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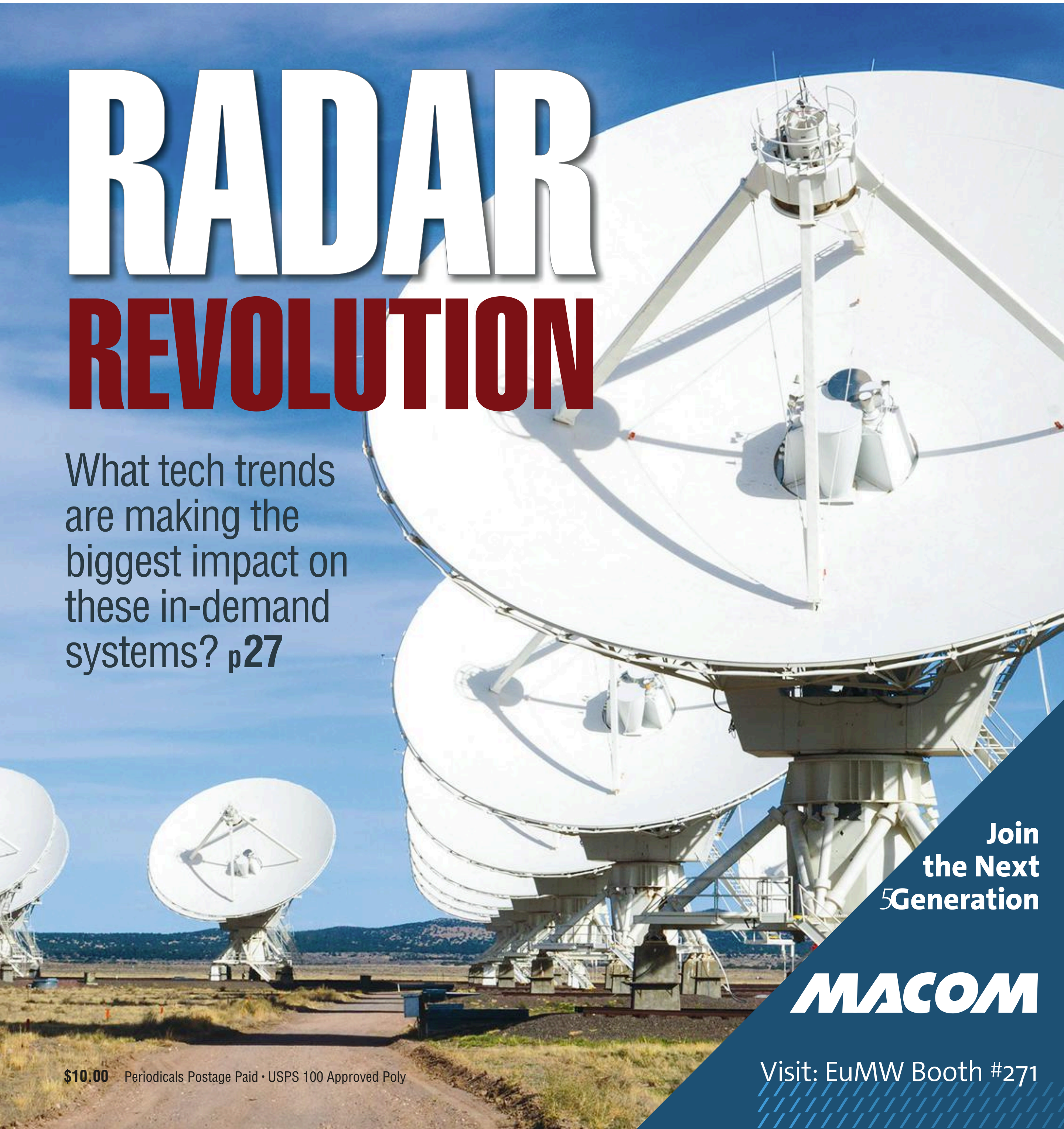

RADAR REVOLUTION

What tech trends are making the biggest impact on these in-demand systems? **p27**

