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NATIONAL INSTRUMENTS™

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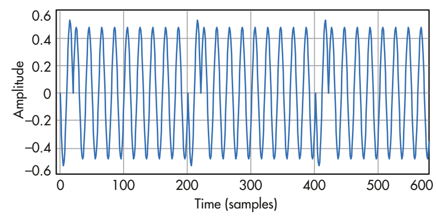

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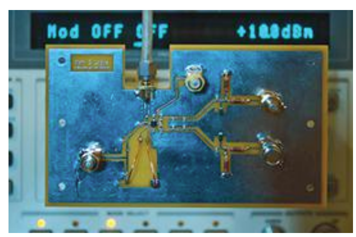

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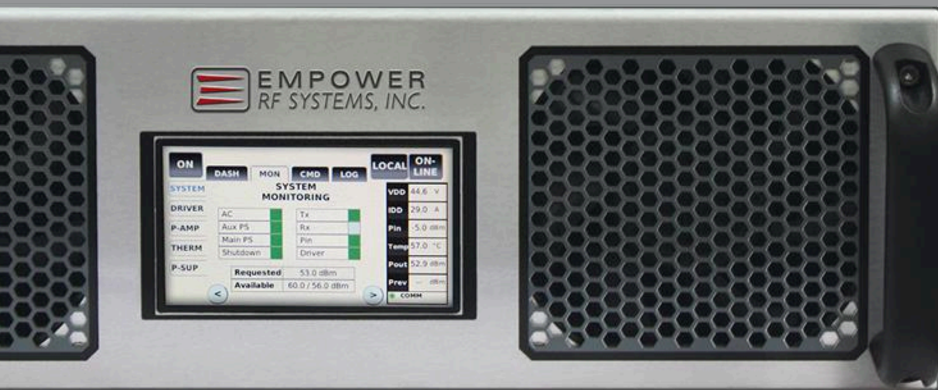
Good Things come in small packages



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BNC, RPSMA, RPTNC & 7/16
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N, 4.1/9.5 / 4.3/10.0 & 7/16 DIN

Low PIM Terminations

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N, 4.1/9.5 & 7/16 DIN

Low PIM Adapters

Up to 18 GHz
SMA, N, 4.1/9.5 & 7/16
RG, LMR & T-flex

Directional Couplers/Hybrids

0.4 - 40 GHz
SMA, 2.92, QMA, N,
TNC, BNC, RPTNC & 7/16
Up to 500 watts

Circulators/Isolators

Up to 40 GHz
SMA, 2.92, N, & 7/16
Up to 250 watts

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Splitters, Adapters & Jumpers
N, 4.1/9.5 & 7/16

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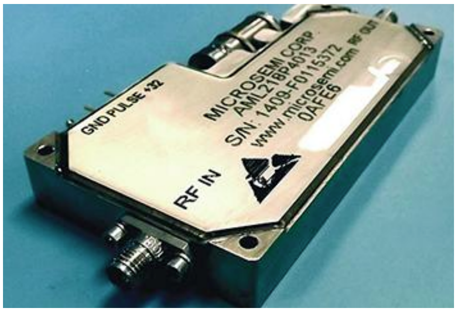
IMAGE GALLERY: HIGH-POWER PRODUCTS

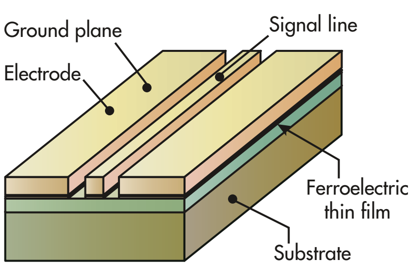


http://mwrf.com/active-components/gallery-6-high-power-rfmicrowave-products#slide-0-field_images-37521

This *Microwaves & RF* image gallery looks at six of the latest high-power products used in applications ranging from satellite communications to wireless infrastructure.

THE MYSTERIES OF TRANSMISSION LINES

http://mwrf.com/systems/untangle-mysteries-transmission-lines



Transmission lines vary structurally and performance-wise, and create challenges during the fabrication process when using different active- and passive-circuit components.

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MODULAR VS. RACK-MOUNT INSTRUMENTS

http://mwrf.com/test-measurement/whats-difference-between-modular-and-rack-mount-instruments

A growing number of PXI/PXIe modular RF/microwave test instruments provide the measurement capabilities and performance levels once possible only with benchtop instruments.

THE FUTURE OF TERAHERTZ LI-FI

http://mwrf.com/blog/terahertz-li-fi-your-future

We already use infrared light for data transmission both on fiber optical cable as well as wireless, but why not visible light? That is the proposed medium for a new wireless technology called Li-Fi (Light Fidelity), similar to Wi-Fi. Read what Contributing Editor Lou Frenzel has to say about Li-Fi in his latest blog. *(Image courtesy of pureLiFi)*

CHRIS DeMARTINO
Technical Editor
chris.demartino@penton.com

Pushing Technology Higher in the Year Ahead

The New Year is upon us, allowing us to have the opportunity to take a closer look at what the RF/microwave industry will have in store for 2016. While we've seen plenty of technology advancements in recent years, many believe that future technology will reach yet unimagined capabilities. Some of the buzzwords you've undoubtedly been hearing recently are "5G," as well as "the Internet of Things" (IoT). Self-driving cars are another topic of interest, as some are predicting that millions of driverless cars could be on the road by the year 2020. We will see if this actually happens, but the idea helps to demonstrate the vision of technology taking an even greater role in all aspects of our lives in the future.

In the telecommunications arena, the much-anticipated 5G will continue to be a major focus throughout 2016. Despite all of its hype, however, no one is exactly sure what 5G will look like. Millimeter-wave frequencies are being proposed for 5G, as a large amount of spectrum is available in these frequency bands. We can expect to hear all sorts of news and updates throughout the year as researchers transition 5G from concept to reality.

The IoT, of course, has been creating major headlines. A Google search on "IoT" would produce countless results. However, opinions of what the IoT actually is and will be vary greatly. Some believe that the IoT promises to bring us a "smarter and more connected" world. In response to a recent article from our sister publication, *Electronic Design* ("11 Myths About the Internet of Things," *http://electronicdesign.com/iot/11-myths-about-internet-things*), however, one reader commented that the IoT is a "passing fad." Another respondent commented that the IoT is "more of a language and culture hype than a technical hype." These responses are in stark contrast to the hoopla surrounding the IoT, proving that the real rollout and implementation of IoT is still up for debate.

Beyond 5G and the IoT, 2016 promises to introduce plenty of innovation from the RF/microwave industry. The many mergers and acquisitions that have occurred in the semiconductor industry are now taking form, as these newly structured companies look to drive technology forward in 2016 and beyond. For example, Qorvo has much in store for 2016 after its successful first year. Following its merger with Freescale Semiconductor, the new NXP Semiconductors plans to deliver a variety of solutions to its customers. And Ampleon—created following the NXP-Freescale merger—intends to offer its own RF power solutions. Stay tuned, as 2016 promises to be very interesting. mw

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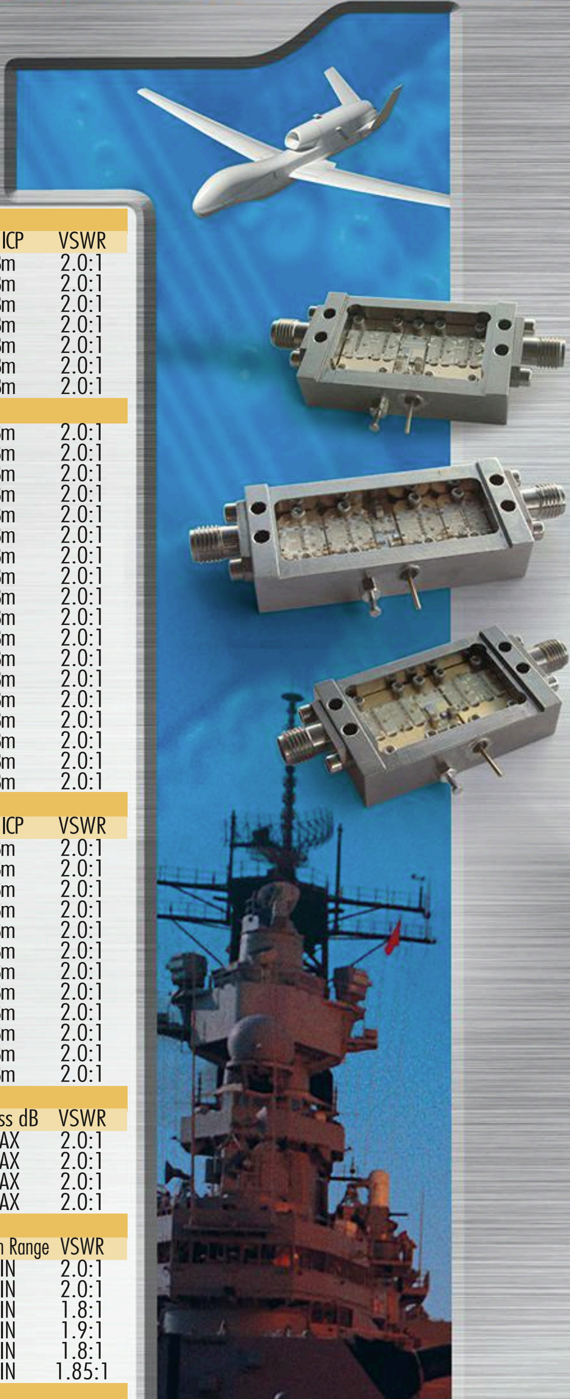

OCTAVE BAND LOW NOISE AMPLIFIERS

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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WHAT'S IN A NAME?

Astute readers may have noticed a bit of an anomaly in the December 2015 issue of *Microwaves & RF*, between the front-cover photography and the Cover Feature article (on p. 63) featuring the model M9393A PXIe vector signal analyzer (VSA) from Keysight Technologies (www.keysight.com). While the high-performance 50-GHz VSAs pictured on the front cover and the first page of the article are the same, the company logos appearing on the top of each instrument module are different: Agilent and Keysight.

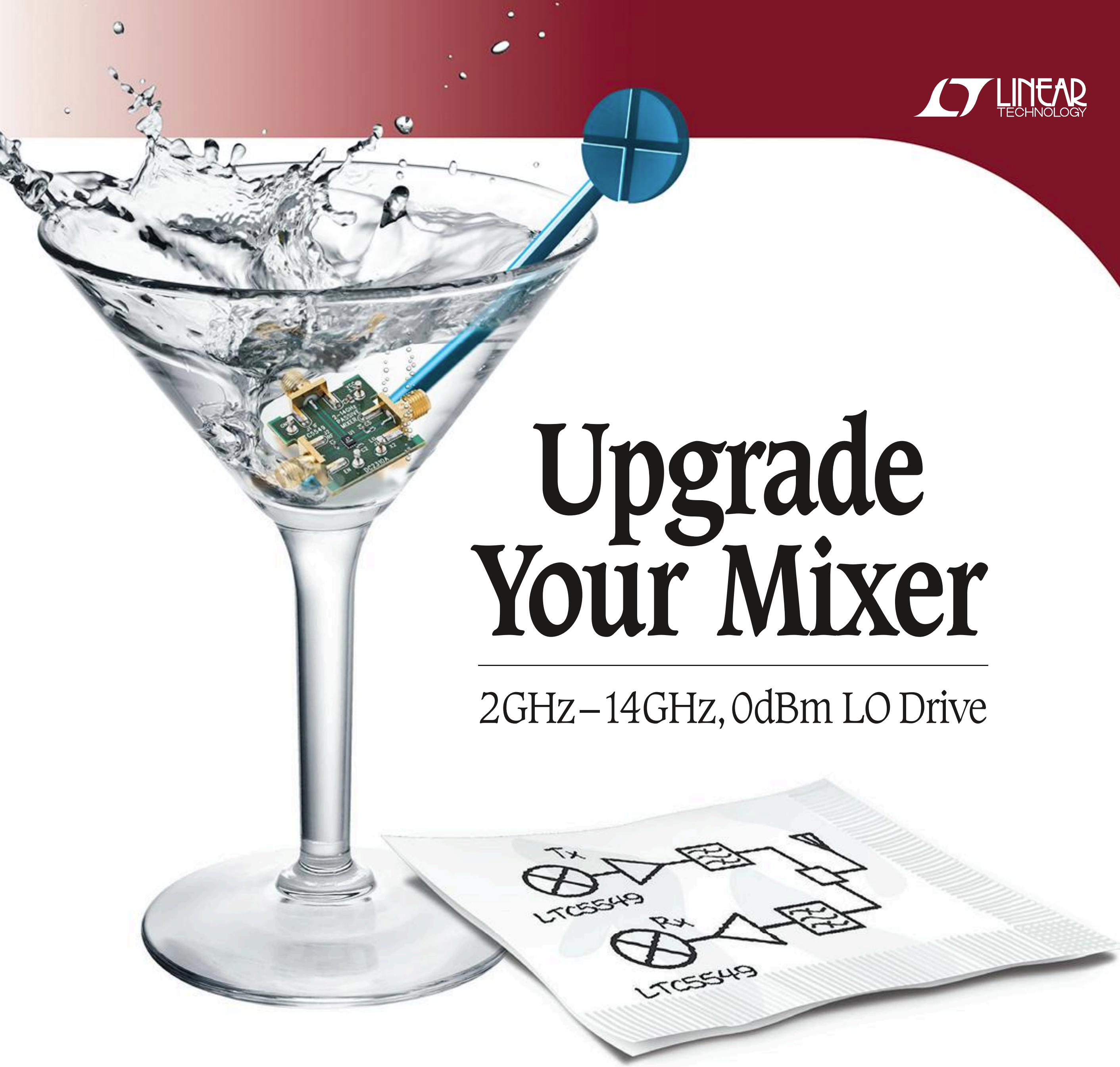
First of all, apologies to our readers for the mistake, and to Keysight Technologies for the misplaced "historical" image showing the "Agilent" logo at the top of this marvelous modular VSA. Due to last-minute juggling of multiple image files between the front cover and the article, an outdated image file found its way to the front cover, with the model M9393A VSA showing a no-longer-valid company logo for Agilent.

The Agilent logo, of course, refers to Agilent Technologies, which is now Keysight Technologies (and has been Keysight Technologies for more than a year). And prior to being Agilent Technologies, this leading developer and supplier of precision test equipment for dc and audio through microwave frequencies was known as Hewlett-Packard Co., perhaps better known now for its computer hardware.

For many years, HP was synonymous with high-performance test equipment. In fact, within the RF/microwave industry, even a mention of the model number HP8510 (or HP8409 to you old-timers) was sufficient to evoke images of the one instrument—a vector network analyzer (VNA)—that perhaps best symbolized the uniqueness of this industry compared to other branches of electronics.

For a number of reasons, the test-and-measurement portion of HP was spun off as Agilent Technologies, and then, some years later, as Keysight Technologies. The names have changed, as we so unwittingly demonstrated with our choice of graphic files, but the engineering excellence, the innovation, and, perhaps most important to its customers, the high performance and quality of its instruments remain. Over time, these instruments speak for themselves, whether as the historically important HP8510 from HP or the model M9393A VSA from Keysight Technologies. Engineers working with these instruments quickly realize the value in them, and feel the comfort that comes from knowing that the measurements will be consistently accurate, whether the logo has been HP, Agilent, or Keysight. For now, the logo happens to be Keysight, and the instruments continue to be innovative.

JACK BROWNE
TECHNICAL CONTRIBUTOR



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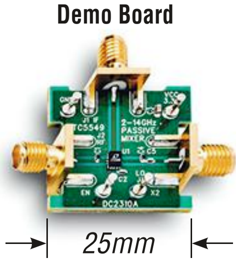

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News

GaN Lowers New Radar's Power Consumption, IMPROVES RELIABILITY

Lockheed Martin recently introduced a new radar technology based on gallium-nitride (GaN) solid-state transmitters, which will eventually serve as a modular replacement for the silicon bipolar-junction transistors (BJT) used in its ground-based surveillance radars.

The Digital Array Row Transceiver system, also known as the DART radar, exploits the significantly high operating temperatures of GaN transmitters to reduce array power consumption, lowering the life-cycle costs and increasing the reliability of the radars, Lockheed Martin says.

Mark Mekker, Lockheed Martin's director of surveillance radar, said in an e-mail to *Microwaves & RF* that with "GaN technology, the power-handling capability and higher-junction temperature tolerances of the DART provide the opportunity to increase transmit duty-cycle on the radar system to provide greater power output."

The new radar was engineered as GaN technology is growing more widespread and production processes are being scaled to greater yields. According to a recent Strategy Analytics report, the market for GaN radio frequency devices is predicted to reach around $560 million in 2019. The report suggests that this growth is largely due to its steady presence in military-grade

(continued on p. 26)

The TPS-77 ground-based radar system can be equipped with the DART transceiver to reduce its power consumption and provide greater power output. *(Image courtesy of Lockheed Martin)*

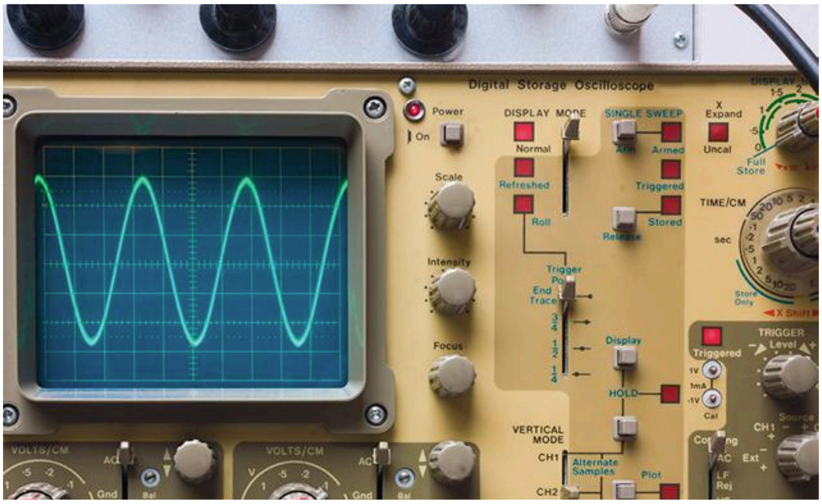
TEST-EQUIPMENT MARKET Capitalizes on LTE Growth

WITH LTE NETWORKS being pushed to the forefront of wireless communications by the steadily increasing demand for mobile data access, the market for test equipment that troubleshoots and monitors these networks is expected to reach $6.20 billion in 2021, according to a recent report from Frost & Sullivan, a test equipment research firm.

The LTE test equipment market, which earned revenues of $2.39 billion in 2014, is expected to be lifted by an increasingly complex breed of smartphones, which incorporate multiple built-in antennas that will require longer testing times. Another major boon to the market, the report says, is the growing number and sophistication of wearable technology, including smart watches and personal health bands. Despite low-power requirements, these devices transmit large amounts of rich data that demand the latency and responsiveness of LTE networks.

In addition to testing devices using LTE signals, the report also stressed the widespread demand for testing LTE gateways and access points, especially as the wireless industry transitions from the large cellular base stations that have dominated cellular data for years. The widespread usage of LTE technology can largely be attributed to the ease with which it navigates the HetNet infrastructure.

"While small cells and heterogeneous networks continue to gain momentum as tools that increase mobile network capacity, their quality of service still leaves much



(Image courtesy of Thinkstock)

room for improvement," says Olga Yashkova, program manager for Frost & Sullivan analyzing test equipment and the Internet of Things (IoT). Improving that quality of service requires constant testing and monitoring, she adds.

The report comes as wireless companies are upgrading their LTE infrastructures to address a firmly entrenched expectation for wireless access. At the same time, companies are slowly incorporating the enhanced capabilities of the LTE-Advanced standard, which itself has been described as the bridge to future 5G communications. For instance, it has been designed with enhanced inter-cell resource and interference coordination (eICIC) and terminal receivers with interference cancellation (IC), allowing small cells and macrocells to coexist on the same channel.

Nevertheless, the report notes that LTE test equipment will struggle with the same issues affecting the entire test and measurement industry. On the one hand, the economic downturn has discouraged manufacturers from buying new test systems. On the side of the fence, the new trend among chipmakers to use manufacturing techniques has heightened costs for test suppliers.

"Increasing collaboration among chipset vendors and test equipment companies will lower testing costs," Yashkova says, "and help LTE testing vendors stay in the running across the global landscape." ■

MECHANICALLY PHASED ARRAY Antennas Provide In-Flight Broadband

GOGO INC. recently completed a series of flight tests with its Ku-band satellite technology, part of its new wireless broadband system for commercial aircraft, which delivers high data rates to passengers traveling not only over the equator, but also in higher latitudes. The tests validated the coordinated pair of mechanically phased array antennas that serve as the foundation of the system.

