides large block data transfers of a 2-sec. in-phase/quadrature (I/Q) buffer memory using the USB link and includes advanced triggering options such as frequency mask triggering and several post-triggering functions. P&A: $12,300; stock.

SIGNAL HOUND, 1502 SE Commerce Ave., St. 101, Battle Ground, WA 98604; (360) 313-7997, www.SignalHound.com

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(ISSN 0745-2993)

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