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PE2-19-6G18G-1R6-16-12-SFF http://www.pmi-rf.com/products-details/pe2-19-6g18g-1r6-16-12-sff	6 - 18	19 dB Typ	2 dB Typ, 2.5 dB Max	+12 to +15 VDC @ 91 mA	25 dBm Typ, 23 dBm Min	1.08" X 0.71" X 0.29" SMA Female
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PEC-30-0R2520R0-5R0-22-12-SFF http://www.pmi-rf.com/products-details/pec-30-0r2520r0-5r0-22-12-sff	0.25 - 20	26.5 dB Typ	5.5 dB Max	+12 to +15 VDC @ 230 mA	+22 dBm Min	1.08" X 0.71" X 0.29" SMA Female
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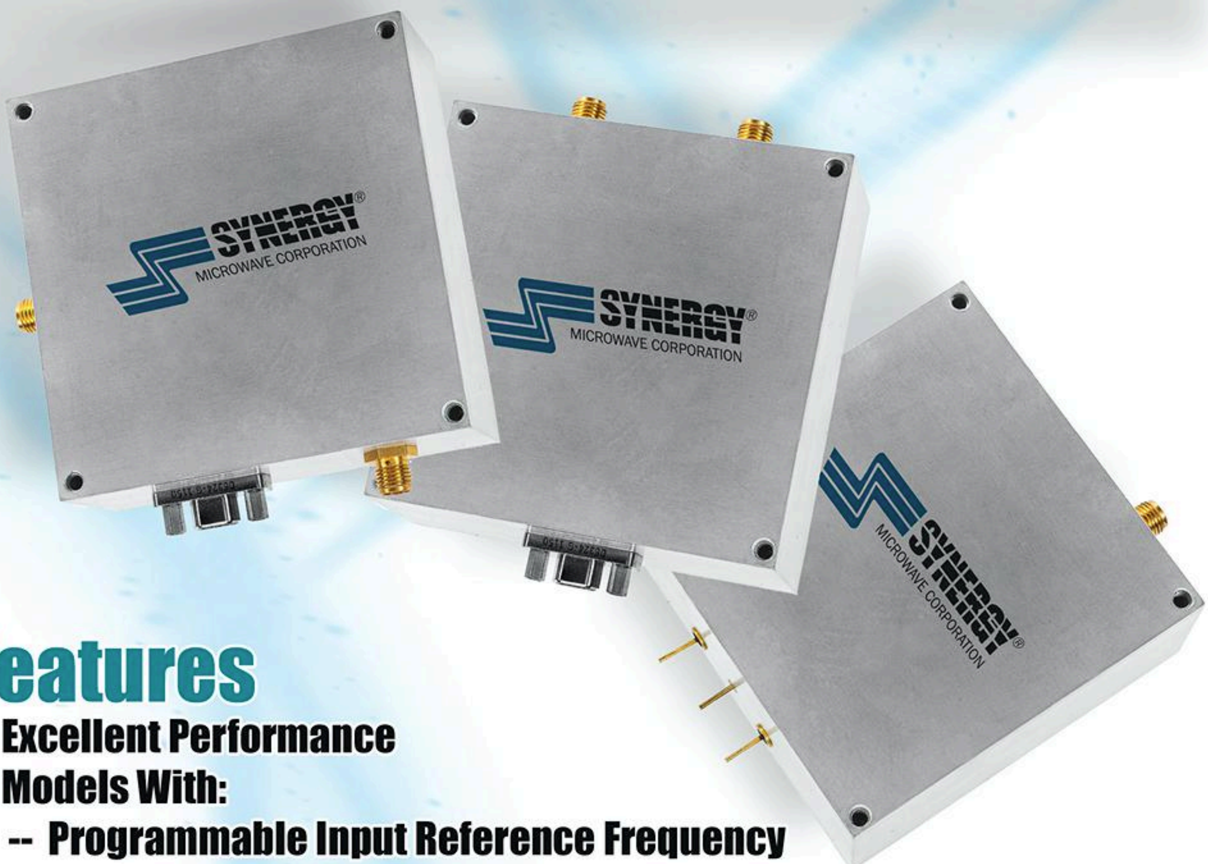