The new technology is significant because it accounts for the disadvantages of electronically and mechanically steered antennas that have been traditionally used to provide broadband service to airlines. Gogo's technology, 2Ku, is built around two beam-forming antennas: one designated for transmitting data, and another for receiving signals from more than 180 compatible Ku-band satellites. The company says that that the dual antennas are symmetrical in design and, because of their large aperture area, have significantly higher spectral efficiency than other in-flight broadband antennas.

The antennas were designed by ThinKom, an antenna design company based in Torrance, Calif., that provides technology for aerospace and other mobile communications. The antennas are unique in that they create beams by mechanically rotating a series of internal plates with precise resonance characteristics. Although the internal disks are moved mechanically, the antennas are not pointed directly at the satellites. Instead, slight changes in the plate position adjust the scan angle in elevation and azimuth direction, according to a patent filing from ThinKom.

The antennas themselves are based on Variable Inclination Continuous Transverse (VICTS) arrays. VICTS were first developed by Raytheon Corp. with research support from ThinKom, MIT, and the Air Force Electronic Systems Center in 2006. The ThinKom version "involves the simple rotation (common and differential) of two coplanar plates, one comprised of a one-dimensional lattice of continuously radiating stubs, and the second one comprised of one or more static line sources," according to a white paper published by Gogo and ThinKom.

What separates the 2Ku system from more conventional aerospace antennas is that it combines technical benefits from both electronic phased arrays and mechanically steered

Gogo's 2Ku technology is built around two beam-forming antennas: one designated for transmitting data, and another for receiving signals from more than 180 compatible Ku-band satellites. *(Image courtesy of Gogo)*

This 2Ku system was placed on the "Jimmy Ray," Gogo's test plane, for a series of in-flight performance tests. *(Image courtesy of Gogo)*

antennas (including reflectors and flat panels). Like electronic phased arrays, the 2Ku antennas support the highest data rates over the equatorial region, where the maximum area of the antenna plate is facing the satellite. In contrast, flat-panel and reflector antennas struggle with interference caused by high-skew angles near the equator. They are forced to compensate for this interference by lowering their transmit power, which reduces data rates to the aircraft.

On the other hand, however, mechanically steered antennas are able to provide better broadband service at higher latitudes than electronic phased arrays, which typically have lower data rates in these regions. Because of the mechanically steered nature of its rotating plates, 2Ku antennas have similar capabilities as flat-panel and reflector antennas at high latitudes.

Nevertheless, antenna gain will inevitably fall as the aircraft moves toward these higher latitudes. "Passengers will notice speeds degrade as they reach the Arctic Circle, and the system will not work over the North Pole," Gogo CEO Michael Small told *Aviation Week* magazine.

Operating over the 10.7 to 14.5 GHz range, the 2Ku technology can achieve peak data rates up to 70 Mbit/s for the downlink and 15 Mbit/s for the uplink. When spot-beam satellites become available, such as Intelsat's EpicNG and Telesat's Telestar 12 VANTAGE, the system is expected to reach peak data speeds of up to 100 Mbits/s.

According to a ThinKom datasheet on its ThinAir Falcon-Ku3030 (the same antenna used in the 2Ku system), the transmit-power spectral density ranges from 15 to 18 dBW/4 kHz at the equator (roughly to within 35 deg. north or south). The G/T is typically around 15 to 18 dB/K and 12 dB/K at 20 deg. elevation. The EIRP has been clocked around 51 to 54 dBW and 49 dBW at 20 deg. elevation.

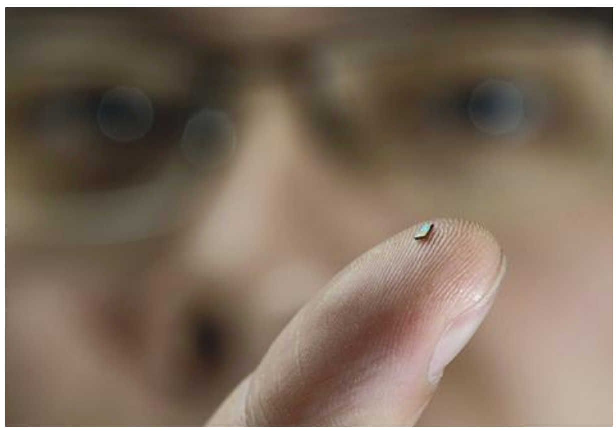
Because of the antenna's performance in the mid-latitudes and its low-profile design, ThinKom's technology is in high demand within the aviation industry. Gogo has reportedly placed an order with ThinKom for more than 500 antenna units, and the company says that eight airlines representing more than 550 aircraft have agreed either to trial or implement the 2Ku technology. ■

WORLD'S SMALLEST Temperature Sensor Powered by Direct MM-Waves

RESEARCHERS FROM THE EINDHOVEN University of Technology in the Netherlands have invented an extremely small temperature sensor, one powered by a largely untapped source: the same radio signals it uses to communicate. Because the sensor harvests energy directly from the radio waves, it does not need an external power source or batteries to stay turned on.

The research project, led by researcher Dr. Hao Gao, could represent a significant advance in the development of smart buildings, which are expected to incorporate thousands of low-power wireless sensors to control lighting and heating systems. Based on 65-nm CMOS technology, the device measures two square meters and weighs only 1.6 milligrams, making it what the researchers have called "the world's smallest temperature sensor."

While other wireless sensors can harvest energy from light or slight changes in pressure, the temperature sensor—also known as PREMISS—represents an emerging breed that uses RF energy. According to an Eindhoven University news release, the sensor



The temperature sensor, seen on the finger of lead researcher Dr. Hao Gao, weighs about the same as a grain of sand. *(Image courtesy of Bart van Overbeeke, Eindhoven University of Technology)*

interacts with a specialized router that sends pencil beams directly into the device, which itself contains tiny antennas that capture the energy. The sensor itself has been designed to consume very little electricity in order to account for the inherent low input voltage taken from the RF signal, according to a research presentation on the technology.

The outstanding feature of the temperature sensor is that it sends information back through the same radio channels from which it harvests energy. After measuring the temperature in the surrounding area, the sensor sends a radio signal to the router. The outgoing signal has a slightly different frequency depending on the temperature, and the router can determine the temperature based on that frequency.

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Aside from its energy-harvesting capabilities, the other major benefit of the antenna is that it can function beneath a layer of paint, plaster, or concrete. Peter Baltus, professor of wireless technology at Eindhoven and research partner with Gao, notes that this quality makes it easier to incorporate into buildings. He suggests that it could be painted onto the wall with latex paint.

Despite its potential benefits, the temperature sensor is far from ready for widespread usage, as it has only been shown to capture energy from a distance of 2.5 cm. The researchers expect that they can increase the range to a meter within the next year, and eventually to 5 meters. As the range increases, the technology will find new applications in wireless payment systems, wireless identification, and industrial production systems.

There have been several advances in RF energy harvesting, but the vast majority depend on ambient RF energy as the main power source. The most recent is the Power Over Wi-Fi system invented by researchers at the University of Washington. This system harvests energy from untapped, ambient Wi-Fi signals, using a router that sends out a superfluous "power packet" on Wi-Fi channels not being used for data transmission.

As opposed to the Wi-Fi harvesting system, the new temperature sensor operates over 60-GHz millimeter wave frequencies. Using these frequencies was one of the reasons why the sensor could be made so small, as high-frequency bands enable the construction of smaller antennas on a substrate chip.

The temperature sensor was designed as part of Gao's doctoral thesis, entitled "Fully Integrated Ultra-Low Power mm-Wave Wireless Sensor Design Methods." The title suggests that the same technology could be adapted to other sensor types. Baltus says that the technology could be used to power motion, light, and humidity sensors. The sensors can also be manufactured at an extremely low cost, the researchers predict. ■

SYNTHETIC DIAMOND POWERS EUV Chip Manufacturing

SYNTHETIC DIAMONDS grown from chemical vapor deposition (CVD) have slowly gained a reputation as a highly-efficient window in multi-kilowatt CO_2 laser systems, an integral component of extreme-ultraviolet lithography (EUV) chip manufacturing. Element Six recently introduced its Diamond PureOptics synthetic diamonds, which have the intrinsic thermal and optical properties required for the extremely high laser power output used in the process.

As the semiconductor industry attempts to construct smaller and smaller transistors, chipmakers have to take advantage of ever-shorter wavelengths of light in optical lithography. This semiconductor printing process depends on CO_2 lasers to pattern transistors onto thin films and substrates. In recent years, manufacturers have begun to transition from deep-ultraviolet (DUV) light, with wavelengths ranging from 193 or 248 nm, to EUV light at 13.5 nm.

One problem with EUV lithography is that it requires an enormous amount of electrical power to process a relatively low yield of semiconductors. The CO_2 laser systems used in the process must be extremely intense—on the order of 200 kW—to generate EUV-radiating plasmas that imprint the substrate.

Aside from being extremely hard, CVD synthetic diamond has the highest thermal conductivity of any material. It also exhibits advanced optical properties, with Diamond PureOptics having a wide transmission range from UV radiation to the RF part of the electromagnetic spectrum.

The Diamond PureOptics material is unique because it does not have an anti-reflective coating to limit reflection losses, which might harm the laser's power output. Instead, Element Six

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replaced the coatings with special structures carved on the surface of the diamond, which resemble the anti-reflective structure of a moth's eye.

The main advantages of the so-called meta-structures etched on the diamond are greater reliability and higher power density for CO2 laser systems. According to Bruce Bolliger, head of marketing at Element Six, the Diamond PureOptic windows exhibit a laser damage threshold 10 times greater than that of windows with an anti-reflective coating. According to Element Six, its tests also confirm that its synthetic diamond lowers window absorption—a critical parameter that keeps operating temperatures low and minimizes beam-distortion.

EUV lithography is widely anticipated to remain a key part of microelectronics manufacturing, as it has the potential to get around the costly practice of multiple patterning steps in the current generation of DUV lithography. The EUV printing process was initially expected to be used with 15 nm-node semiconductors in 2018 or 2019. ASML, the primary supplier of EUV lithography tools, predicts that the process will be introduced in 2018 on semiconductor nodes smaller than 7 nm.

In recent years, CVD diamond has also been the subject of research in solid-state RF power amplifiers, power electronics, and other passive components. Specifically, it has received attention as a substrate for gallium-nitride (GaN) semiconductors. ■

GaN Lowers Consumption

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radars, in addition to its increased usage in wireless infrastructure.

Aside from the benefits gained from GaN materials, the DART radar combines the row transmitter and row receiver into a single line replaceable unit (LRU). Mekker added that DART was designed to take the place of five different parts in legacy ground-based radars, decreasing the failure rate of the LRUs it replaces by over 50%. In addition, the DART's modular design gives technicians better visibility into the health of the radar system, he said.

The DART was launched in Lockheed Martin's TPS-77 Multi-Role Radar system, which was first issued to the Ministry of Defense of Latvia earlier this year. According to a news release, Latvia's version of the TPS-77 system was designed to perform different roles as the radar rotates through its 360-deg. scan. When facing one direction, it can perform long-range flight surveillance and automatically adjust to search for medium-range, low-level aircraft in another region. ■

GRID-ARRAY ANTENNAS
OBTAIN ULTRAWIDE-BAND PERFORMANCE

GRID-ARRAY ANTENNAS (GAAs) are planar array antennas formed by radiating elements and transmission lines. They can provide a number of advantages, such as high gain and easy construction. Recently, GAAs have been proposed to enable automotive radar technology. But many of these antennas can only achieve narrowband performance. It is therefore essential to develop GAAs with ultrawideband (UWB) performance for automotive radar sensors. To achieve this, a group of researchers from both the SSN College of Engineering and Anna University in India recently designed a GAA with an enhanced bandwidth. The proposed design is targeted for automotive UWB radar sensors that operate in the 24-GHz frequency range.

The GAA was fabricated on a 1.6-mm-thick Rogers RO3003 substrate. The team implemented an amplitude-tapering technique, which utilizes variable-sized radiating elements. This can provide several advantages in comparison to a GAA with uniform-sized radiating elements. To demonstrate the benefits of the amplitude-tapering technique, both forms of GAAs were built and tested. When measured over a frequency range from 21 to 27 GHz, the amplitude-tapered GAA achieved a lower voltage standing wave ratio (VSWR) than the GAA with uniform-sized radiating elements. An impedance bandwidth of 25% was attained by the amplitude-tapered GAA, as well as radiation bandwidth of 10.4%. It was also demonstrated that the side-lobe levels (SLLs) can be reduced when using this technique. See "Bandwidth-Enhanced Grid Array Antenna for UWB Automotive Radar Sensors," *IEEE Transactions on Antennas and Propagation*, Nov. 2015, p. 5,215.

CONTINUOUS-TRANSVERSE-STUB ARRAYS
EMPOWER KA-BAND ANTENNAS

KA-BAND SATELLITE CONSTELLATIONS have been deployed to meet the increased demand for broadband satellite-communication (satcom) systems. This band has an allocated frequency range from 17.7 to 21.2 GHz for receiving (Rx) units, while transmitting (Tx) units span 27.5 to 31.0 GHz. Both the Tx and Rx bands place stringent requirements on the antenna.

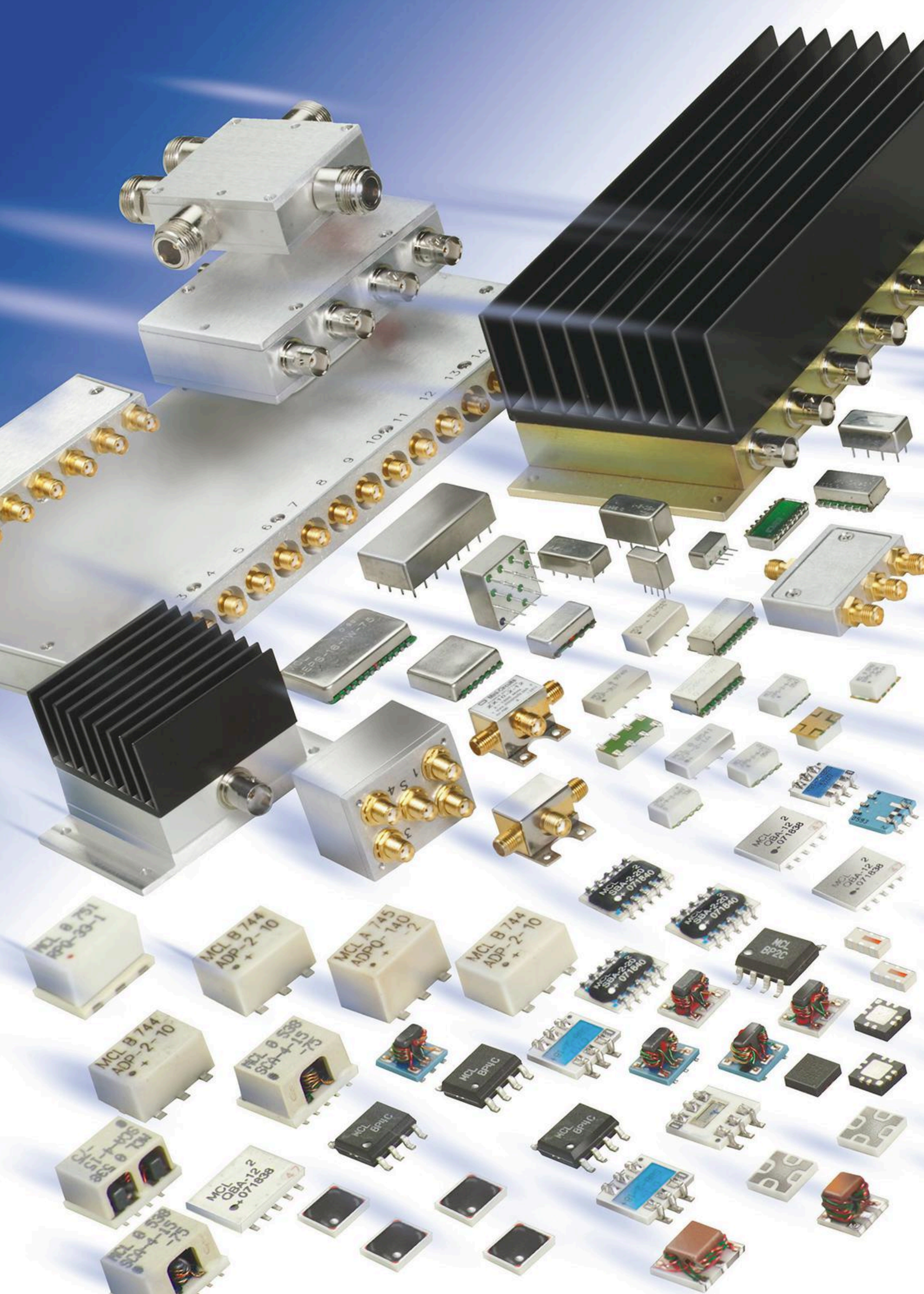
To meet these, several solutions have recently been proposed. Arrays of continuous-transverse-stubs (CTSs) are a good candidate for advanced antenna systems, owing to their advanced performance and fabrication stability. By way of example, researchers from the University of Rennes 1, Sorbonne University, and the Centre National d'Etudes Spatiales (CNES) in France recently developed a CTS array for Ka-band applications.

CTS arrays, which can resemble connected arrays of slots, consist of broad stubs connected to a parallel-plate waveguide (PPW) feeding system. When the PPW structure feeds the stubs in parallel, the CTS array can achieve a very wide bandwidth and wide scanning capability. The team designed a CTS array of 16 slots, targeting an operating frequency range of 27.5 to 31.0 GHz. A PPW corporate-feed network was utilized to feed the CTS array in parallel. The antenna achieved greater than 27.6 dBi of gain as well as efficiency in excess of 80% across the entire frequency range. See "Continuous Transverse Stub Array for Ka-Band Applications," *IEEE Transactions on Antennas and Propagation*, Nov. 2015, p. 4,792.

ADVANCED CMOS TECHNOLOGY
SPARKS TERAHERTZ APPLICATIONS

INTERCONNECTS IN CMOS technology can suffer from high resistivity as they become thinner and smaller. At millimeter-wave and terahertz frequencies, this problem is even more severe. As a result, intra-/inter-chip wireline communications can limit overall system performance. Chip-to-chip wireless communication using on-chip antennas can potentially overcome the limitations of broadband wireline signal transmission. As the terahertz band generates increased interest, nanoscale CMOS technology has demonstrated the potential to be used at these frequencies. Recently, a fully integrated 210-GHz transceiver based on 40-nm CMOS technology was developed by researchers from San Jose State University. This transceiver, which employs on-off-keying (OOK) modulation, utilizes wireless chip-to-chip communication.

The transceiver's receiver (Rx) contains a modified on-die dipole antenna. A similar on-chip antenna is also used in the transmitter (Tx) path. The Rx consists of an eight-stage low-noise amplifier (LNA), while the power amplifier (PA) that was incorporated into the Tx was designed with a four-stage differential topology. A triple-push, circular-geometry, voltage-controlled oscillator (VCO) was employed in the phase-locked loop (PLL). The transceiver achieved equivalent isotropically radiated power (EIRP) of +6.8 dBm. It also attained a data rate of 10.7 Gb/s over a 1-cm distance between the Rx and Tx. See "A 210 GHz Fully-Integrated OOK Transceiver for Short-Range Wireless Chip-to-Chip Communication in 40 nm CMOS Technology," *IEEE Transactions on Terahertz Science and Technology*, Sept. 2015, p. 737.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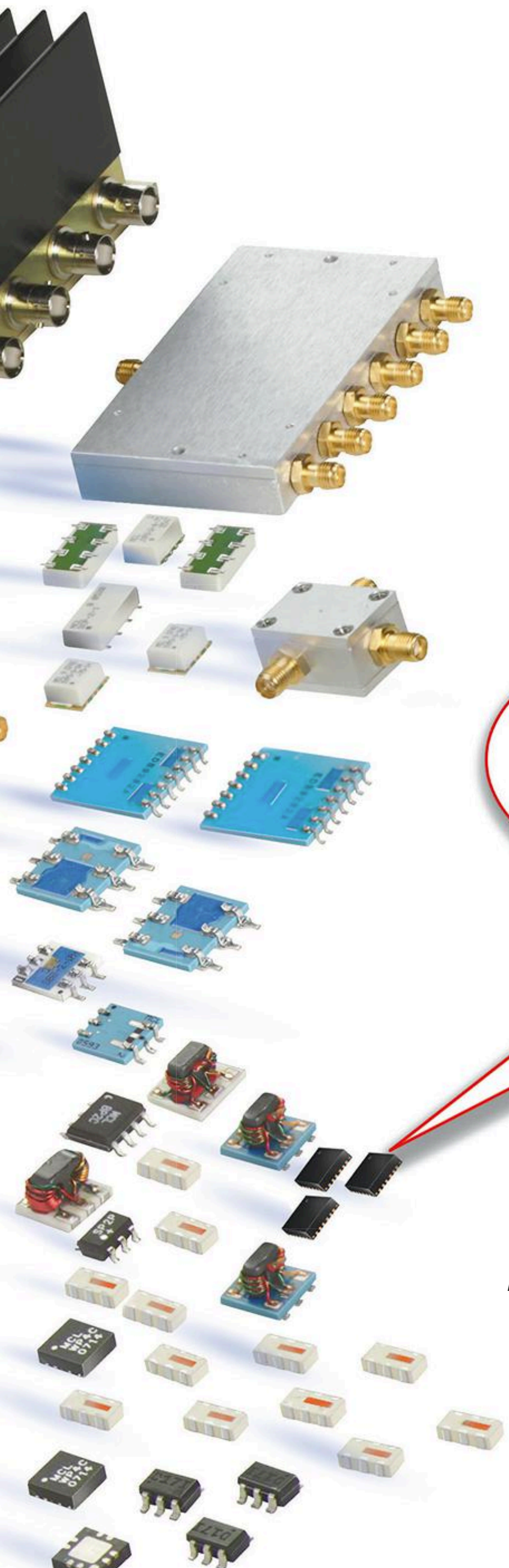


CHRIS DeMARTINO | Technology Editor

Technology Breakthroughs Prepare to CHANGE THE WORLD

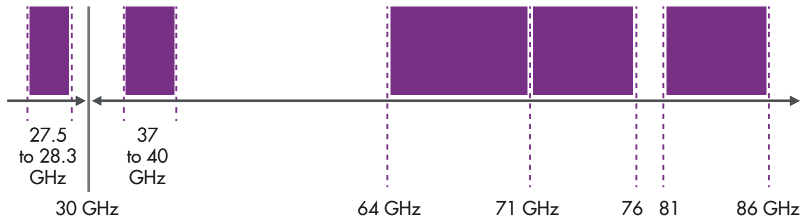
Expect 2016 to be a busy year, as plans are in motion to create technologies with capabilities that push past the boundaries of today's state-of-the-art solutions.

WHEN SURVEYING THE microwaves and RF landscape, it becomes apparent that 2016 could be a watershed year for high-impact technology developments. We've seen numerous advances in recent years, but many other possibilities still exist that could have a significant impact on every aspect of our everyday lives. As engineers, researchers, and scientists work hard to create tomorrow's innovations, cutting-edge technology seems poised to break through on multiple fronts. Most already know about the fuss concerning the Internet of Things (IoT), as it aims to provide connectivity to the very

objects that we use daily. Some predict that we could see tens of billions of connected devices within the next several years. Another talking point is 5G, as future wireless networks could achieve performance levels that far exceed today's capabilities. Expect a flurry of announcements to spin out through the year as development efforts continue regarding the IoT and 5G.

Although the IoT and 5G are receiving a large amount of attention, other new technologies loom on the horizon. One such example is RF cooking. This concept enables food to be cooked by means of solid-state RF technology, potentially replacing conventional magnetron-based microwave ovens. We may soon see cooking appliances based on this technology arriving in our homes.

In addition, newly structured companies emerging from various mergers and acquisitions in the semiconductor industry will look to push technology forward in 2016 and beyond. On top of that, as gallium-nitride (GaN) technology finds its way into more applications, look for GaN-based products to continue to play a major role in 2016.



1. A number of frequency bands are being considered for future 5G networks.

5G TECHNOLOGY

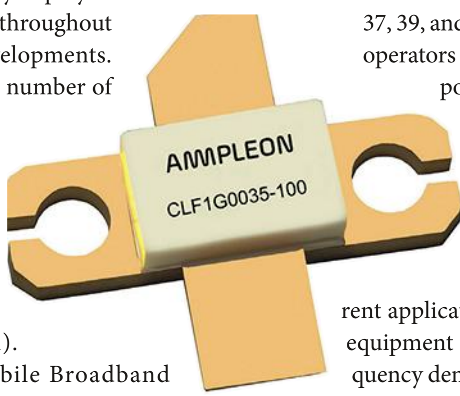
Expectations are high for 5G, with the potential for groundbreaking wireless data rates in the purview. However, it also comes with plenty of challenges that must be addressed by researchers. Although it is not expected to be widely deployed until 2020, we will hear plenty of news throughout the year regarding 5G technology developments. Standards have yet to be defined, but a number of solutions are being proposed for 5G.

"The standardization bodies have begun the process of setting requirements for 5G. This includes defining three use cases," says James Kimery, director of wireless research and software-defined radio (SDR) at National Instruments (www.ni.com). "These use cases are enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra Reliable, Low Latency (UL/LL). The 5G goals will be matched to each use case. Many companies and research groups are aligning their investigations toward solving the unique challenges that each use case presents."

Kimery adds, "The 3rd Generation Partnership Project (3GPP) has divided the 5G standardization into two phases. Phase 1, which will focus on the eMBB use case, will evaluate technologies both below and above 6 GHz. The goal is to define Phase 1 of a 5G standard by mid-2018. Phase 2 will follow 15 months later."

Although the available spectrum below 6 GHz is nearly depleted, a large amount of spectrum exists in the millimeter-wave bands. As a result, these higher frequencies are being examined as a means to enable future 5G networks *(Fig. 1)*. For instance, at Nokia Networks, researchers have already demonstrated a prototype that consistently streamed data faster than 10 Gb/s at 73.5 GHz.

"To handle the data rates proposed for the eMBB use case, millimeter-wave frequencies must be carefully considered," says Kimery. "Available spectrum is highly correlated to data rates and capacity according to the Shannon-Hartley theorem. However, not much spectrum is available below 6 GHz. Conversely, spectrum above 6 GHz is plentiful and lightly licensed. The Federal Communications Commission (FCC) recently issued a notice of proposed rulemaking (NPRM) that proposes new flexible service rules in the frequency bands of 28, 37, 39, and 64 to 71 GHz. Compared to what service operators are using today, the spectrum being proposed is more than 10 times greater."



2. This 100-W GaN device operates from dc to 3.5 GHz. *(Courtesy of Ampleon)*

HIGHER-FREQUENCY REQUIREMENTS

In addition to being considered for future 5G networks, millimeter-wave frequencies are used in several current applications, prompting test-and-measurement equipment suppliers to respond to these higher-frequency demands.

"The test-and-measurement market continues to expand with the growing interest in new standards, such as E-band, 5G experimental deployments, and other high-frequency links—for instance, those supporting IoT," says John Cowles, general manager at Analog Devices (www.analog.com). "The need for higher-frequency instrumentation is driving demand for key microwave and millimeter-wave building blocks. Furthermore,

test equipment is expected to support multiple standards and require less calibration. These both demand wideband operation with a premium on gain flatness over frequency."

High-performance millimeter-wave components will also be essential. Cowles adds, "These trends in instrumentation will demand better performance from components. Wideband power amplifiers (PAs), low-noise amplifiers (LNAs), and driver amplifiers must cover multiple bands at frequencies as high as 90 GHz. They also require low harmonic distortion and better efficiency. Synthesizers must simultaneously offer fast- and fine-resolution tuning with low close-in phase noise. Silicon-on-insulator (SOI) switches as well as silicon-germanium (SiGe) up/downconverters and detectors must have wide bandwidths with a flat response."

THE SEMICONDUCTOR INDUSTRY IN 2016

By now, most already know about the mergers and acquisitions that occurred in the semiconductor industry. As the dust settles, these newly structured companies will seek to deliver numerous technology solutions in 2016 and beyond. Qorvo (www.qorvo.com), for example, fresh off completing its first year of operation in 2015, plans to shift from 4-in. to 6-in. GaN wafers this year.

Another major shakeup saw NXP Semiconductors (www.nxp.com) recently complete its merger with Freescale Semiconductor. Among the goals of the merged company is to provide technology that will enable self-driving cars.

"NXP will play a key role in making the securely connected self-driving car a reality—much sooner than most people would expect," says Paul Hart, executive VP and general manager at NXP. "We are accelerating the development of a one-chip solution by leveraging NXP's position in RF CMOS radar front ends (FEs) and Freescale's position in radar processing."

The NXP-Freescale union had further ramifications, as the RF Power business line of the former NXP Semiconductors was sold off following the merger's completion. This transaction resulted in the creation of a new company called Ampleon (www.ampleon.com). Ampleon has assumed responsibility for the former company's line of products, and in fact already offers a selection of laterally diffused metal-oxide semiconductor (LDMOS) and GaN devices *(Fig. 2)*.

Cree also separated its Power and RF division into a standalone company in 2015, naming it Wolfspeed (www.wolfspeed.com). It intends to continue providing silicon-carbide (SiC) and GaN technology solutions.

GaN technology not only is a major emphasis of the aforementioned companies, but with several others like Toshiba (www.toshiba.com) and Sumitomo Electric Device Innovations (www.sei-device.com). GaN continued its surge in 2015, demonstrated by the arrival of many new GaN-based products. The technology has gained considerable traction the last few years, extending into applications such as satellite-communications (satcom), radar, and cellular infrastructure.

Additionally, suppliers hope to push the capabilities of GaN technology into higher frequencies. For example, Wolfspeed is developing a 0.15-μm process for higher-frequency applications. This will allow the company to reach markets like higher-frequency satcom and wireless backhaul. Qorvo is also developing GaN technology at millimeter-wave frequencies. Higher-frequency performance ties in to 5G, as these future networks will very likely require GaN technology.

THE INTERNET OF THINGS

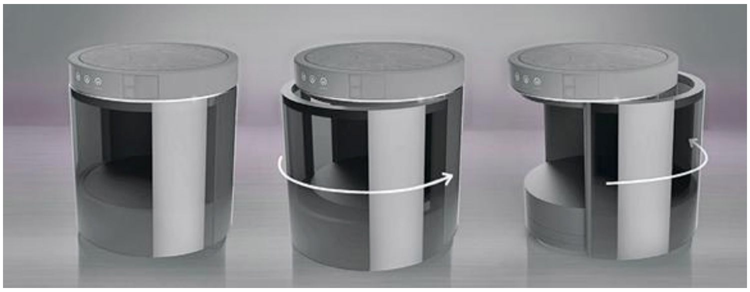
Everyday objects like lamps, switches, thermostats, fans, coffee makers, vehicles, and televisions could soon connect to the Internet, creating the oft-quoted "smarter and more connected world." Some are predicting that we may see 50 billion connected devices by 2020. This will undoubtedly have a major positive impact on the semiconductor market, given the enormous amount of IoT devices coming down the road.

Because the IoT spans a wide range of applications, no single technology will be the one and only solution. The list of wireless communication technologies that could enable IoT connectivity includes Wi-Fi, Bluetooth, and ZigBee, to name a few. And wired connections, such as Ethernet, have a role to play in the IoT, too.

Countless wireless sensor networks (WSNs) will be required to support the IoT. A WSN is a collection of distributed sensors that can monitor physical or environmental conditions, such as temperature, sound, and pressure. The data from each sensor then passes through the network.

Linear Technology (www.linear.com), for instance, has developed its SmartMesh WSNs for IoT environments. These products comprise embedded chips and pre-certified printed-circuit-board (PCB) modules along with intelligent wireless-mesh-networking software. SmartMesh WSNs represent just one example, as we expect to see more activity in this area.

In addition, test-equipment manufacturers will need to prepare for the demands of the IoT, with wireless connectivity appearing in a vast number of products. One company making strides in this arena is LitePoint (www.litepoint.com). It



3. This appliance concept utilizes RF solid-state devices to deliver precise cooking results. *(Courtesy of NXP Semiconductors)*

intends to provide reference test platforms for IoT-specific reference designs, thus streamlining the entire process. It will be interesting to see how the IoT will drive new test methodologies in the future.

RF COOKING

One interesting technology to keep an eye on is solid-state RF cooking, as it could potentially replace magnetron-based microwave ovens in homes. Those developing solid-state RF cooking technology believe it has many advantages when compared with traditional microwave ovens. Two companies leading this charge are NXP Semiconductors and Ampleon.

An RF cooking concept has already been introduced by NXP (at that time, Freescale) *(Fig. 3)*. The concept, called "Sage," can control the amount of heating energy directed into food. This enables more precise cooking that can improve consistency, taste, and nutrition. The cooking concept is based on LDMOS technology.

NXP's RF cooking appliance can also be seen as a potential IoT-based product. For instance, the oven could access a library of recipes that were written specifically for the appliance and stored in a cloud-based server. Once someone selects one of the recipes, the oven simply cooks the meal based on the instructions. These recipes could be downloaded from cooking websites or social communities.

To summarize, these future technologies could significantly impact each one of us. They could extend into our homes, such as, for instance, the IoT bringing connectivity to our kitchens. Microwave ovens may be usurped by cooking appliances based on solid-state RF technology.

Of course, 5G technology offers many future possibilities. Driverless cars may also be on the road very soon. In addition, GaN technology will assume an even bigger role in new developments, as manufacturers look to push performance capabilities to new levels. It goes without saying that the RF/microwave industry will be at the forefront of tomorrow's technology. mw

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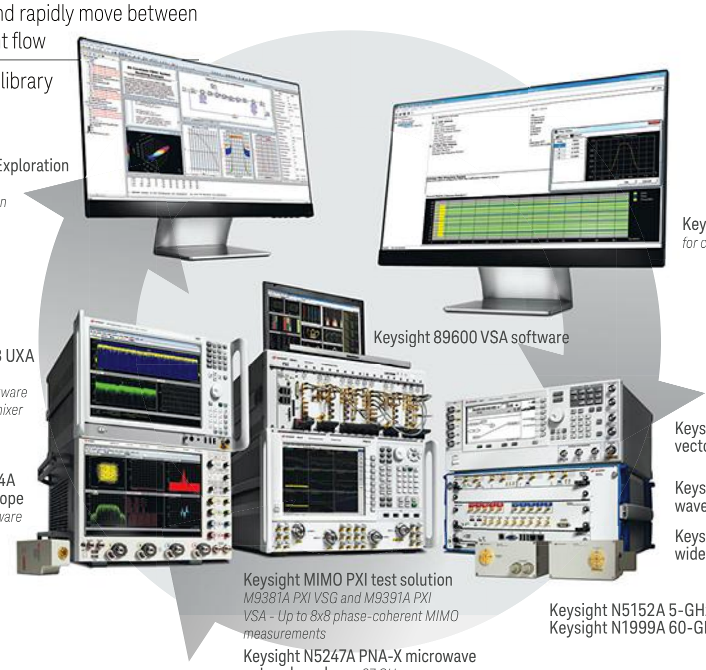

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JACK BROWNE | Technical Contributor

Taking Steps Toward Practical THz Technology

The potential for terahertz waves is enormous for imaging and communications applications—if practical semiconductor THz detectors and generators can be developed.

AS "LOWER-FREQUENCY" APPLICATIONS, such as wireless communications, continue to consume bandwidth, researchers of imaging systems look beyond even the millimeter-wave range for available spectrum. For many applications, including materials research, medical diagnostics, and homeland-security systems, terahertz (THz) technology offers great promise. Located in that mysterious part of the electromagnetic (EM) spectrum where millimeter-wave EM energy makes the transition to infrared (IR) optical energy, THz imaging is able to provide greater focus and control than x-ray radiation.

1. THz technology offers great promise in medical diagnostics, including for early detection of cancers. *(Courtesy of the University of Leeds)*

Known as the "THz gap," this band of the EM spectrum between about 300 and 3,000 GHz (0.3 to 3 THz) contains signal wavelengths that are particularly useful for detecting dielectric differences in materials. It can be applied to a wide range of applications, from early detection of tooth decay to detection of hidden weapons and explosives. THz technology may even support high-data-rate, short-range wireless communications one day *(see "Is Terahertz Li-Fi in Your Future," at http://mwrf.com/blog/terahertz-li-fi-your-future)*. One key to realizing this promise will be the practical fabrication of semiconductor devices that can generate energy at THz frequencies.

Much research has been conducted on this portion of the EM spectrum due to the versatility of these small-wavelength electro-optical signals for material analysis and medical diagnostic applications, including for early detection of cancer *(Fig. 1)*. A great deal of progress has been made in the development of passive components, such as antennas, needed for THz systems through the application of microelectromechanical-system (MEMS) technology and small-wavelength circuit transmission-line techniques like substrate-integrated-waveguide (SIW) technology.

THz RESEARCH

Still, lots of work must be done in the areas of generating and detecting electro-optical THz energy. The trend of decreasing power with increasing frequency that's common to the millimeter-wave EM portion of the frequency spectrum continues into the THz range, with signal power hard to come by at THz frequencies.

Organizations such as the University of Leeds (Leeds, UK) and the Rensselaer Polytechnic Institute (Troy, N.Y.) and its RPI Center for THz Research (www.rpi.edu/terahertz) have devoted much effort to the study of THz technologies and the development of practical semiconductor solutions for the generation of THz energy.

Device developers for THz frequencies typically look to high-speed switching semiconductors, such as Impatt diodes. These are based on semiconductor substrates long associated with high-frequency analog and high-speed digital circuitry, including gallium arsenide (GaAs) and indium phosphide (InP).

> "THz signal generation has included exploration of plasma-wave excitation in submicron field-effect transistors (FETs), including those based on GaAs substrates."

In contrast to X-rays, researchers at RPI, with numerous patents on THz generation and detection, refer to THz energy as T-rays. With funding from a diverse group of investors, including the National Science Foundation, the U.S. Army Research Laboratory (ARL), and the Defense Advanced Research Projects Agency (DARPA), RPI's research focuses on generating, measuring, and recording THz waves.

THz signal generation has included exploration of plasma-wave excitation in submicron field-effect transistors (FETs), including those based on GaAs substrates. The goal is to allow the THz laboratory to develop tunable, solid-state THz devices that will make many of the potential applications for THz technology possible and practical.

NOT OUT OF GaAs

Sources of THz energy are not plentiful, although some suppliers of millimeter-wave components and equipment also extend their engineering efforts into the THz range. They include Insight Product Co. (www.insight-product.com) with THz frequency synthesizers and TeraSense (www.terasense.com) with Impatt-diode THz generators *(Fig. 2)*. Although solid-state devices for generation of THz energy are limited in availability, a number of firms offer commercial THz-based test and diagnostic equipment.

2. Many currently available THz sources are based on discrete semiconductor diodes, such as this Impatt-diode THz generator. *(Courtesy of TeraSense)*

For example, TeraView Ltd. (www.teraview.com) developed three-dimensional (3D) THz-pulsed-imaging (TPI) technology that operates at room temperature. Products such as the firm's TPS Spectra 3000 use high-speed lasers along with photoconductive semiconductor switches to generate and detect THz pulses without need of superconductors or cryogenic liquids to high-speed/high-frequency operation. A femtosecond laser operating at a wavelength of 800 nm and 100-fs pulse widths excites GaAs semiconductor substrate material to generate THz photon energy. Detection of the photon energy is performed by another GaAs semiconductor device excited by the same laser pulses.

Systems such as the TPS Spectra 3000 can measure the amplitude and phase of THz signals independently, to determine the absorption and refractive index of different materials in order to calculate the complex permittivity of those materials. This capability has clear benefits for materials analysis, such as analysis of semiconductor substrates and printed-circuit-board (PCB) laminates. However, it can also be used to find small defects in materials, like those mentioned earlier.

TOOLS TAKE ON THz

In addition, Advantest (www.advantest.com) offers a number of THz imaging systems with coverage to 7 THz. The firm's model TAS7400SU, for example, is a wideband system capable of operating from 0.5 to 7.0 THz. It generates and detects THz radiation, holding a sample for analysis within a sealed chamber. The system works with an external personal computer (PC) for control and data analysis. Two versions are available, each handling different operating temperature ranges (within the sample chamber): –10 to +80°C and +25 to +300°C.

Zomega Terahertz Corp. (www.zomega-terahertz.com) enters the fray with a number of THz-based diagnostic tools, including its compact Mini-Z time-domain spectrometer. The spectroscopic material measurement system is compact enough to be transported to any research or industrial site for nondestructive analysis of samples. It's designed to fit within small equipment cases about the size of a notebook computer. The company offers standard and high-speed models for different measurement requirements, bringing portability to high-precision THz analysis.

Many THz test and diagnostic systems employ discrete devices rather than ICs. Wider application of cost-effective THz technology will depend on the development of more integrated THz transceiver options. Use of nanoscale fabrication methodologies with existing semiconductor technologies, such as GaAs FET and silicon biCMOS processes, could help realize the small circuit dimensions required for terahertz wavelengths.

As this technology's potential becomes more apparent for applications in the medical-diagnostics and materials-analysis fields, among others, demand will no doubt take off. Strong efforts from research organizations around the world will continue to improve integrated terahertz device solutions, creating a more practical technology that's destined to become widespread. mw

JACK BROWNE | Contributing Editor

Smaller Filters Screen Shrinking RF Circuits

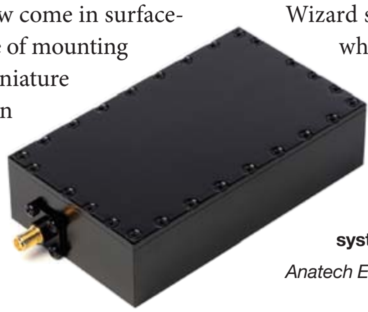
The relentless trend for miniaturization in high-frequency electronics has RF/microwave filter designers looking for new ways to create high-performance filters in a fraction of the size.