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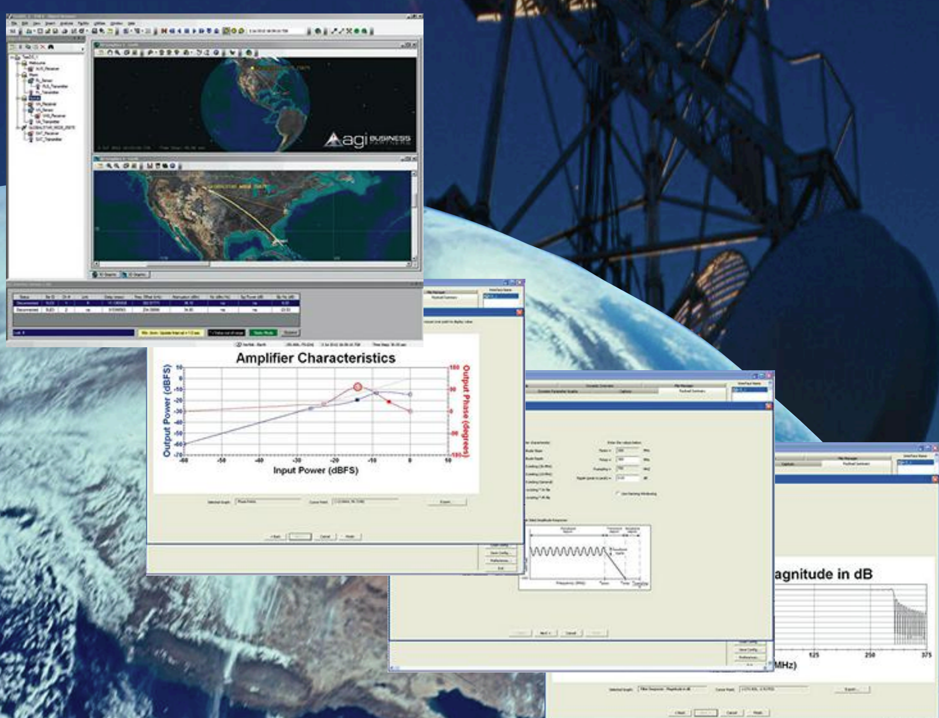

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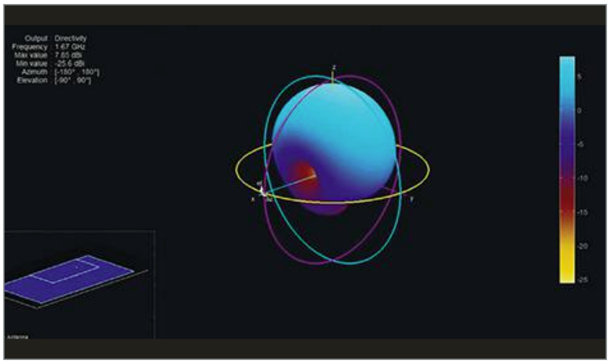


Generate Your Antenna Gerber Files from MATLAB

This latest "Algorithms to Antenna" blog post from MathWorks' Rick Gentile explores how to fabricate printed-circuit-board antennas with MATLAB and Antenna Toolbox.

https://www.mwrf.com/software/algorithms-antenna-generate-your-antenna-gerber-files-matlab

5G Runs on Different Fuel

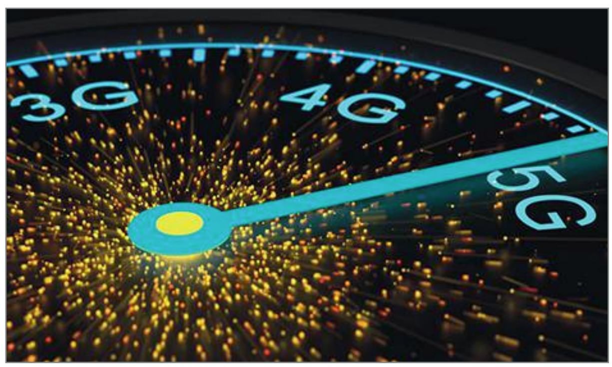
With 5G reality inching closer, one company is focusing on meeting the technology's requirements through GaN and GaAs developments and by exploiting sub-6-GHz and mmWave frequencies.

https://www.mwrf.com/semiconductors/5g-runs-different-fuel

Metamaterials Mold Multiband Resonator

How did researchers build this triple-band compact resonator using a new configuration of right/left-handed metamaterial-based transmission lines?

https://www.mwrf.com/materials/metamaterials-mold-multiband-resonator



Integrated Radio Transceiver Confronts Challenges from Every Corner

This "single radio platform" solution is equipped for current and emerging (particularly 5G) wireless applications, as well as the military and test-and-measurement realms.

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Editorial

LOU FRENZEL | Contributing Editor
lou.frenzel@informa.com

Communications Latency: How Low Can You Go?

Latency has become a critical factor in many communications applications these days. Latency, of course, is the short delay that occurs due to the time it takes a signal to travel from one point to another, either in free space or some medium. In the past, latency did not matter that much. After all, most electronic signals travel at the speed of light or a bit less, and for most of us that's fast enough. We can never go faster than that anyway. Let's face it, there's no such thing as zero latency. But less would be welcome.