SQUEEZING HIGH-FREQUENCY COMPONENTS into increasingly smaller systems has become the norm. Filters are no exception, with the latest design and fabrication techniques aimed at fitting them into minuscule, high-power-level packages. A growing number of filters of every type now come in surface-mount-technology (SMT) packages for ease of mounting on printed circuit boards (PCBs), while miniature filters in pin packages simplify the integration of filters into multilayer PCBs.

Needless to say, more services are being packed into available wireless bandwidths. And with the coming deluge of Internet of Things (IoT) devices, which will automate homes and automobiles, and link people to things as well as machine-to-machine (M2M), filters become more important than ever at doing what they do quite well: Keep RF and microwave signals free of interference from the many signals surrounding them.

Filters achieve this goal by means of numerous spectral responses: bandpass, high-pass, low-pass, and band-reject (or notch). Specifying a filter starts with deciding which response is best for a particular requirement, such as a bandpass filter for minimizing the noise and loss of a signal at a particular center frequency and eliminating surrounding signal interference in the frequency bands above and below the center frequency.

Quite simply, a filter should pass desired signals with as little distortion or change in amplitude, phase, and delay characteristics as possible, and provide as much attenuation of unwanted signals as possible. These types of functions can be described in various ways. Typically, it involves a series of specifications that include definitions (such as 3 dB) for bandwidth and parameters for maximum power-handling capability, operating temperature range, and package style.



1. This bandpass filter is designed for indoor or outdoor Wi-Fi systems. *(Courtesy of Anatech Electronics)*

FACILITATING FINDING FILTERS

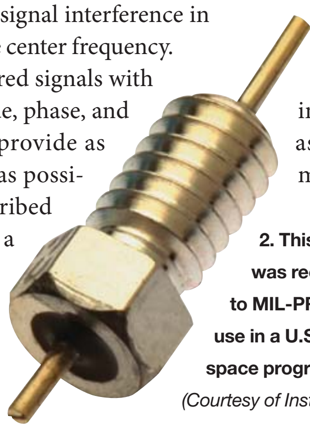
One longtime supplier of RF/microwave filters, K&L Microwave (www.klmicrowave.com), developed an online tool to simplify the task of finding the right filter for a job. The firm's Filter Wizard software allows specifiers to "fill in the blanks" when it comes to the requirements for a particular filter application. This includes whether the filter is defined according to its 0.5-, 1.0-, or 3.0-dB bandwidth, its required maximum power level, filter response type (with graphical depictions of bandpass, band-reject, low-pass, and high-pass shapes), spurious levels, connector types, and operating temperature for performance specifications (–40 to +85°C, 0 to 50°C, or room temperature of +25°C).

After entering a set of specifications into the software program, it searches through the firm's filter products for the best match, saving the task of downloading and comparing datasheets. Both fixed-frequency and tunable-frequency filters are available with a wide range of package and connector options.

SPACE-SAVING EXAMPLES

RF/microwave filters continue to shrink in size for a given frequency and power rating, leveraging advances in the quality of substrate materials such as ceramic and polytetrafluoroethylene (PTFE) PCB material reinforced with glass and/or ceramic fillers.

Filter designers are also experiencing increased demand for smaller, low-loss filters in portable devices, especially as communications-signal density increases within each communications protocol (e.g., Bluetooth, Wi-Fi, and LTE wireless standards).



2. This tiny EMI filter was recently certified to MIL-PRF-28861 for use in a U.S. government space program. *(Courtesy of Instec LLC)*

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3. These miniature 512- and 700-MHz low-pass filters are housed in 1206 SMT packages for PCB mounting. *(Courtesy of AVX Corp.)*

As an example of a more traditional filter design, Anatech Electronics (www.anatechelectronics.com) recently introduced a bandpass filter for Wi-Fi applications, with a 22-MHz passband from 2426 to 2448 MHz. Available in versions for indoor or outdoor use, the model WIFI2437-6 *(Fig. 1)* is a cavity filter built to handle as much as 20-g shock and vibration and up to 50-W CW power. Insertion loss is 3 dB or less across the passband, with more than 60-dB rejection of out-of-band signals and more than 90-dB high-side signal rejection. The robust filter measures 4.25 × 2.20 ×1.00 in. with Type N coaxial connectors and operates at temperatures from –40 to +85°C.

Bandstop or band-reject filters can also effectively separate closely spaced wireless signals. For example, the 18704 bandstop filter from Microwave Filter Co. (www.microwavefilter.com) isolates the 700- and 800-MHz frequency bands, passing 800-MHz mobile-radio signals with minimal loss while rejecting public-safety radio signals in the 700-MHz range.

The 18704's passband loss is typically only 1 dB while the out-of-band rejection increases close to 800 MHz, with 45-dB rejection from 763 to 777 MHz, 60-dB rejection from 77 to 787 MHz, and 70-dB rejection from 787 to 794 MHz. The filter, which can handle power levels to 40 W CW, comes with BNC female coaxial connectors. It measures 10.43 × 5.18 × 2.39 in. (26.5 × 13.2 × 6.10 mm).

Some designers save space by integrating filters with other required system components, such as the 803437 series of switched filter/amplifier units from Bree Engineering (www.breeeng.com). These modules, measuring 3.0 × 6.0 × 1.2 in. (excluding SMA or TNC connectors), integrate filters, amplifiers, and switches to cover multiple passbands within the 20-MHz to 6-GHz frequency range.

With switching speed of 5 µs or better, these modules are suitable for saving space in demanding communications, electronic countermeasures (ECM), and radar systems. They can handle temperatures from –40 to +85°C and even include a dc-dc power supply to enable the use of a wide range of voltage supplies.

As filters shrink, the power ratings shrink with them, although board-level connectors generally are not required to pass more than about one watt (+30 dBm) of signal power. Impressive for its size and power, model SXBP-1940+ is one of a line of SMT bandpass filters from Mini-Circuits (www.minicircuits.com) for applications from 2 to 8750 MHz.

This bandpass filter measures just 0.44 × 0.74 × 0.27 in. (11.18 × 18.80 × 6.86 mm), but handles power levels to 6 W. The filter features a passband from 1710 to 2170 MHz with 1-dB typical passband insertion loss and more than 20-dB out-of-band rejection. Operating temperature range is –40 to +85°C.

SMALLER IS BETTER FOR MILITARY APPS, TOO

Small filter size should not be totally synonymous with commercial wireless applications, since military and aerospace customers can also benefit from more compact, lighter-weight components, whether on the ground or in space. As an example, Instec LLC (www.instec-filters.com), a supplier of filters for screening electromagnetic interference (EMI), recently achieved certification to the U.S. Department of Defense (DoD) specification MIL-PRF-28861 for a miniature EMI feedthrough filter *(Fig. 2)*. The filter will be used to suppress EMI in a U.S. government space program.

The bolt-style, resin-sealed EMI filter is rated for 5 A and 100 V dc. It features an operating temperature range of –55 to +125°C, and provides 25-dB EMI suppression at 100 MHz and 40-dB suppression at both 1 and 10 GHz. The device consists of a silver-plated brass case that includes a silver-plated copper nail-head lead.

A pair of integrated-thin-film (ITF) 512- and 700-MHz low-pass filters from AVX Corp. (www.avx.com) rate among the smallest RF/microwave filters of recent vintage, measuring just 3.10 × 1.60 × 0.60 mm in 1206 packages for PCB mounting *(Fig. 3)*. The land-grid-array (LGA) filters are suitable for commercial and military communications.

In spite of the small size, they handle as much as 3-W power over operating temperatures from –40 to +85°C. According to Larry Eisenberger, senior marketing application engineer at AVX Corp., "Our new high-performance, low-pass ITF filters provide wireless systems engineers with peak performance and quality in an ultra-miniature 1206 chip size that's compatible with the smaller and more-crowded PCBs that next-generation wireless electronics frequently feature."

The trend for smaller electronic products with more densely packed PCBs should only increase the demand for miniature filters. Up to now, RF/microwave product designers have been able to meet that demand, learning to combine advanced materials and packaging with innovative designs that defy the seemingly conflicting tradeoffs between small size and power-handling capabilities. mw

JACK BROWNE | Technical Contributor

Making Connections in the IoT Cloud

Widespread use of the Internet for communicating with sensors and actuators will enable the programming and remote control of automobiles, homes, and businesses.

INTERNET-BASED COMMUNICATIONS may have started out slow a few decades ago, but few would have foreseen that so many electronic devices would one day be using the Internet to send and receive information of some form. Various market predictions now project more than 50 billion electronic devices connected to the Internet by 2020 as part of the rapidly growing Internet of Things (IoT) phenomena.

Not all of these devices will be like your father's PC. Most will rely on wireless technology and RF/microwave components of some form, typically as integrated circuits (ICs) in smaller mobile products. Others may rely on more discrete components in wireless IoT gateways, and as parts of the wireless Internet infrastructure that makes the interconnection of all those data-generating devices possible.

In addition to computers and mobile communications devices such as smartphones, the Internet and its ever-growing collection of networks known as the "cloud" is already flooded with a large and increasing number of sensors of different kinds. These include temperature, motion, and position sensors used for applications in monitoring room occupancy (for controlling lights and heating when a room is occupied); security; health and fitness monitoring; and even for control of robots and unmanned vehicles.

Some of these sensors will be interactive, requiring a response from someone receiving a message; some will operate as stand-alone units. Most of these sensors (except for hardwired devices) will require wireless access to the Internet and generous bandwidth for communicating an enormous amount of data from all of these sensors.

Already, a number of firms are offering medical alert devices, typically worn as pendants on a wrist by the elderly and others greatly in need of medical attention. A simple push of one button can alert medical and emergency services personnel by means of a wireless connection to the Internet. With the aid of a Global Positioning System (GPS) receiver, these same medical devices can provide location information. They are designed with devices and packaging that can withstand rough handling.

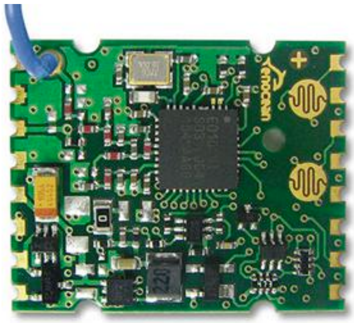
1. Working closely with Intel Corp. (www.intel.com), Yanzi Networks has developed IoT sensors and gateways that can be used to quickly transform a standard office into a "smart office." *(Photo courtesy of Yanzi)*

As the IoT expands, this basic concept of using wireless communications to monitor patient health can be applied by different types of sensors—even those embedded within a human body—allowing medical professionals to monitor patient heart-beat rate, blood pressure, and other key health parameters from a distance, and at any time. This significantly reduces the costs of doctor visits and health care in general.

In many ways, the evolution of RF/microwave components for Internet of Things applications will parallel the development path taken by high-frequency manufacturers of devices and components for mobile communications products. Essentially, two sets of devices and components will be needed: miniature, low-power electronic devices for use in wireless portable, mobile, and wearable IoT products; and larger, higher-power devices and components intended for IoT infrastructure equipment.

IoT gateways, which connect wireless IoT devices to the Internet using available wireless protocols such as cellular Long Term Evolution (LTE), Bluetooth, Wi-Fi, and ZigBee, will parallel the many cellular base stations that now provide the ease of use for mobile wireless handsets.

Wireless communications and IoT devices such as actuators and sensors are combining to make office buildings, warehouses, and homes "smarter" by allowing monitoring and control of security and environment functions via remote control from any communications device with Internet access *(Fig. 1)*. Home building supply stores are already selling IoT smoke detectors, thermostats, motion detectors (for monitoring room occupancy), and "smart plugs" that can be used to turn off lights from a distance.



2. Model PTM 330U is a 902-MHz wireless transmitter that operates without batteries, harvesting energy from nearby power sources. *(Photo courtesy of EnOcean)*

A software application for remote control of a smart home may show a graphical representation of the home with the different IoT devices appearing on the screen of a monitoring device, such as a smartphone or tablet. As an example, a homeowner may simply click on the on-screen image of a television set with a simple menu, allowing the set to be turned on, switched to a low-power mode, or turned off as required. This can take place anytime and from anywhere with Internet access.

The IoT cloud is essentially one massive network consisting of possibly millions of "subnetworks"—such as cellular telephone networks and homeowner's WLANs—linked together to provide data storage and applications. An IoT network will consist of the "things" that communicate to a local gateway either by wired connection, such as an Ethernet local-area network (LAN) or wireless LAN (WLAN), Bluetooth, or Wi-Fi, with the Internet-connected gateway.

The millions of wired and wireless gateways and their local subnetworks combine with the Internet to form the cloud. This connects back-end devices—such as servers, smartphones, and other data storage, software, and communications devices—to the wired and wireless "things" that are sending their data through this massive network.

Compared to hardwired devices, wireless technology offers a great deal of flexibility in mounting sensors throughout a location, and in making changes in sensor locations when necessary. These different sensors typically perform dedicated functions, such as detecting motion, temperature, or pressure; turning on or off lights; and communicating their data to a gateway by means of a particular wireless protocol, such as Wi-Fi, Bluetooth, or the IEEE 802.15.4 standard at 868, 915, and 2,400 MHz.

These sensors, or network nodes as they are known, connect to the Internet through a gateway, which translates each sensor's proprietary protocol to the Internet Protocol (IP) that allows interaction on the Internet. In addition, some sensors are equipped with IP connectivity and can connect directly to an IP server where available. Rather than simple network nodes, these edge sensors boast their own memory and microprocessor.

FACING THE FUTURE

As wireless IoT technology spreads throughout multiple industries, including automotive, business, communications, industrial, healthcare, and transportation markets, a number of concerns arise concerning the large numbers of sensors and actuators and their eventual competition for bandwidth. The very capacity of the Internet will be a concern with the amount of data predicted from billions of worldwide sensors and the need to store and process that data.

In addition, the power requirements of the many IoT devices that will be mounted, worn, carried, or embedded within users is forcing circuit and device designers to rethink energy efficiency for their circuits, and take novel approaches to providing energy for emerging IoT applications.

Numerous researchers have explored methods of harvesting energy from already-present power sources in a system. For example, a version of Wi-Fi WLAN technology known as power over Wi-Fi, developed by engineers at the University of Washington, gathers energy from a Wi-Fi router's signals for reuse to power sensors in a wireless sensor network.

In addition, recent research from the Eindhoven University of Technology in the Netherlands examined energy harvesting from 60-GHz line-of-sight millimeter-wave signals to power temperature sensors *(see "World's Smallest Temperature Sensor Powered by MM-Waves," at mwrf.com)*.

EnOcean (www.enocean.com) has developed patented energy-harvesting technology that it is already licensing to a number of wireless-device developers. The technology employs 315 MHz in North America and 868 MHz in Europe to transfer power from an energy source to IoT devices in need of power. The firm has also developed a series of energy-harvesting wireless sensors and controls for building automation systems, for use at 315, 868, and 902 MHz *(Fig. 2)*.

Conservation of bandwidth may yet be another challenge for the growing IoT ecosystem, as more and more wireless devices compete for limited available frequencies. In some cases, millimeter-wave frequencies such as 60 GHz may be used while in other cases, the spectral spaces between existing wireless standards, known as "Weightless," may be recruited to link IoT devices to IP gateways.

The design challenges are certainly intriguing, and with billions of IoT products forecasted for so many different markets, not without tremendous motivation for solutions.

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Compressed UNB-OFDM Delivers HIGH DATA RATES

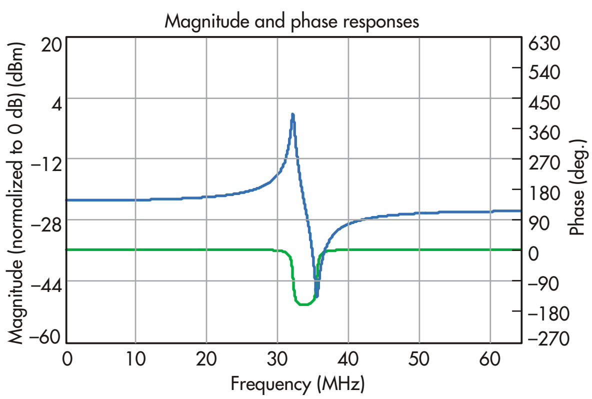
High data rates are achievable by trimming sidebands—without consuming the large amounts of bandwidth required for conventional wideband modulation schemes.

Ultranarrowband (UNB) modulation has been proposed for several decades as an alternative to traditional broadband modulation techniques; it is a means of achieving high data rates without immense consumption of available bandwidth. Different researchers offer different views on a modulation format that functions without sidebands, some positive and some negative.[1,2]

A great deal of work on UNB modulation can be traced back to the innovative findings of Harold Walker during the early days of the current "wireless revolution." [3-5] As the current research will show, UNB modulation is a fundamental modulation format as valid as binary-phase-shift-keying (BPSK) modulation, with some unique advantages.

Proponents of UNB technologies have often questioned the need for wide continuous spectrum.[6-8] In theory, without sidebands, UNB communications channels can be closely spaced while still making it possible to receive demodulated UNB modulated signals. As will be shown, different UNB channels can be closely spaced while still enabling effective communications at high data rates. Also, a wide continuous spectrum is unnecessary, and the spread continuous spectrum can be compressed as narrow as possible—as much as Shannon's limit defines, such as 1 Hz or less for UNB methods.

Traditional filtering techniques will not work with UNB modulation methods, owing to the large group delay of those filters.[3,5] Filters with zero or negative group delay or similar mathematical methods realizing the same zero-group-delay principle are required to compress or filter modulated UNB



1. This plot of magnitude and phase as functions of frequency shows the response for a negative-group-delay filter for UNB modulation systems.[2]

signals. For example, a fractal transform can be used to compress the unnecessary sideband to achieve the goal of filtering UNB-modulated signals.

Figure 1 presents a filter with negative group delay.[3] With such a filter, any UNB-modulated information can be retained after filtering, even though the filter's 3-dB bandwidth is extremely narrow (for instance, 1 to 2 kHz). To demonstrate UNB modulation, *Fig. 2* shows a recovered UNB-modulated signal passed through a filter with negative group delay, while *Fig. 3a* shows the frequency characteristics of the filter and *Fig. 3b* displays the signal's power spectral density (PSD).

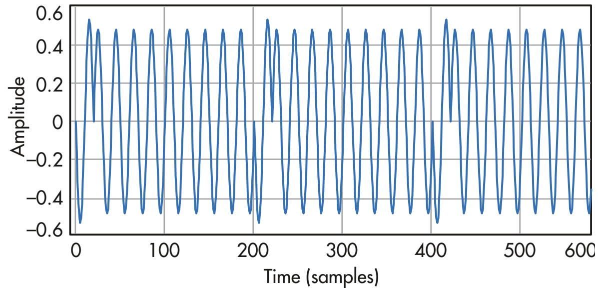
As can be seen, while there is no sideband for the UNB signal, the phase characteristics are not degraded. Some amplitude attenuation occurs with a zero-group-delay filter for UNB modulation, but the amplitude can be regained through amplification.[1]

As these filter response plots show, the modulated signal sideband for UNB modulation is unnecessary and can be compressed to a large extent. This allows multiple UNB-modulated signals to be placed closely together for multiple-signal or multiple-band communications with higher data rates compared to single-channel UNB communications schemes. Multifold data rates can be achieved through the use of closely spaced UNB modulated signals *(Fig. 4)*.

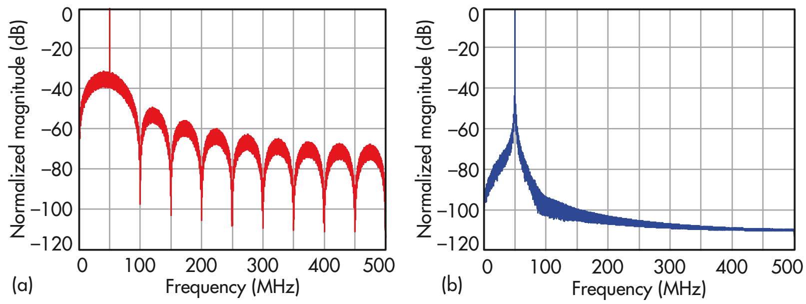
In *Fig. 4*, the red trace represents the original UNB modulated signal. The continuous spectrum is very wide due to the use of asymmetrical modulation.[6]

Once UNB-modulated signals have been compressed, multiple UNB signals can be placed within the same frequency band. As *Fig. 4* shows, at least 10 compressed UNB signals with the same data rate can be placed within a limited bandwidth, improving the data rate by a factor of 10 compared to a single UNB signal in the same bandwidth.

For example, starting with a single signal data rate of 12 Mb/s,[3] a data rate of 120 Mb/s can be achieved with 10 closely placed UNB-modulated signals within a

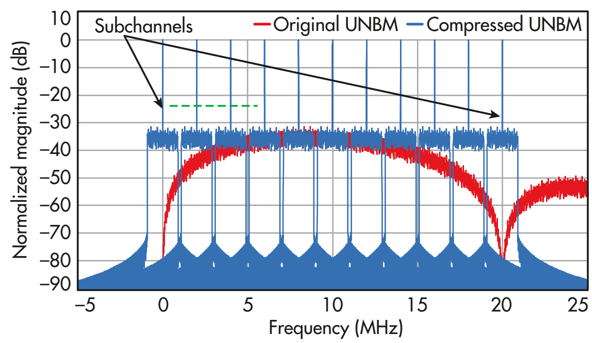


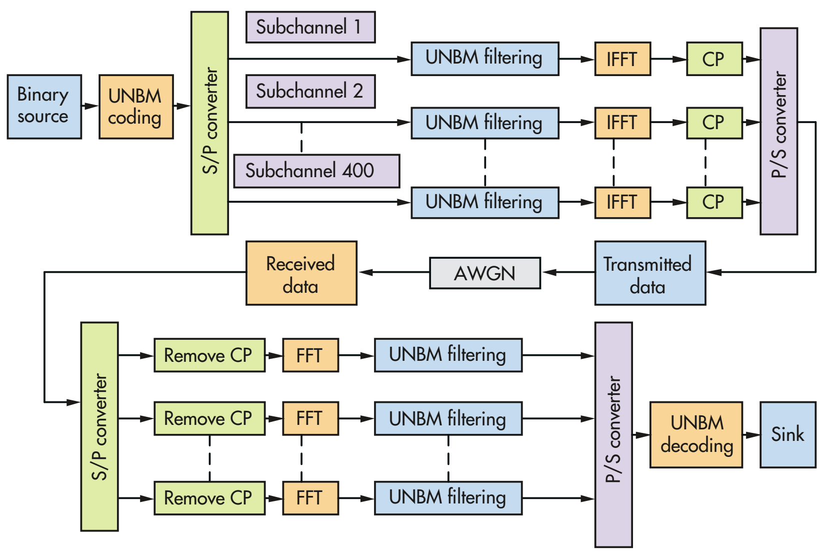
2. This consistent waveform was recovered from UNB modulated transmission using a special filter with almost no delay.



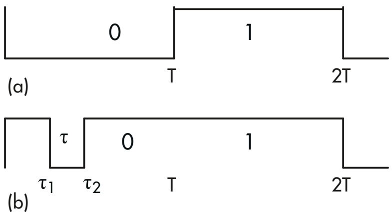
3. The plots represent (a) modulation without the "grass" spike and (b) PSD for the waveform of Fig. 2.

4. Comparison between single-carrier UNB and compressed UNB-OFDM.





5. This block diagram shows the essential functions and components of a compressed UNB-OFDM system.



6. The diagram shows the principle of asymmetric modulation.

common bandwidth. Orthogonal frequency division multiplexing (OFDM) is an efficient multichannel communications technique that can be applied to the use of multiple UNB-modulated signals to achieve an increase in data rate in this manner *(Fig. 5)*.

The high spectral efficiency of OFDM has made high data rates possible in many communications systems and devices. With the ready availability of fast-Fourier-transform (FFT) technology in communications integrated circuits (ICs), OFDM has become practical and widespread in commercial systems. This is also why it has been possible to implement a compressed UNB-OFDM communications system.

A multicarrier communications system divides available bandwidth into subchannels, each with its own data stream, and then multiplexes them prior to transmission. Each subchannel can be reserved for distinct data streams, or one data stream can be divided into N-data streams for N-subchannels.[9] *Figure 5* shows a block diagram of a multicarrier system, where the block labeled "Binary Source" features UNB-modulation coding. A serial-to-parallel converter transforms coded UNB-modulation data to parallel data streams, which correspond to the different subchannels.

Each subchannel is filtered, with its bandwidth compressed using negative-group-delay filters or other mathematical approaches (such as the use of fractal transforms). This results in OFDM using FFT techniques, with cyclic prefix (CP) appended to limit intersymbol interference (ISI). Following this, parallel modulated data is converted to a serial data stream for transmission, with an arbitrary white Gaussian noise (AWGN) channel used to transmit compressed UNB-modulated OFDM signals.

At the receiver, received data is reshaped to parallel subdata streams and the CP is removed, with UNB filtering applied to enhance the modulation characteristics. All of the subchannels are reshaped to the original serial data to decode the UNB-modulated signals and recover the binary data. In this way, a system with a high-data-rate requirement can be divided into N lower-rate subchannels. The lower rates feature longer symbol durations than higher-rate signals and, with an added guard band, can help minimize intersymbol interference (ISI).

If the subchannels are narrow enough, the channel frequency response is approximately constant with respect to each subchannel. This makes equalization much less complicated than in a single-carrier system. While the subchannels can be chosen in any manner with respect to bandwidth, center frequency, and guard interval, a special case was considered in which subchannel parameters allow for increased bandwidth efficiency (near-Nyquist efficiency) and computationally efficient modulator and demodulator design.

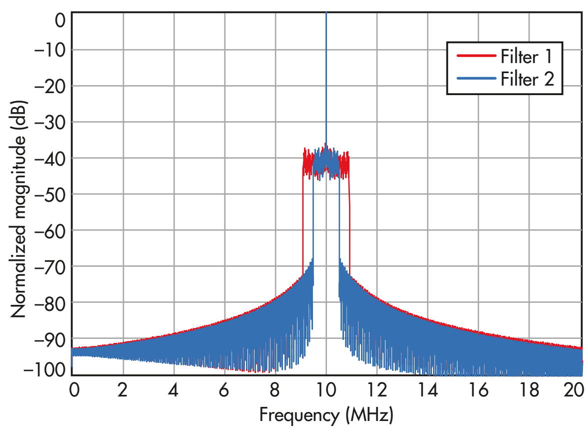
The general wave function for UNB modulation can be written as Eq. 1[6]:

$$g_0(t) = \begin{cases} \Pi(f_c, t, \theta_0) & 0 \le t < \tau_1, 0 \le \tau_1 \le T - \tau \\ \Delta(f_c, t, \theta, \theta_0) & \tau_1 \le t < \tau_2, 0 \le \theta, \theta_0 \le \pi \\ \Pi(f_c, t, \theta_0) & \tau_2 \le t < T \end{cases} \tag{1}$$

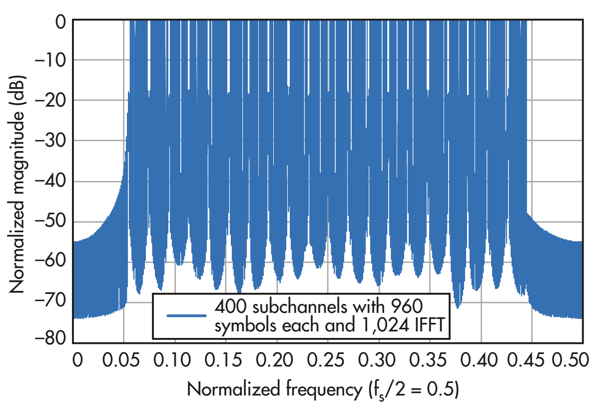
$$g_1(t) = Asym(g_0(t))$$

where $\Pi(f, t, \theta_0)$ can represent a variety of different digital sig-

7. PSD for two different UNBM signals. The wide continuous spectrum has been compressed greatly.



8. Compressed UNB-OFDM PSD.



nals, such as sine-wave or rectangular-wave signals, with $\tau = \tau_2 - \tau_1$; Δ is the change or modulation to the $\Pi(f, t, \theta_0)$ wave in amplitude, phase, or frequency; θ is the modulation phase angle within the range $[0\ \pi]$; θ_0 is the initial phase of the signal, which can have any value in the range $[0\ \pi]$; Asym indicates asymmetric operation; and f_c is the carrier frequency of the modulated signal.

Additional parameters are T, which is the bit period, while τ is the duration of the modulation, with a value between 0 and T. Also, $g_0(t)$ represents a digital "0" state, while $g_1(t)$ is the digital "1" state. The parameter τ/T can be seen as the modulation duty cycle while also representing the degree of asymmetry for $g_0(t)$. The basic principle is illustrated in *Fig. 6*.

If $\Pi(f_c, t, \theta_0) = \cos(2\pi f_c t)$, $\Delta(f_c, t, \theta, \theta_0) = \cos(2\pi f_c t + \theta)$, and $g_0(t) = \cos(2\pi f_c t)$, pulse-position phase reversal keying (3PRK) can be denoted by Eq. 2:

$$g_0(t) = \begin{cases} \cos(2\pi f_c t) & 0 \le t < \tau_1, 0 \le \tau_1 \le T - \tau \\ \cos(2\pi f_c t + \theta) & \tau_1 \le t < \tau_2, 0 < \theta \le \pi \\ \cos(2\pi f_c t) & \tau_2 \le t < T \end{cases} \quad (2)$$

$$g_1(t) = \cos(2\pi f_c t)$$

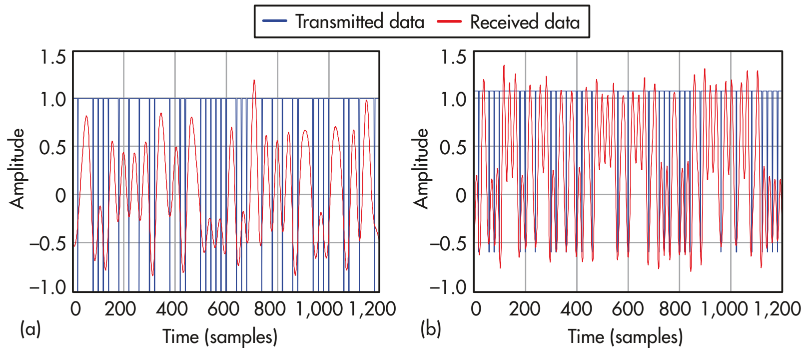
where the variables have been defined for Eq. 1, and where $\theta \neq 0$, $g_0(t)$ and $g_1(t)$ denote biphase modulation, and the modulation angle is defined by the range of $[0, \pi]$. If $\tau = T$, the modulation is BPSK.

If W is the channel bandwidth and N is the number of subcarriers, then the subchannel bandwidth is described by $\Delta f = W/N$ and the effective symbol rate is $T_s = 1/\Delta f = N/W$. The subcarrier frequencies are $f_n = n\Delta f = n(W/N)$, where the subcarrier spacing is $\Delta = W/N$ for $n = 0, 1 \ldots N - 1$. The basic pulse waveform for UNB modulation can be defined by Eq. 3[9]:

$$\psi(t) = \begin{cases} \frac{1}{\sqrt{T_s}} e^{i2\pi f_n t}, & 0 \le t < T_s, \text{for } n = 0,1,\ldots, N-1 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

which expresses a normalized rectangular pulse at frequency f_n. The inner product has the property described by Eq. 4:

$$\begin{aligned} \langle \psi_n(t)\psi_m(t) \rangle &= \int_{-\infty}^{\infty} \frac{1}{\sqrt{T_s}} e^{-j2\pi f_n t} \frac{1}{\sqrt{T_s}} e^{-j2\pi f_m t} dt \\ &= \frac{1}{T_s} \int_{-\infty}^{\infty} e^{-j2\pi (f_n - f_m)t} dt \\ &= \begin{cases} 1 & \text{for } m = n \\ 0 & \text{for } m \neq n \end{cases} \end{aligned} \quad (4)$$



9. The plots show the two received signals from Fig. 6 as time samples: (a) filtered signal 1 and (b) filtered signal 2.

The OFDM symbol is a linear combination of the subchannel symbols or pulses, which can be considered as a set of orthogonal basis vectors. Thus, the OFDM symbol can be described by Eq. 5:

$$s_k(t) = \sum_{0}^{N-1} X_{n,k} \psi_n(t - kT_s) \quad (5)$$

where k is the kth OFDM symbol; n is the nth subchannel; and $X_{n,k}$ is the kth UNB symbol in the nth subchannel. The transmitted signal can then be described by Eq. 6:

$$S(t) = \sum_{k=-\infty}^{\infty} s_k(t) \quad (6)$$

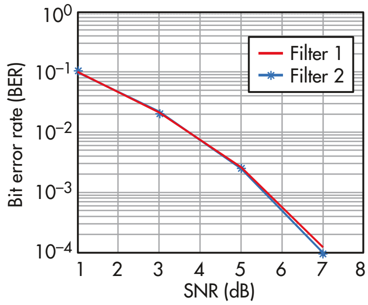
Assuming an AWGN channel, the received signal for the kth OFDM symbol can be found by means of Eq. 7:

$$\begin{aligned} \widetilde{X}_{n,k} &= \int_0^{T_s} y_k(t)s_k(t) + n(t)\psi_n^*(t)dt \\ &= \int_0^{T_s} [s_k(t) + n(t)]\psi_n^*(t)dt \\ &= \int_0^{T_s} \sum_0^{N-1} X_{m,k}\psi_n(t - kT_s)\psi_n^*(t)dt + \int_0^{T_s} n(t)\psi_n^*(t)dt \\ &= \sum_0^{N-1} X_{m,k} \int_0^{T_s} \psi_m(t)\psi_n^*(t)dt + n \\ &= X_{m,k} + n \end{aligned} \quad (7)$$

where n(t) is an additive Gaussian random process. To demodulate the nth OFDM symbol, the received signal is correlated with matched filter $\Psi^*_n(t)$. Because the pulses are orthonormal, the correlation will be 0 for m = n and 1 for m = n.

Based on the theory so far presented, a computer simulation was carried out on the UNB system. The simulation was based on a frame with 400 subchannels, each with 960 symbols, and a 1,024-point FFT. For UNB modulation, coding rates from 1 to 10 were employed.

Figure 7 offers a comparison of the power spectral densities (PSDs) for different bandwidths—one a Nyquist bandwidth,



10. The plot shows the BER of two different UNB-modulated signals.

and the other a two-fold Nyquist bandwidth. These two different-bandwidth signals were used during the simulation to calculate the BER and to verify that continuous spectrum is not necessary for effective use of UNB modulation for high-data-rate communications.

Depending upon different scenarios, UNB-modulated signals can be placed close together, without sidebands to separate them. In contrast to the two different bandwidth signals of *Fig. 7*, *Fig. 8* shows the PSD of an UNB-OFDM signal with all subchannels closely spaced.

Figure 9 presents the recovered time wave signals of the two corresponding different UNB-modulated signals of *Fig. 6*. The phase reversal is clear after being demodulated, which directly shows that the redundant sideband is not necessary, and can be compressed.

After 20 simulation runs, the average BER curves were plotted *(Fig.10)*. The data from those simulations is presented in *Table 1*.

The curve with an asterisk marker corresponds to the BER for the Nyquist bandwidth, while the other curve is the BER plot of the UNB-modulated signal with two-fold Nyquist bandwidth. As is apparent, the BER is not deteriorated by bandwidth compression. This revelation emphasizes that sidebands are not needed in order to separate the multiple channels in an UNB-OFDM system and, as a result, they can be compressed.

For UNB modulation, the continuous spectrum spread is represented by T/τ. For RF modulation such as UNB modulation, the width of the continuous spectrum is 2T/τ. As has been shown, a wide continuous spectrum can be compressed. Using compressed UNB-OFDM, T/τ to 2T/τ different subchannels can be deployed in the same frequency band that is occupied by a single-carrier UNB continuous spectrum. This can improve the data rate by T/τ to 2T/τ, compared to data rates provided by single uncompressed UNB modulated signals.

Table 2 offers a comparison between compressed UNB-OFDM and PPM UNB. Data rates can be improved by T/τ to 2T/τ times using compressed UNB-OFDM, while PPM-UNB only increases the data rate by $\log_2$ (T/τ) times. In the case of a typical 500-MHz UWB frequency band, assuming compressed UNB-OFDM is deployed, a data rate of 500 Mb/s can be achieved.

The spectral efficiency is significantly improved with UNB-OFDM compared to conventional UWB communication methods, even when PPM technology is used. For a single user in an extreme case, for the full UWB frequency band, a data rate of about 7 Gb/s is possible with UNB modulation, making it an intriguing candidate for emerging 5G communications applications. mw

ACKNOWLEDGMENT
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TABLE 1: SUMMARIZING NYQUIST AND TWO-FOLD NYQUIST BANDWIDTH CHARACTERISTICS

Bandwidth	SNR (dB)/BER				
Two-fold Nyquist bandwidth	1/0.0990	3/0.0222	5/0.0025	7/0.0001	9/0
Nyquist bandwidth	1/0.1007	3/0.0214	5/0.0026	7/0.0001	9/0

TABLE 2: COMPARING COMPRESSED UNB-OFDM AND PPM UNB

Modulation	Parameters/Folds				
	T/τ	T/τ = 16	T/τ = 32	T/τ = 64	T/τ = 128
Compressed UNB	T/τ 2T/τ	16 – 32	32 – 64	64 – 128	128 - 256
PPM-UNB	$\log_2$T/ τ	4	5	6	7

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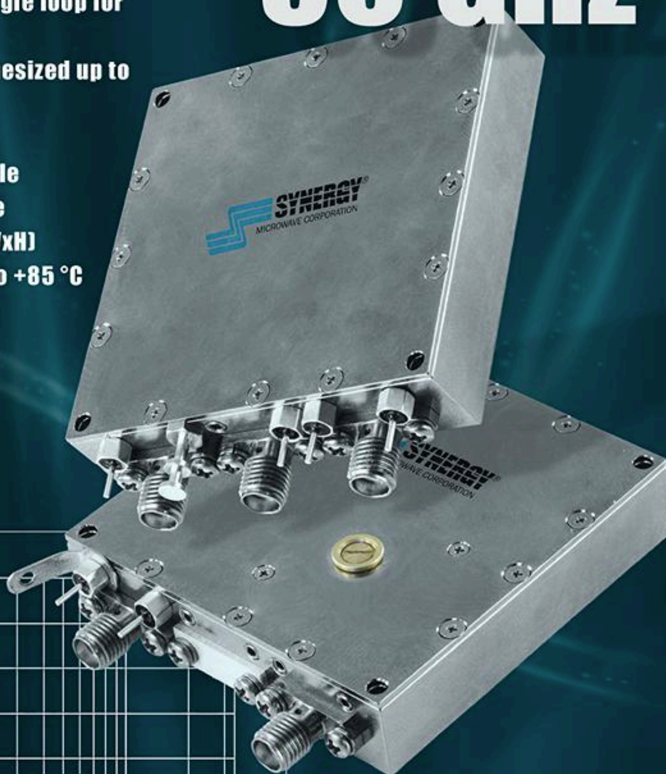

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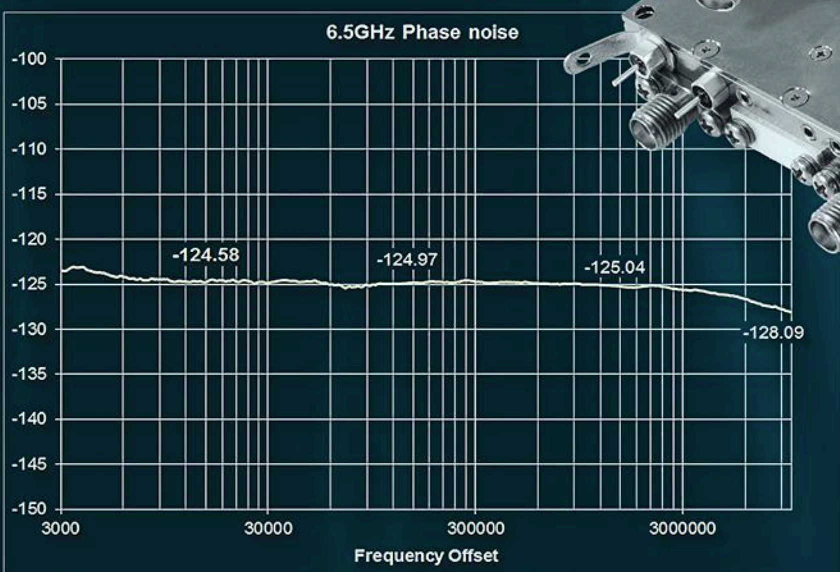

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Design Feature

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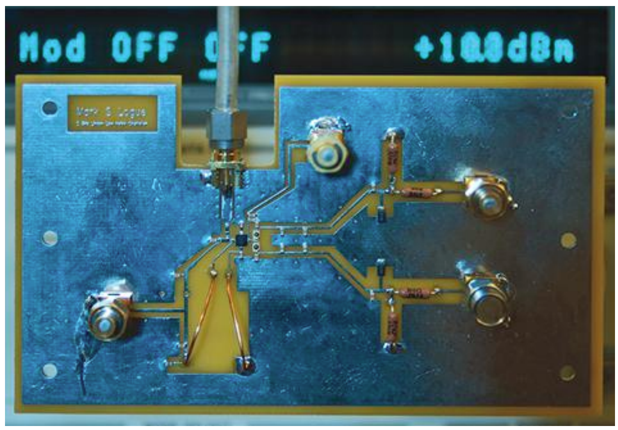
Design Method Predicts RF Oscillator Noise

This novel simulation method effectively analyzes a 2-GHz oscillator to better understand and optimize its noise performance.