Some of the newer communications applications require or would like less latency. Factory control systems often need short and deterministic timing to be successful. The new 5G wireless systems have been created to keep latency to a minimum. The target has been to get below 10 ms, down to about 1 ms. Self-driving and other connected cars with vehicle-to-vehicle (V2V) communications must have low latency to function safely and effectively. A more recent demanding application involves financial trading operations.

Electronic trading is mostly automated, so buying and selling happens super-fast. The faster, the better, as you can exploit your competition and take advantage of arbitrage opportunities. To make the most profit, communication delays must be very short. A few milliseconds make all the difference between success and failure.

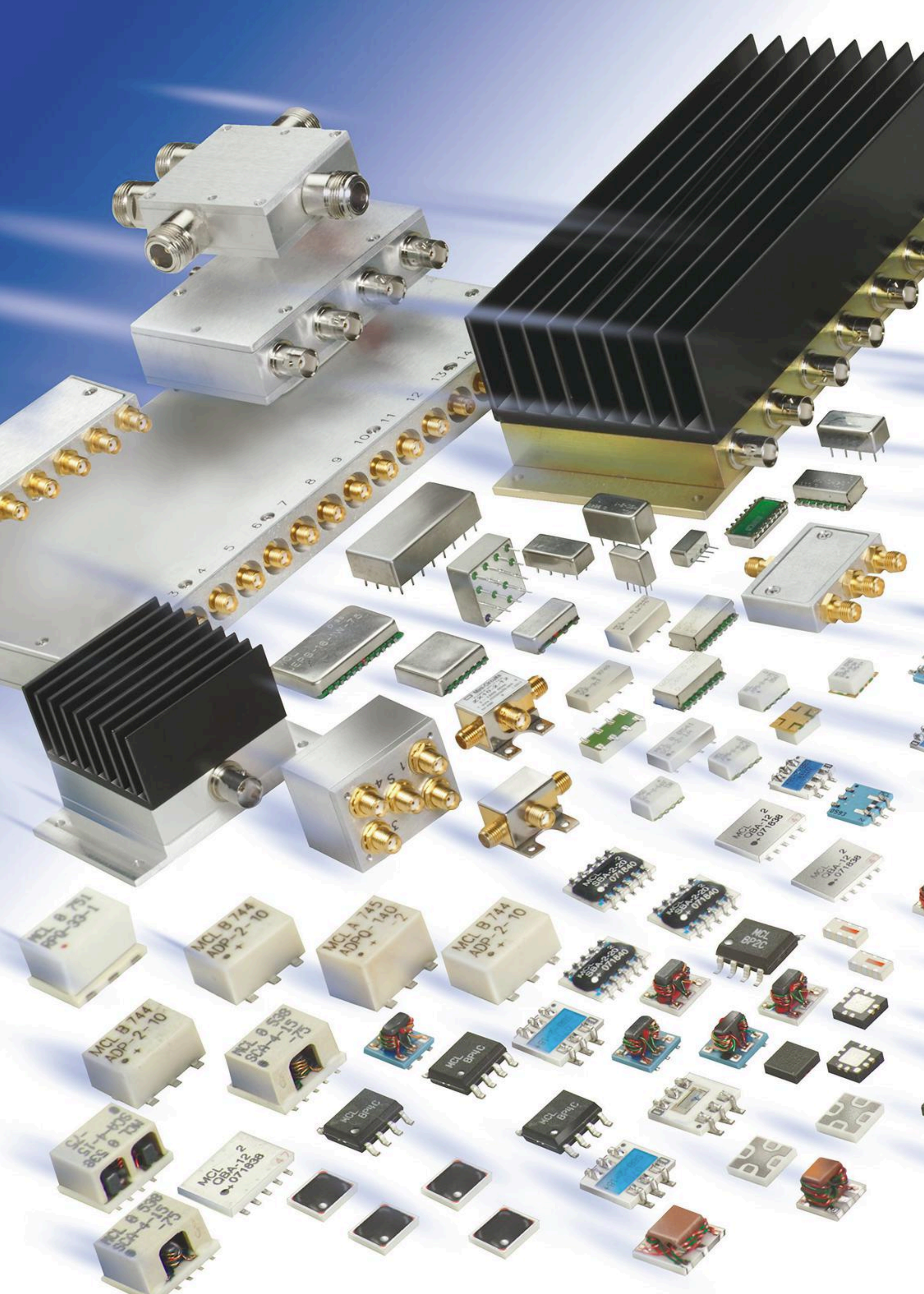
Banks and other financial institutions use fiber-optic links for electronic trading. While fast, the optical networks also have latency. The speed of light slows down when passing through glass fiber. The index of refraction and IR signal wavelength determine the amount of delay. A general rule of thumb is a delay of 5 µs/km or about 8 µs/mile for single-mode fiber. Of course, other factors like electrical-to-optical conversion time and vice versa, SERDES, and packet format and length will have an impact on the overall transmission time.