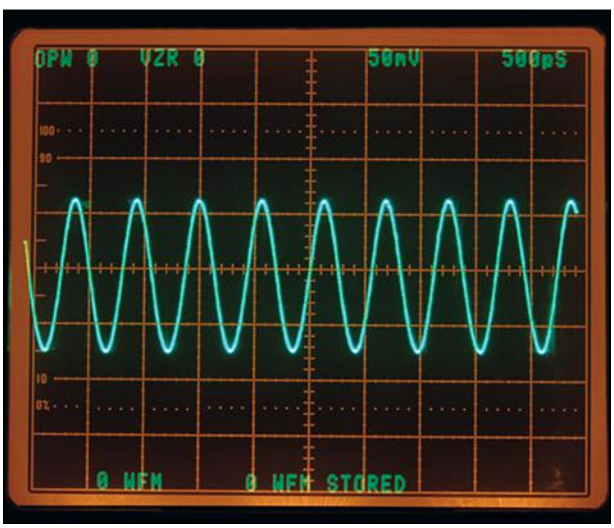
Noise plagues most RF/microwave systems at some level. The majority of system-level designers aim to achieve the highest signal-to-noise ratios (SNRs) possible to ensure optimum reception of signals in, say, receivers. Minimizing noise usually starts with the signal source, whether it's an oscillator or an oscillator with a phase-locked loop (PLL) in a frequency synthesizer.

Designing a quiet source requires paying close attention. But, as will be shown with the design of a low-noise, 2-GHz microwave oscillator, it's possible to better understand active device noise mechanisms through rigorous analysis. One benefit of this analysis is an opportunity to design and construct a stable, low-noise oscillator that operates well within the linear region of its active device, a gallium-arsenide (GaAs) field-effect transistor (FET).

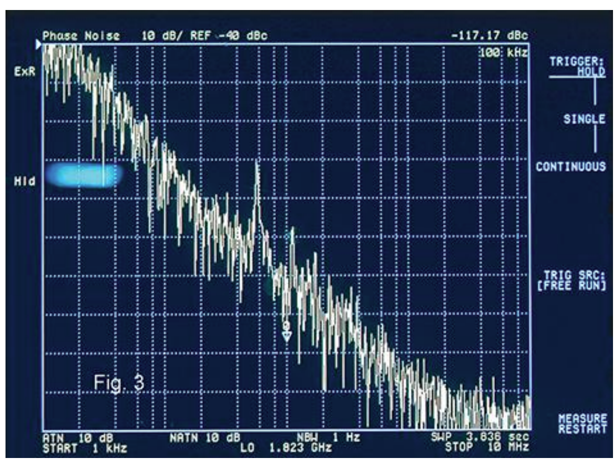
The 2-GHz oscillator is based on a clamped, linear 40-GHz Schottky-barrier diode approach, operating within the linear region of a small-signal GaAs FET. The oscillator design is able to drive a 50-Ω load with low-noise 2-GHz energy, relatively free of harmonic distortion. The oscillator design was



1. This is the test circuit used to evaluate the performance of the 2-GHz oscillator.



2. This oscilloscope screen display reveals the low harmonic content of the 2-GHz oscillator design.



3. This phase-noise display was created with a reference at –40 dBc and for offsets from 1 kHz to 10 MHz.

analyzed with a discrete Fourier transform (DFT) program that featured a dynamic range of greater than 260 dB.

As a rule, microwave oscillators will exhibit some level of harmonic distortion when driving a 50-Ω load. Ideally, harmonic, subharmonic, and spurious signal distortion can be minimized without degrading oscillator single-sideband (SSB) phase noise. Traditionally, signal-source harmonics and phase noise have been analyzed by means of harmonic-balance frequency-domain methods to track the steady-state nonlinear responses at higher frequencies. But by using the time domain, followed by a novel DFT analysis method, excellent results were achieved in the analysis of the 2-GHz GaAs FET oscillator.

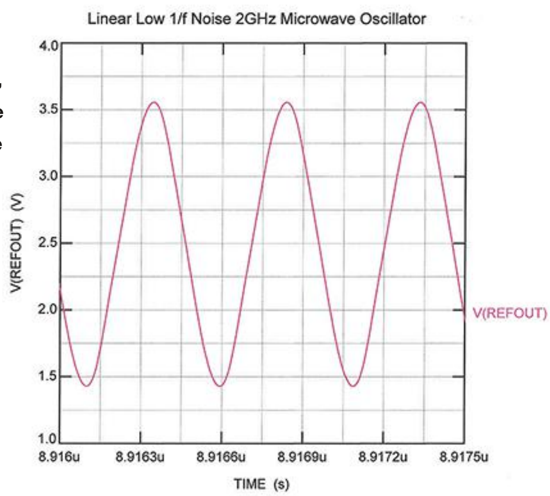
TEST SETUP

In the novel oscillator analysis approach, two identical oscillators were constructed for simulation purposes. They were injection locked at their FETs' gates, so that both oscillators would remain in phase relative to each other. One of the oscillators was considered a reference and the other the device under test (DUT), with a random noise source injected into the DUT. The output of the DUT oscillator (TESTOUT) is then subtracted from the output of the reference oscillator (REFOUT), followed by a DFT to produce the desired results.

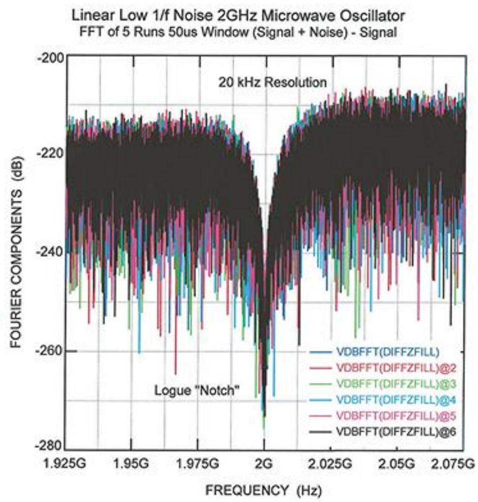
The analysis method has been capable of measuring extremely low noise levels in the nanovolt range. The random noise source (V1) drives a transconductance block (G2) with a value of 1.0, injecting random current into the drain and source of the DUT. Multiple simulation runs are performed, with each run using random-noise-generator "seed" values to produce a series of random voltages that are unique for each simulation run. The random noise generator operates with one step every 1.000055 ns, with peak values of ±1 nV, which in turn drive the transconductance block (G2).

The negative resistance seen at the gate of the oscillator is obtained by providing a capacitive load at the source of each FET at 2 GHz. The inductors in the FET sources act as a bias tee, providing only dc bias to the device. The diodes in each FET's gate are Schottky-barrier GaAs diodes rated at 40 GHz. They provide a small load to the tank circuit while biased at low forward voltages.

The linear gain of the oscillator at 2 GHz is the value of the load resistance (50 Ω), divided by the capacitive reactive loading at the FET source. The capacitor's value in the source of the FET is chosen to provide a negative resistance as seen at the FET gate and the desired



4. Produced with computer-aided-design (CAD) software, this plot represents the output of the reference oscillator as a function of time.



5. In this CAD simulation, the test oscillator went through an FFT of five runs for a 50-μs window from 1.925 to 2.075 GHz.

amount of linear gain for oscillation.

Figure 1 shows the hardwired test fixture for evaluating the oscillator's performance, fabricated on FR-4 printed-circuit-board (PCB) material using chip and discrete circuit elements. The unused ports were terminated into the characteristic 50-Ω system impedance to protect against static discharge when the photograph of the fixture was being taken.

THE RESULTS ARE IN

Figure 2 shows the output of the test oscillator in the text fixture on the screen of a commercial sampling oscilloscope. The traces reveal very low harmonic distortion into 50-Ω impedance.

To evaluate the test oscillator's phase noise, a commercial signal analyzer from Agilent Technologies (now Keysight Technologies; www.keysight.com) was used to measure the plot of *Fig. 3* with reference level at –40 dBc. For comparison, a voltage plot of the reference oscillator (*Fig. 4*) was produced with the assistance of the TopSpice computer-aided-engineering (CAE) software, a mixed-signal, analog/digital circuit-design program available from a variety of online sources, including Penzar (www.penzar.com).

A time-domain plot *(to view this plot, go to the online version of the article at http://mwrf.com)* shows low-noise characteristics similar to those of *Fig. 3*. Again, the reference oscillator is identical to the test oscillator, with the difference being that the test oscillator is being driven by a random noise source with zero mean deviation.

A combination of TopSpice (a PC version of SPICE modeling software) and a custom FFT program was used to produce a fast Fourier transform (FFT) display of the test oscillator for five runs across a 50-μs window across a frequency range of 1.925 to 2.075 GHz with 20-kHz resolution (*Fig. 5*). Similarly, Spice was employed in the design of the phase-locked injection-lock circuitry used to drive the gates of both the reference and test oscillator circuits (see *Fig. 7 in the online version of this article*).

The computer simulation reveals second-harmonic distortion is extremely low: 42 dB removed from the fundamental frequency amplitude level. Third-harmonic distortion is –30 dBc from the fundamental-frequency level. To reduce aliasing and higher-order harmonic levels in the 2-GHz oscillator simulation, a five-stage, 22.7-GHz filter was included in the simulation results (see *Fig. 8 in the online version of this article*).

Overall, the noise components from the computer simulation are more than 210 dB removed from a 0-dB reference, for impressive performance achieved with the aid of comparing performance for the two 2-GHz oscillators when injecting current noise *(see Fig. 9 in the online version of this article)*. Though the analysis technique essentially requires the fabrication of dual computer-model prototypes, it lends itself to low-noise oscillator design and development across a wide range of frequencies. mw

JACK BROWNE | Technical Contributor

Receive a Clear Picture of Antennas

Antennas are among the most important components in any RF/microwave system, sending and receiving high-frequency signals and their messages across free space.

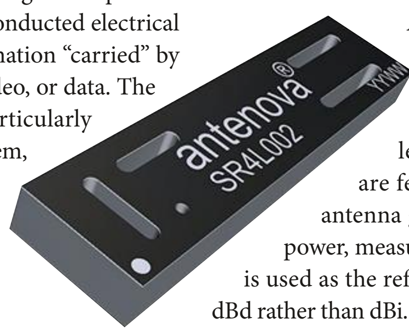
Antennas may be among the most critical but under-appreciated components in a microwave system. They are the electromagnetic (EM) interfaces for the environment, sending and receiving EM energy and its voice, video, and data content. They come in many shapes and sizes—fitting into both the smallest mobile devices and the largest towers and battleships—with power levels that are proportional to size.

Understanding the intricacies of RF/microwave antennas can take a lifetime, but knowing some of their basic workings can help narrow the search when it is time to match an antenna to a particular application.

A transmit antenna converts conducted electrical current fed to it into EM radiation for propagation through free space. A receive antenna converts EM radiation to conducted electrical current for processing to decode the information "carried" by the modulated EM waves, such as voice, video, or data. The old expression "it takes two to tango" is particularly fitting for antennas in an RF/microwave system, although the two antennas are often of different types and sizes.

Antennas have as many different forms as any RF/microwave component, with sizes ranging from resonant circuits on integrated circuits (ICs) to parabolic dish antennas aiming out at deep space in search of a signal. The many types of high-frequency antennas include spiral, patch, blade, monopole, dipole, lens, log periodic, helix, and horn. Most antennas can be used for both transmit and receive purposes, although the physical size will have a great deal to do with the antenna's wavelength/frequency and power-handling capability for transmit purposes.

1. This horn antenna design is formed of aluminum and available with coaxial or waveguide feeds for use from 2.6 to 40.0 GHz. *(Photo courtesy of ARRA Inc.)*



2. These miniature SMT antennas are designed to mount on the PCBs of LTE and other wireless communications systems *(Photo courtesy of Antenova Ltd.)*

SIZING UP SPECS

When sizing up antenna performance, a handful of specifications serve to compare different units. These include frequency range, bandwidth, gain, directivity, polarization, impedance, return loss or VSWR, radiation pattern, beamwidth, efficiency, and sidelobe levels. Antennas can either be constructed for maximum efficiency at selected, narrow bandwidths, or designed for broadband, multiple-octave bandwidths. They also can be designed for multiple frequency bands, such as several different wireless communications bands.

Antenna gain usually assumes a loss-free isotropic radiator as the reference. It compares the radiated power of an antenna in question to the radiated power level of the isotropic radiator when both are fed with the same input power level. The antenna gain is then the logarithmic difference in power, measured in dBi. Sometimes a half-wave dipole is used as the reference, in which case the gain is given in dBd rather than dBi.

The physical length of an antenna will determine its operating frequency. The simplest antennas, monopoles (which can be as basic as a straight wire), are generally designed for one-quarter wavelength. Dipoles typically have a length of one-half wavelength. Another simple version, the inverted-F antenna (IFA), is the most common miniature antenna designed into or embedded in portable communications devices (such as handsets and smartphones). It is as essential as quarter-wavelength transmission line, such as microstrip, on a printed-circuit-board (PCB) substrate with a ground plane.

Although the antenna concept is simple, saving space is usually important for most embedded antenna designs, and IFAs are usually folded into different shapes for the appropriate quarter wavelength in order to save PCB real estate. For any such microstrip antenna, the choice of PCB material is critical: Circuit material properties like dielectric constant and dissipation factor can impact antenna performance.

The microstrip patch antenna is another simple antenna design for embedded applications. It is a directional antenna, with propagation and reception in the direction away from the PCB ground plane, and can be formed of half- or quarter-wavelength circuit structures.

Poor return loss at an antenna (denoted by a high VSWR) will reflect received signal power back toward the source of the signals and transmitted power back toward a transmitter's electronic circuitry, typically a power amplifier driving the antenna with high-power transmit signals.

Antennas can have linear, circular, or elliptical polarization, where polarization is determined by the direction of the electric field vector. In linear polarization, the electric field vector changes only in magnitude. In circular polarization, the direction of the electric field vector changes and rotates around the direction of propagation, in right-handed or left-handed directions. In elliptical polarization, both the magnitude and the direction of the electric field vector change. Employing antennas with consistent polarization is important, since as much as one-half the amount of transmitted signal power can be lost at the receiving end by using transmit and receive antennas with different polarization characteristics.

Antenna aperture is the area that captures energy from a passing radio wave—e.g., the area of the mouth of a horn antenna. An antenna with a larger aperture will provide more gain than an antenna with a smaller aperture. A larger-aperture antenna can receive more energy and radiate more energy in that direction than an antenna with a smaller aperture. Antennas with large apertures typically provide high efficiency.

A traditional horn *(Fig. 1)* may best graphically illustrate the concept of aperture, since it is a structure formed of conductive materials with a large opening to send and receive EM energy. Depending on frequency, horn antennas can be designed with various feed types, including coaxial connectors or waveguide flanges at higher frequencies. For those seeking more information on the types and operating parameters of RF/microwave antennas, the "Antenna Basics" white paper from Rohde & Schwarz (www.rohde-schwarz.com) is available as a free PDF download from the company's site. In addition, Besser Associates (www.besserassociates.com) offers an Antenna Design Course.

3. Developed for in-building wireless communications, this antenna provides an unobtrusive profile while overcoming many of the propagation problems posed by multiple-story buildings. *(Photo courtesy of Pulse Electronics Corp.)*

ANTENNA EVOLUTION

Antennas can be large, small, active, or passive. Active antennas are typically used at lower frequencies (200 MHz and less) where atmospheric noise is high and where the active circuit elements can be applied to shrink the size of the antenna at lower frequencies.

With the proliferation of wireless technologies for a growing number of applications in automotive, medical, and home automation, antenna designers are seeking smaller and more efficient designs that can fit within housings as small as surface-mount-technology (SMT) packages, and even on semiconductor chips.

Antennas are evolving well beyond the traditionally large structures of military radar and commercial broadcast systems. Those designers will depend more strongly on the insights offered by computer-aided-engineering (CAE) software simulation tools, notably electromagnetic (EM) simulation software.

As an example of this trend toward smaller designs, Antenova Ltd. (www.antenova-m2m.com) recently unveiled its Lucida line of SMT antennas *(Fig. 2)* for cellular telephones, IoT applications, and multiple-input, multiple-output (MIMO) communications systems. The miniature antenna is particularly well suited for Long-Term-Evolution (LTE) wireless applications. It operates in all mobile communications bands, including 700, 850, 900, 1,800, 1,900, 2,100, 2,300 to 2,400, and 2,500 to 2,590 MHz. The miniature antenna is also versatile; it can be used in base stations as well as portable and wearable wireless devices.

The Lucida antenna measures just 35.0 × 8.5 × 3.2 mm. It can be placed on a PCB as any other SMT component, providing a great deal of layout flexibility when attempting to miniaturize high-frequency products for these competitive communications applications.

Another recent novel antenna design, the latest addition to the Clarity family of antennas from Pulse Electronics Corp. (www.pulseelectronics.com), is intended for UHF use, including at 380 to 520 MHz and 698 to 960 MHz. The antenna features a plastic radome just 311 mm in diameter and protruding just 9.5 mm below the ceiling of a building, allowing for an unobtrusive profile for in-building applications. In spite of the small size *(Fig. 3)*, it maintains clear communications throughout multiple-story buildings. " mw

JACK BROWNE | Technical Contributor

To Terminate or ATTENUATE?

Terminations and attenuators can handle high power levels at microwave frequencies, and advanced materials are enabling them to do so in smaller packages.

Attenuators and terminations are commonly used components in high-frequency systems, used to adjust or absorb power, respectively. In many ways, the two types of components are similar, since they are both designed to stop RF/microwave power. Attenuators decrease some portion of the power, in fixed or variable amounts, while terminations stop power applied to them altogether.

Both types of components are available in various forms, from miniature chips to higher-power coaxial components and the highest-power waveguide assemblies. Both types of components play important roles in high-frequency circuits and systems, especially when high-power signals must be managed.

Microwave terminations are available in a wide range of package styles, with power-handing capability a function of size, while connection types often dictate frequency range. *(Courtesy of Res-Net Microwave)*

Attenuators and, in particular, high-power terminations are usually specified with size, weight, power-handling capability, and frequency range as essential parameters for comparison. Power-handling capability is generally a function of size, with the highest-power components occupying the greatest amount of volume in a design.

A termination is a one-port component meant to absorb all of the power applied to it, while an attenuator is a two-port component that reduces the level of the power passing through it by a fixed or variable amount. Attenuators can reduce signal power by a fixed amount or provide an adjustable range of attenuation. For the most part, adjustments are continuously variable or switched in discrete steps.

Terminations are typically connected at an unused port in a system, such as an unused port of a power divider that is splitting off signal power to other parts of the system. In addition, terminations are used when a passive component (such as a filter or a coupler) is being matched to 50 Ω for measurement purposes, as is the case when testing for return loss or power-handling capability. Terminations used for establishing reference impedances at high power levels are usually referred to as dummy loads.

Matching an attenuator or termination to an application is a matter of understanding the main operating parameters and making the best choice of component for a particular set of requirements. Attenuators are available with fixed attenuation values for a particular frequency range or with a range of attenuation settings that can be set in steps or under continuously variable control.

Whether fixed or variable, attenuators can be compared in terms of bandwidth, attenuation flatness across the frequency range, insertion loss, return loss or VSWR, power-handling capability, operating temperature range, size, and weight. *(For more on the fundamental operating parameters of RF/microwave attenuators, see "Know When To Add Attenuation" at www.mwrf.com)*

TERMINATING POWER

As with attenuators, terminations are available in many form factors. These include miniature chips, coaxial packages, and high-power waveguide com-

> "An important function of an RF/microwave termination is its capability to dissipate heat. Any type of power-absorbing component can dissipate heat by means of conduction, convection, or radiation."

ponents, generally with power ratings to match their sizes. Terminations are characterized by fewer parameters than attenuators, since they do not exhibit amplitude responses as a function of frequency. Rather, the frequency range of a termination is the span of frequencies over which it can maintain an impedance match with a system's characteristic impedance—usually 50 Ω, but sometimes 75 Ω for broadcast applications or other impedances for specialized uses.

An important function of an RF/microwave termination, especially for high-power models, is its capability to dissipate heat. Any type of power-absorbing component, such as a termination, can dissipate heat by means of conduction, convection, or radiation. Conduction takes place by means of physical contact of different materials, such as a flange-mounted termination to a heat sink.

Conduction occurs when heat is dissipated as it moves from areas of higher energy to areas of lower energy. Convection is a dissipation of heat from a source by means of a flowing liquid (such as water) or a flowing gas (including air, as in fan-cooled terminations). Thermal radiation occurs when a source emits EM waves that carry the heat energy—e.g., infrared (IR) radiation, as used in space heaters.

Any resistive element, including attenuators and terminations, will generate heat that must be dissipated to minimize temperature-related stress and ensure the long-term reliability of a component, circuit, or system. For that reason, terminations are usually fabricated from or packaged in a material with a high value of emissivity or heat-radiation efficiency.

An ideal thermal radiator would have an emissivity value of 1. While no materials exhibit that thermal radiating efficiency, aluminum comes close, with an emissivity of 0.9. For that reason, aluminum is often used to construct extremely high-power terminations, dummy loads, and attenuators.

SPECIFYING TERMINATIONS

Terminations are somewhat simpler to specify than RF/microwave attenuators, since the primary goals of any termination are to establish a good match with the system characteristic impedance and to absorb and dissipate a certain amount of power. As for attenuators, the number of suppliers for high-frequency terminations is large, with package styles ranging from tiny chip terminations to much larger waveguide terminations. As noted, heat must be dissipated, so the power-handling capabilities of these different terminations are related to physical size and connections to surrounding circuitry.

For example, American Technical Ceramics (www.atceramics.com), which supplies both attenuators and terminations, supplies circuit-board-mountable components, but in different packages and with different power ratings. The firm's leaded and surface-mount-technology terminations are well suited for densely packed PCBs. However, these tiny components cannot match the power-handling and thermal-management capabilities of slightly larger flange-mount terminations and their larger cross-sectional mounting connections for effective thermal dissipation.

Res-Net Microwave (www.electrotechnik.com) builds its chip terminations and resistors on thermally dissipative beryllium oxide (BeO) substrate material, allowing for relatively large power-handling capabilities in small component sizes. The firm supplies terminations in most major package styles *(see figure)*. These include conduction- and convection-cooled coaxial terminations with SMA connectors for use at power levels to 250 W from dc to 4 GHz, and the same power rating through 3 GHz with Type-N and TNC coaxial connectors.

The power-handling capabilities drop with increasing frequency, to about 50 W for SMA terminations operating to 18 GHz. The firm offers chip terminations based on its BeO substrates rated to 15 W at microwave frequencies.

Another material building block for high-power terminations is aluminum oxide, Al_2O_3, also known as alumina, long a favorite substrate for high-power passive RF/microwave components. As an example, the chip resistors fabricated by US Microwaves (www.usmicrowaves.com) on alumina substrates can also be used as chip terminations at power levels beyond 100 W through microwave frequencies.

The material supports a wide operating temperature range, from −65 to +200°C. Similarly, aluminum-nitride material has been shown to be effective for thermal dissipation, and is often used in packaging for high-power attenuators and terminations.

In spite of the thermal advantages of composite materials, higher power levels will require larger terminations to safely dissipate heat from a high-frequency design. Material advances have made possible some impressive power ratings for chip and SMT resistors, terminations, and attenuators. Nevertheless, higher-power applications, such as communications transmitters and radar systems, will still require the largest terminations and attenuators, usually with waveguide flanges for consistent dissipation of power levels that often exceed 1 kW CW. mw

DIRECTIONAL COUPLERS IMPACT POWER MEASUREMENTS

DIRECTIONAL COUPLERS ARE typically used when measuring the output power of an amplifier system, as well as the reflected power of load impedance, an antenna, or some other device under test (DUT). Their physical characteristics can significantly affect the measurement accuracy of a test setup. While some of these characteristics can be nullified by means of calibration, directional couplers have others that cannot be counterbalanced.

In a white paper titled "Influence of a directional coupler's parameters on the results of forward and reflected power measurements," Rohde & Schwarz describes specifically how directional couplers used in test setups can affect measurement results.

The white paper begins with a general overview of the parameters of a directional coupler. More specifically, mathematical definitions for coupling, directivity, and isolation are provided in the document. When performing reflected power measurements in particular, the directivity of a directional coupler can have a significant impact on results. Because directivity cannot be canceled by means of calibration, high-power measurements can be corrupted as a result of poor directivity.

An example of a typical test setup is presented. In this setup, a directional coupler and a DUT are separated by a specified distance. The reflected wave from the DUT and the coupler's finite directivity can be represented as two vectors, both of which are added at the directional coupler's reflection port. The DUT's reflected wave is transformed by a phase angle that is determined by the distance between the directional coupler and the DUT, as well as the frequency.

Several mathematical examples are presented in the white paper. The first example calculates the measurement error when using a directional coupler with good directivity. A directional coupler with lower directivity is employed in the next example, demonstrating an increased measurement error.

Another example further demonstrates how measurement results are affected by the distance between a directional coupler and a DUT by placing two directional couplers at the output of an amplifier system. Finally, the document includes an example to explain how different voltage-standing-wave-ratio (VSWR) values will make an impact on measured results.

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SOLVE IEEE 802.11AC TEST CHALLENGES

TO MEET DEMANDS for higher throughput, the IEEE 802.11 wireless-local-area-networking (WLAN) standard has continually advanced. The recent IEEE 802.11ac standard was specified as an extension of the previous-generation IEEE 802.11n. Although IEEE 802.11ac offers faster data rates and greater bandwidths than previous standards, its increased complexity demands additional test requirements. In the application note "Testing New-Generation WLAN 802.11ac," Keysight Technologies discusses the design and test challenges associated with IEEE 802.11ac.

The application note presents an overview of the key specifications of IEEE 802.11ac. A list of IEEE 802.11n specifications is also provided, allowing readers to see how the two standards compare with one another. The technical differences between IEEE 802.11n and IEEE 802.11ac are explained in further detail. For example, a description of the wider channel bandwidths used in the IEEE 802.11ac standard is presented. Multi-user multiple-input, multiple-output (MU-MIMO), which is new to IEEE 802.11ac, is explained in the document as well.

The IEEE 802.11ac standard includes a set of transmitter and receiver tests. Error-vector-magnitude (EVM) is an example of a critical test parameter. EVM testing and troubleshooting can be performed by a vector-signal-analysis (VSA) tool, such as Keysight's 89600 VSA software. Power amplifiers (PAs) for IEEE 802.11ac applications are utilizing digital pre-distortion (DPD) and envelope tracking (ET) to improve linearity and efficiency, respectively. The document goes into detail about test solutions for these latest PAs.

In addition, because wider-bandwidth signals are required for IEEE 802.11ac, the application note examines various test instruments that can both generate and analyze these wideband signals. Software solutions are also explained, as they are used in combination with test instrumentation to perform tasks like waveform creation and signal analysis. MIMO and beamforming design verification present another difficult challenge. Techniques to meet these challenges are discussed in greater detail for both receivers and transmitters. The application note concludes with a description of Keysight's EXM WLAN manufacturing test solution.

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CHRIS DeMARTINO | Technology Editor

MM-Wave Products Enable the Next Frontier

Millimeter-wave technology has become more widespread, as evidenced by the large number of higher-frequency products available today. With 5G on its way, millimeter-wave bands will generate even greater interest as a means to enable future technology.

MILLIMETER-WAVE TECHNOLOGY is now spearheading a wide range of applications. Once reserved for military use, this technology has become more widely used today. Wireless backhaul is one such example, as V- and E-band backhaul networks have become increasingly common. Many small-cell deployments are utilizing these networks, demonstrating the importance of millimeter-wave technology. Automotive applications are another example, as radar detectors and electronic sensors are utilizing millimeter-wave frequencies.

Millimeter-wave technology is likely to become even more prevalent in the days ahead. The main focus regarding millimeter-wave frequencies revolves around the highly anticipated arrival of 5G. A large amount of spectrum is available in the millimeter-wave bands, potentially enabling the faster data rates required for 5G. "The growth of the internet continues to be exponential," says Anuj Srivastava, president of Renaissance Electronics & Communications, LLC (REC; www.rec-usa.com). "We all want faster downloads, better connections, and the means to connect to all our data. 5G—and the millimeter-wave technology it will employ—could allow us to reach 10-Gb/s download speeds on our phone."

WIRELESS BACKHAUL

Backhaul plays an important role in a network design, as it enables data to be transported from the core network to the edge network. Millimeter-wave technology has become a desirable option for wireless backhaul. As mentioned, V- and E-bands are now being utilized for small-cell deployments, allowing performance and cost benefits to be achieved. The V-band frequency range of 57 to 64 GHz has been allocated as an unlicensed frequency band, while the E-band frequency ranges of 71 to 76 GHz and 81 to 86 GHz have been allocated as lightly licensed bands.

Millimeter-wave backhaul offers several benefits—greater bandwidth, for one. Today's network operators, therefore, have a number of reasons to consider millimeter-wave technology.

"Because of the ever-increasing demand for data, along with the dissociation of traffic revenues, network operators must look for cheaper and more efficient backhaul options without compromising stringent quality-of-service (QoS) requirements," says Kerem Ok, product line manager of the microwave integration and VSAT group at Analog Devices (www.analog.com). "Although traditional microwave will continue to play a major role in backhaul, the cornerstone of capacity enhancement will be millimeter-wave deployments—primarily E-band (71 to 86 GHz). It is expected to be the growth leader among all microwave/millimeter-wave bands, reaching 20% of all new deployments by 2020. E-band technology unlocks widely available spectrum to enable wireless throughput in excess of 10 Gb/s."

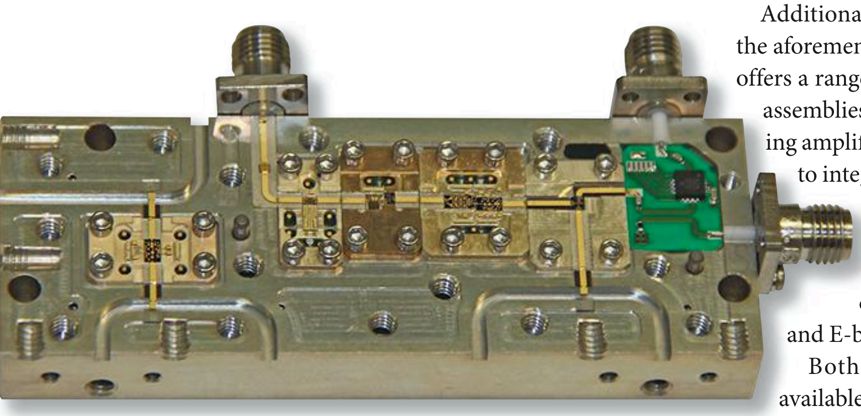
1. This E-band transceiver is intended for wireless-backhaul applications. *(Courtesy of Infineon Technologies)*

Analog Devices offers a selection of monolithic microwave integrated circuits (MMICs) that are well-suited for E-band backhaul applications. MMICs are available that cover 71 to 76 GHz, such as the HMC7543 power amplifier (PA) and HMC8120 variable-gain amplifier (VGA). The company also offers MMICs that span 81 to 86 GHz, such as the HMC8142 PA and HMC8121 VGA.

For its part, Infineon Technologies (www.infineon.com) has developed millimeter-wave transceivers for wireless-backhaul applications *(Fig. 1)*. This product family includes models BGT60, BGT70, and BGT80. The BGT60 is a V-band transceiver chipset, covering a frequency range from 57 to 64 GHz. The BGT70 and BGT80 E-band transceivers span 71 to 76 GHz and 81 to 86 GHz, respectively. These transceivers are based on Infineon's silicon-germanium (SiGe) technology.

Another company supporting backhaul applications is Peraso (www.perasotech.com), a fabless semiconductor company specializing in the development of 60-GHz wireless chipsets. Peraso offers products like the PRS1125, a single-chip millimeter-wave radio transceiver. This transceiver suits small-cell backhaul, as well as 60-GHz point-to-point/point-to-multipoint radios. In addition to the PRS1125, Peraso offers additional 60-GHz products like the PRS2152 transmitter and PRS2153 receiver. These low-power millimeter-wave modules support channel bandwidths as high as 2 GHz.

In addition, the E-band diplexer from MTronPTI (www.mtronpti.com) will find homes in backhaul applications. This diplexer has a low-band frequency range of 71 to 76 GHz, as well as a high-band range that covers 81 to 86 GHz. Its insertion loss is less than 0.65 dB in both bands. Furthermore, the diplexer boasts more than 60 dB of transmit-receive isolation.



2. This millimeter-wave transmitter operates from 70 to 77 GHz. *(Courtesy of HXI)*

AUTOMOTIVE RADAR

Millimeter-wave frequencies also can foster other applications, such as 77-GHz automotive radar. NXP Semiconductors (www.nxp.com), which just recently completed its merger with Freescale Semiconductor, announced its new single-chip 77-GHz radar transceiver. Roughly the size of a postage stamp, it can be invisibly integrated anywhere in a car. NXP says the chip can ultimately help enable self-driving cars.

In addition to its wireless backhaul transceivers, Infineon Technologies offers integrated circuits (ICs) for 77-GHz automotive-radar applications. The company's radar system IC (RASIC) series is intended to provide customers with a system solution for 77-GHz automotive long-range radar (LRR) and mid-range radar (MRR) applications. This solution promises to slash the number of required components.

MILLIMETER-WAVE COMPONENT SUPPLIERS

Millimeter-wave components (as well as subassemblies) are offered by many suppliers to support a variety of applications. A notable example is SAGE Millimeter (www.sagemillimeter.com), which offers products that include amplifiers, oscillators, control devices, frequency converters, and more.

One recently released product is the SSR-9630831560-10-S1, which is a W-band receiver that spans from 92 to 100 GHz. In addition, the SFA-106SF-S1 is an active X6 frequency multiplier that covers an output frequency range of 90 to 98 GHz when driven by input frequencies ranging from 15 to 16.33 GHz.

For its part, Millimeter Wave Products Inc. (MI-WAVE) (www.miwv.com) provides an array of products that operate at millimeter-wave frequencies. For example, the company has a line of ferrite components that includes isolators, circulators, polarization switches, and phase shifters. Among its many other millimeter-wave products are amplifiers, mixers, filters, and adapters. MI-WAVE can support both commercial and military applications.

Additional suppliers of millimeter-wave products include the aforementioned REC. Its subsidiary, HXI (www.hxi.com), offers a range of millimeter-wave components and integrated assemblies. Customers can select from components including amplifiers, mixers, detectors, and many more. In regard to integrated assemblies, the company can deliver products like receivers, transmitters, and transceivers. For example, HXI offers a transmitter that spans 70 to 77 GHz *(Fig. 2)*. In addition, the company provides millimeter-wave radios for V- and E-band applications.

Both millimeter-wave and terahertz products are available from Virginia Diodes Inc. (VDI; www.vadiodes.com), which offers an assortment of higher-frequency devices and systems. Such products include receivers, mixers, detectors, and frequency multipliers. In addition, VDI provides test-and-measurement solutions for millimeter-wave and terahertz applications by offering extension modules for vector network analyzers (VNAs), spectrum analyzers, and signal generators.

These modules can be used with standard test equipment to extend test and measurement capability to terahertz frequencies. Currently available extension modules will allow for coverage of frequencies as high as 1.1 THz.

Given the wide range of millimeter-wave products that are available today, this article can only provide some examples. A large and growing number of companies are supporting the needs of applications that utilize these higher frequencies. As the usage of millimeter-wave frequencies continues to increase, we can expect to see additional products reach the market in the days ahead.

New companies also will enter the fray. With the much-anticipated 5G on the horizon, many companies will focus more attention on millimeter-wave technology with the hope of delivering future cutting-edge performance. mw

CHRIS DeMARTINO | Technology Editor

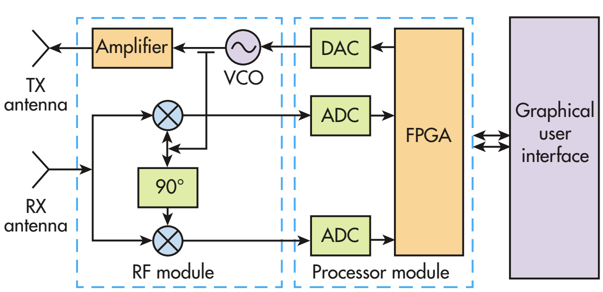
SDR Evaluation Kits Reach Wide Range of Applications

With its software-defined architecture, these evaluation kits provide an integrated solution to customers in various markets.

A SOFTWARE-DEFINED-RADAR (SDR) system utilizes software protocols to implement transmitting and receiving functionality. These systems are hitting the market thanks to companies like Ancortek. The Virginia-based company, founded in 2013, offers short-range, lightweight, low-power SDR evaluation/development kits to support applications like industry automation, medical diagnosis, and public safety and security.

These SDR systems offer a number of advantages, such as their compact size and flexibility. Operating modes, waveforms, bandwidths, and processing functions can be changed without requiring hardware modifications. Expandable waveform bandwidth, real-time processing, programmability, and re-configurability are additional benefits of these SDR systems.

Each SDR evaluation kit includes an RF module, an FPGA-based processor module, and a graphical-user-interface (GUI). Five different RF modules are currently offered: the SDR-RF 240B, SDR-RF 580B, SDR-RF 620B, SDR-RF 980B, and SDR-RF 2500B. These modules have operating-center frequencies of 2.45, 5.80, 6.20, 9.80, and 25.0 GHz, respectively. Ancortek offers five separate SDR kits—one for each RF module. The part numbers for the kits are SDR-KIT 240B, SDR-KIT 580B, SDR-KIT 620B, SDR-KIT 980B, and SDR-KIT 2500B. The SDR-PM 402 processor module is compatible with all RF modules, and is included in every kit.



This block diagram demonstrates the functionality of the software-defined-radar system.

An SDR system block diagram illustrates the RF module, processor module, and GUI (*see figure*). In addition to the FPGA, the processor module consists of a 12-bit digital-to-analog converter (DAC) and two 12-bit analog-to-digital converters (ADCs). Because the SDR kits are intended primarily for short-range applications, a frequency-modulated-continuous-waveform (FMCW) radar-system architecture is utilized. This architecture enables short range and velocity to be measured accurately and simultaneously. A direct-conversion homodyne receiver mixes the received signal with the transmitted FMCW signal, resulting in a signal with very low frequency—in the hundreds of kilohertz. As a result, the ADC sampling rate requirements can be eased considerably. Specifically, the DAC and ADCs operate at sampling rates of 40 Msamples/s. Continuous-wave (CW) and frequency-shift-keying (FSK) waveforms are also available with the same system architecture.

The GUI includes a control panel, a graphic panel, and a video display. Users can select various options for operation modes, signal waveforms, operating parameters, filtering types, display modes/parameters, and data recording for exporting. Users can record raw data streams, which can be saved as binary data files for post-processing. For academic research purposes, a MATLAB version of the GUI and its source codes is also available. This allows users to save raw data as a MAT file or to modify MATLAB source code to implement user-developed signal processing and analysis tools.

In regard to RF module performance, the SDR-RF 2500B, which operates from 24 to 26 GHz, achieves typical transmitter output power of +19 dBm. Its receiver attains 28 dB of gain along with a noise figure of 6.4 dB. The SDR-RF 2500B boasts typical phase noise of –100 dBc/Hz at 1-MHz offset. Its tuning voltage ranges from 0 to +5 V with a tuning sensitivity of 1.5 GHz/V. The SDR-RF 2500B typically draws 800 mA current from a supply voltage of +5 VDC. It is built for an operating temperature range of –40°C to +85°C. mw

JACK BROWNE | Technical Contributor

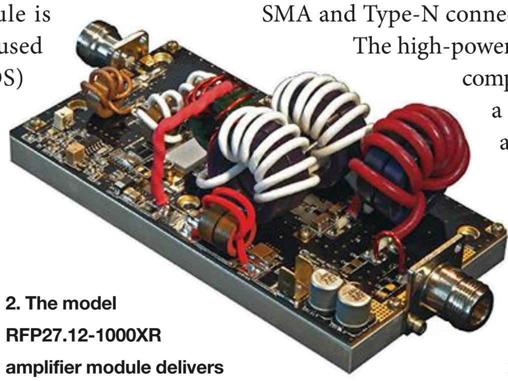
Modular Amps Bring High HF Power Levels

These compact amplifiers provide high output levels at HF, either as standalone units or as "building blocks" for higher-power system requirements.

HIGH POWER LEVELS are essential for many applications in the high-frequency (HF) range, including for communications and industrial-scientific-medical (ISM) systems. Electron tubes have traditionally supplied thousands or tens of thousands of watts of power for these applications, but solid-state solutions continue to gain ground in terms of high power from small packages.

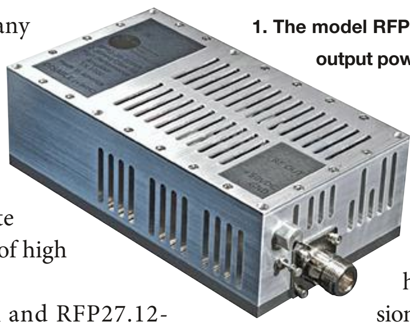
As examples, models RFP2-30-500XR and RFP27.12-1000XR are amplifiers from RF and Microwave Power Technology LLC capable of delivering 500- and 1,000-W CW output power, respectively, at HF. In addition, they can be assembled into thermally efficient modular configurations that enable system integrators to combine multiple amplifiers to achieve truly "tubelike" power levels in the HF range.

Each high-power amplifier module is constructed with silicon laterally diffused metal-oxide-semiconductor (LDMOS) transistors. Both are impressive examples of how much power is possible from a small package when thermal management is properly applied. Model RFP2-30-500XR *(Fig. 1)* is the broadband, linear member of the pair, designed for use across the full frequency range from 2 to 30 MHz. It provides 500-W CW output power at 1-dB compression across that range. The Class-AB amplifier boasts generous typical gain of 26.5 dB, maintained to typical ±1.0-dB gain flatness across the full bandwidth.



2. The model RFP27.12-1000XR amplifier module delivers 1000 W output power at 3-dB compression at 27.12 MHz.

The compact unit draws 15.6-A typical current from a +50-V dc supply and holds typical third-order intermodulation distortion (IMD) to −33 dBc for clear communications in HF military radios. As required for proper thermal management, the efficiency is high—typically at 64%. Amazingly, for such high output power, the amplifier module measures just 2.95 × 5.65 × 1.90 in.



1. The model RFP2-30-500XR amplifier module provides 500-W output power at 1-dB compression from 2 to 30 MHz.

The model RFP27.12-1000XR amplifier module *(Fig. 2)* targets narrowband applications at twice the power. It is a highly tuned and thermally optimized version of the RFP2-30-500XR for ISM systems at 27.12 MHz. This narrowband amplifier module is well-suited for RF energy markets, with 1,000-W CW output power at 3-dB compression.

The model RFP27.12-1000XR runs on 23.8-A drain current at +50-V dc supply voltage. It is close in size to the model RFP2-30-500XR, measuring 2.95 × 5.65 × 2.10 in., and comes with SMA and Type-N connectors or with all Type-N connectors. The high-power unit also incorporates temperature-compensated bias and can be supplied with a heatsink and fan where operation as an individual amplifier is desired.

Both high-power amplifier modules can be used as standalone amplifiers, and they offer the high efficiency that turns most of the applied bias energy into RF signal power, and not heat. But these small-footprint amplifiers are also excellent for systems in need of "serious" output-power levels in the multiple-kilowatt range, without having to expend all that saved energy into some way of dissipating excess heat. Both amplifiers have matched drivers available, and are designed and built for high reliability in the most demanding military and industrial system applications. mw

RF AND MICROWAVE POWER TECHNOLOGY LLC, 2380 Solitude Dr., Reno, NV 89511; (775) 842-3280, *www.rfmpt.com*

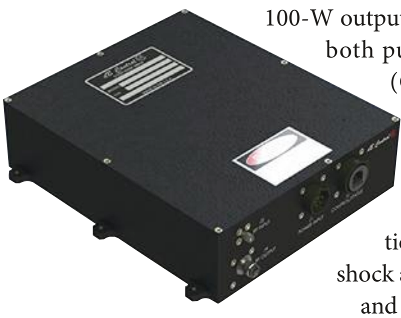
JACK BROWNE | Technical Contributor

Smart MPM Powers 100 W to 18 GHz

By combining solid-state and vacuum-tube device technologies, this power-amplifier module can provide 100-W pulsed or CW output power from 6 to 18 GHz.

VACUUM TUBES CAN yield impressive amounts of microwave power in small packages, but they must be properly cooled for long-lifetime operation. On that front, the model dB-4150 microwave power module (MPM) developed by dB Control combines a first-stage solid-state amplifier and second-stage traveling-wave-tube (TWT) power booster with effective conductive cooling.

This novel configuration *(see figure)* delivers 100-W output power from 6 to 18 GHz in both pulsed and continuous-wave (CW) operating modes. It is engineered and constructed for the challenging environmental conditions found in military applications, including under extreme shock and vibration, high humidity, and wide temperature ranges.



The dB-4150 MPM is a microwave power module (MPM) that integrates solid-state and vacuum-tube stages to minimize noise and optimize output power to 100 W for both CW and pulsed signals from 6 to 18 GHz.

The dB-4150 MPM is a compact but robust wideband amplifier well-suited for wideband military applications in electronic-countermeasures (ECM) systems and electronic-warfare (EW) simulators. It is at home boosting either CW signals or signals with high pulse-repetition-frequency (PRF) pulse modulation. It can handle pulse widths as narrow as 1 μs through CW signals at maximum PRFs to 10 kHz.

The MPM achieves 50-dB gain at its rated 100-W output-power level with spurious levels controlled to –50 dBc. Harmonics at the most "susceptible" frequency, 6 GHz, are –4 dBc (with harmonics above 9 GHz outside the operating frequency range of the MPM). Exhibiting input VSWR of 2.0:1 at 50 Ω, the power module is specified for maximum load VSWR of 1.50:1 for full compliance with its performance specifications.

SMALL WITH SMARTS

This rugged little MPM measures just 12.876 × 9.4 × 2.563 in., but it is densely packed, weighing 9.5 lb. It comes with female SMA input connectors and female TNC output connectors. The primary supply voltage is +270 V dc, with an option for +28 V dc. It operates with differential or transistor-transistor-logic (TTL) modulation control and includes an Ethernet interface (and is available with a serial interface as an option).

As a "smart" MPM, it features monitors for forward and reverse power, along with status indicators for power and equipment faults.

For those concerned with reliability, especially for such a small unit that generates such high output-power levels, the MPM is generously equipped with protection. It incorporates protection mechanisms to guard against overly high reflected power levels and exceeding the current limits for the TWT helix, the voltage limits for the TWT cathode, and the operating-temperature limits of the TWT and the MPM.

The dB-4150 MPM is designed to handle extremely hostile operating conditions, including high vibration levels and shock to 15 g. It can function in environments with as much as 95% relative humidity (RH) and at altitudes to 50,000 ft. for avionics applications. Operating temperature ranges from –40 to +85°C. As an option, the MPM can be supplied for use from 5 to 18 GHz for extremely broadband applications. mw

DB CONTROL, 1120 Auburn St., Fremont, CA 94538; (510) 656-2325, *www.dBControl.com*

JACK BROWNE | Technical Contributor

Synthesizers Shave Phase Noise to 24 GHz

These stable broadband signal sources, which come in three different packages, minimize noise levels across wide bandwidths to 24 GHz and beyond.

FREQUENCY STABILITY, an essential parameter for most RF/microwave applications, is usually synonymous with a signal source capable of low noise levels. The PHS 8400 family of frequency synthesizers from Pronghorn Solutions exemplifies a line of stable signal sources, but with a unique twist: The synthesizers are available in three different form factors—benchtop, modular, and handheld configurations—that will fit any application.

The modular versions of the frequency synthesizers, such as model PHS-8400M *(Fig. 1)*, show how the small size does not force users to sacrifice flexibility. In addition to the expected interconnections for dc power and RF output signals, the frequency synthesizers include a modulation/trigger input, an input/output port to use an external frequency reference or access signals from the PHS-8400M's internal frequency reference, and even a Universal Serial Bus. The model numbers for the rack-mountable benchtop and miniature handheld versions reflect their different form factors, PHS-8400B and PHS-8400H.

The basic or "starting" frequency range is 0.7 to 24 GHz, but it can also start at 10 MHz, 0.5 GHz, or 1 GHz and stop at 12, 18, 24 GHz or higher, depending on the customer's needs. As noted, these are stable signal sources, with standard frequency stability of ±10 ppm. They can be supplied with a 10- or 100-MHz internal crystal-oscillator frequency reference and work with an external frequency reference.

1. The modular version of the model PHS-8400 line of frequency synthesizers (model PHS-8400M) measures a mere 6.00 × 3.54 × 0.70 in. and weighs less than 1 lb., even with its many input, output, and control interfaces.

2. This plot shows phase-noise measurements on a 10.1-GHz carrier for a PHS-8400M frequency synthesizer. Testing is performed with a commercial frequency-downconverter and phase-noise test set from Keysight Technologies.

As expected for a stable source, the noise levels are low, with single-sideband (SSB) phase noise of less than –120 dBc/Hz offset 100 kHz from a 10-GHz carrier and better than –111 dBc/Hz offset 100 kHz from a 24-GHz carrier. Measurements with a commercial phase-noise analyzer from Keysight Technologies (www.keysight.com) reveal that the phase noise at 10 GHz remains low for offsets closer to the carrier *(Fig. 2)*.

The PHS-8400 frequency synthesizers deliver at least +5 dBm output power across the full frequency range, with +7 dBm or more output power through 18 GHz. All three versions of the synthesizer include USB ports, and they ship with software drivers for control with a PC.

The benchtop and handheld models include displays and keypads, while benchtop and modular versions offer SCPI/IVI-compatible SPI and LAN interfaces as options. mw

PRONGHORN SOLUTIONS, 4610 South Ulster St., Ste. 150, Denver, CO 80237; (720) 808-9832, *www.pronghorn-solutions.com*

JACK BROWNE | Contributing Editor

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PRONGHORN SOLUTIONS, 4610 South Ulster St., Ste. 150, Denver, CO 80237; (720) 808-9832, *www.pronghorn-solutions.com*

Dividers/Combiners Go Four Ways to 12.4 GHz

A LINE OF COAXIAL four-way power dividers/combiners provide robust power-handling capabilities from 5 MHz to 12.4 GHz. The components, which are supplied with MIL-C-39012 grade Type-N female connectors, can handle 20-W average power and 1-kW peak power. As an example, model N4200-4 is designed for applications from 2 to 4 GHz. Across that 2-GHz bandwidth, it features 18-dB minimum isolation with 0.50-dB maximum insertion loss and 1.50:1 maximum VSWR. Amplitude balance among channels is tightly controlled, with maximum deviation of ±0.3 dB and phase unbalance among channels controlled within ±3 deg. The rugged power divider/combiner measures 5.55 × 4.00 × 0.50 in., not including the Type-N connectors.

ARRA INC., 15 Harold Ct., Bayshore, NY 11706-2296; (516) 231-8400, FAX: (516) 434-1116, *www.arra.com*

Isotropic Antennas Aid EMF Testing to 6 GHz

THE ELECTROMAGNETIC FIELD (EMF) Measurement System is now available with isotropic antennas that provide frequency coverage from 9 kHz to 6 GHz. The system, which is compatible with the firm's various handheld analyzers such as the LMR Master, Spectrum Master, and Cell Master instruments, can detect EMF radiation around wireless networks and their infrastructure equipment to ensure compliance with national emissions standards. The two isotropic antennas employ triaxis sensors with an integrated RF switch, microcontroller, and memory to transmit/receive a spherical radiation pattern so that all radiation is measured at the antenna's geographical position, regardless of the source's location. A third isotropic antenna is also available, for use from 700 MHz to 6 GHz.

ANRITSU CO., 490 Jarvis Dr., Morgan Hill, CA 95037-2809; (408) 778-2000, *www.anritsu.com*

32-kHz Quartz Crystals Trim Power Consumption

A LINE OF 32-kHz QUARTZ crystal resonators, designed for use in oscillators, has been developed for low-power-consumption applications. The "tuning-fork" crystals offer stable operation with fast startup time. The crystal resonators are both RoHS- and REACH-compliant. They are available with frequency stabilities of ±10 ppm or ±20 ppm and in compact surface-mount-device (SMD) configurations, which helps facilitate mounting of the resonators on circuit boards.

GEYER ELECTRONIC AMERICA INC., 270 E. Douglas Ave., El Cajon, CA 92020; e-mail: sales@geyer-usa.com, *www.geyer-electronic.com*

Power Module Drives Ka-Band Airborne Systems

MODEL M1292-02 IS A KA-BAND microwave power module (MPM) qualified for airborne applications to 50,000 ft. altitude. The millimeter-wave MPM operates from 28.5 to 40.0 GHz with 100-W saturated output power, and is well-suited for communications systems requiring linear output power and high efficiency in a compact housing. It handles temperatures from –40 to +85°C and runs on a +28-V dc supply. The MPM measures just 9.75 × 8.50 × 1.50 in. and weighs less than 8 lb. A number of options, including forced-air cooling and integrated block upconverter (BUC), will soon be available.

L3 ELECTRON DEVICES, 960 Industrial Rd., San Carlos, CA 94070; (650) 591-8400, *www.L3com.com*

Mixer Downconverts 70 to 76 GHz

MODEL SFS-73336315-12SFKF-E1-M is an E-Band sub-harmonically pumped mixer based on gallium-arsenide (GaAs) monolithic-microwave-integrated-circuit (MMIC) technology. It works with a local oscillator source from 35 to 38 GHz and +16 dBm to downconvert RF input signals from 70 to 76 GHz to an intermediate-frequency (IF) range of dc to 5 GHz. Conversion loss is nominally 15 dB. The amplitude unbalance is within ±1 dB, while and phase unbalance is typically ±20 deg.

SAGE MILLIMETER INC., 3043 Kashiwa St., Torrance, CA 90505; (424) 757-0188, *www.sagemillimeter.com*

Phase Shifters Program 360-Deg. Range

A series of 8-b programmable phase shifters provide a 360-deg. phase adjustment range in as many as 255 steps with 1.4-deg. increments and high accuracy. The phase shifters are operated by means of transistor-transistor-logic (TTL) control. The phase shifters, which are available in frequency bands from 500 MHz to 37 GHz, are ideal for aerospace and defense radar and electronic-warfare (EW) applications that involve phased-array antennas, phase discriminators, beamforming networks and RF communication systems. Typical phase-shift error spans ±0.9 to ±5 deg. with fast switching speed from 30 to 450 ns. The components handle input-power levels from +10 to +30 dBm, depending on the model.

PASTERNACK, 17802 Fitch, Irvine, CA 92614; (949) 261-1920, *www.pasternack.com*

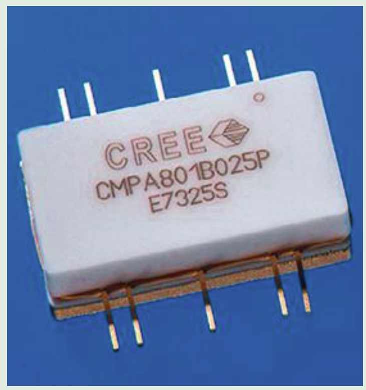
Synthesizer Selects 2250 to 3750 MHz

MODEL FCPH225375-10 is a low-noise, surface-mount-technology (SMT) frequency synthesizer that performs simple binary digital tuning by selecting four data lines. It provides different output frequencies in 10-MHz steps from 2250 to 3750 MHz with +6-dBm minimum output power. The RoHS-compliant, lead-free synthesizer operates with a 10-MHz reference input frequency, with reference input voltage range of 1.0 to 3.3 V peak to peak. The selectable-frequency-synthesized signal source offers excellent spectral characteristics, with typical harmonic levels of –20 dBc and typical spurious levels of –70 dBc. Single-sideband (SSB) phase noise is typically –96 dBc/Hz offset 1 kHz from the carrier, improving to typically –107 dBc/Hz offset 100 kHz from the carrier. The patented frequency synthesizer is designed for operating temperatures from –40 to +85°C. The synthesizer draws 200 mA maximum current from a single +5-V dc supply and achieves short power-up time of typically 90 ms. The SMT synthesizer measures 1.25 × 1.00 × 0.23 in.

SYNERGY MICROWAVE CORP., 201 McLean Blvd., Paterson, NJ 07504; (973) 881-8361, e-mail: sales@synergymwave.com, *www.synergymwave.com*

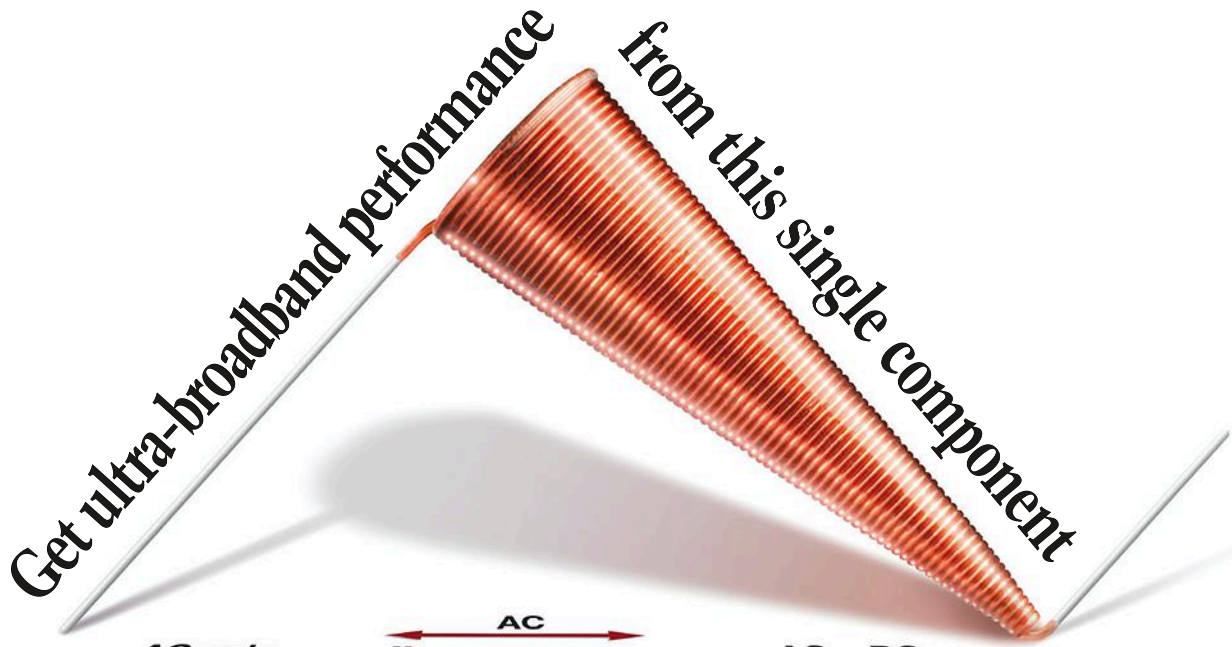
GaN MMIC Amplifier Pushes 25 W to 11 GHz

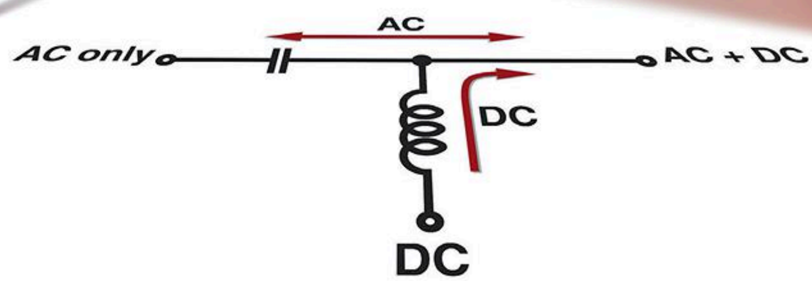
WELL-SUITED FOR RADAR and broadband communications applications, model CMPA801B025 is a gallium-nitride (GaN) monolithic-microwave-integrated-circuit (MMIC) power amplifier capable of 25 W or more output power from 8 to 11 GHz. With 37-W typical output power and 16-dB power gain across that frequency range, the compact amplifier suffers less than 0.1-dB power droop. It achieves 35% typical power-added efficiency (PAE)



and is internally matched to 50 Ω for ease of installation in RF/microwave circuits and systems operating with that characteristic impedance. The amplifier operates from a +28-V dc supply with 36% typical drain efficiency. Fabricated in the firm's own semiconductor foundry (which also offers services to outside customers), the GaN MMIC power amplifier is available in a 10-lead metal/ceramic flange housing and a miniature pill package.

WOLFSPEED, A CREE COMPANY, 4600 Silicon Dr., Durham, NC 27703; (800) 533-2583, (919) 313-5300, FAX: (919) 313-5558, *www.wolfspeed.com* *www.cree.com*.





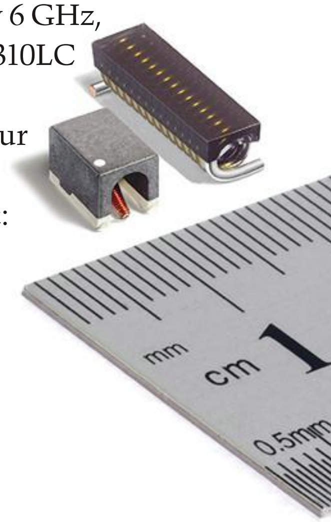
Ideal for use in Bias Tees, Coilcraft conical inductors offer flat bandwidth and high impedance to 40 GHz

Coilcraft BCL/BCR Series conical inductors operate across a frequency range of 10 MHz to 40 GHz, letting you replace a series of narrow band inductors with one part.

Both series provide excellent return loss and insertion loss. Their unique conical shape optimizes the effects of capacitance, maintaining high impedance across your frequency spectrum.

Choose from a rugged, surface mount package or our flying lead configuration. And for applications below 6 GHz, try our high current 4310LC wideband bias choke.

Learn more and order your free evaluation samples by visiting us online at: **coilcraft.com/conicals.**



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