Right now, a typical link from New York to London has a one-way latency in the 30- to 40-ms range. But that's not fast enough for many. It's led to research into alternative solutions. Then radio waves were rediscovered. Radio waves travel faster in free space than in a fiber cable.

Some organizations have adopted the unexpected use of shortwave (SW) radio in the 3- to 30-MHz part of the spectrum. Signal propagation is by sky wave, which is refracted from the ionosphere back to earth and in some cases reflected back up for another bounce. The result is that a small signal can easily travel around the globe using multiple skips. Latency must be less than 30 ms to be useful. It's not known what frequencies are being used.

Just remember that at these low frequencies, bandwidth is severely limited to only a few kilohertz max. And propagation is variable depending on how the ionosphere changes during different times of the day. Still, it's working. Will we be seeing giant Yagi's on bank rooftops? A new use for the HF spectrum other than ham radio?

We are living in an age where the speed of light is not fast enough. But what can we do about it? mw



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News

DEVELOPING NEXT-GEN TECHNOLOGY
While Recruiting Next-Gen Talent

One company focused on equipping the defense industry is Mercury Systems *(www.mrcy.com)*, evidenced by multiple defense prime contractors utilizing the company's solutions for various applications. At the recent IMS 2018, those who visited Mercury's booth had the opportunity to learn about its latest developments. On top of that, the company is actively engaged in efforts to bring more young people into the RF/microwave industry.

Advanced packaging techniques and millimeter-wave (mmWave) development are two of Mercury's target technology areas. Another is high-power gallium-nitride (GaN) development, which is taking place in the company's Oxnard, Calif. location. Furthermore, its San Jose, Calif. facility is involved in satellite-communications (satcom) development. Its GaN-based solid-state power amplifiers (SSPAs) are currently used in space.

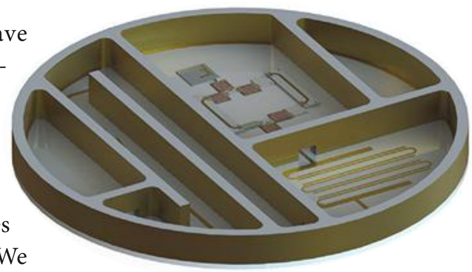
Kevin Beals, VP of Mercury Systems' RF and microwave group, recently spoke about some of the trends that he is seeing—and that the company is addressing. He said, "We're seeing that our customers are looking to build and conceive more multi-functionality (one antenna for multiple purposes). And in the amplification realm, we have to build multipurpose amplifiers that can handle both comms and electronic warfare (EW). This has typically been handled by two different amplifiers." Essentially, rather than optimizing either the linearity or saturated efficiency of an amplifier, Mercury is now developing the technology to maximize both.

While microwave assemblies have traditionally been built using chip-and-wire construction, Beals pointed out that the company is relying more on surface-mount technology (SMT). "We're trying to move toward SMT technology at higher frequencies and broader bands," he explained. "We want to build cost-effective 'tune-free' products."

It should be noted that realizing successful high-frequency, broadband SMT designs is not easy. To address the associated challenges, Mercury is exploiting advanced nonlinear device modeling and automated assembly to reduce both variation and the sensitivity to variation.

Using advanced packaging techniques to build products in much smaller sizes is another one of Mercury's focal points. "Densities are going way up," noted Beals. "We have some unique capabilities to densely package multi-function microwave circuits." Furthermore, a recent blog post from Mercury delves into the topic of "smaller, faster, and more affordable" solutions in more detail. In it, the author, Mario LaMarche, discusses miniaturized EW systems and more *(see figure)*.

As mentioned, mmWave development is also an area of concentration. "We've been building 20- to 100-GHz circuits for some time—specifically for airports," added Beals. "We're now leveraging this in the military market. We're seeing more demand due to the greater threats. It's important to move up in frequency to counter these threats."



Shown is a densely integrated RF multichip module that offers ruggedization in a miniaturized size.

RECRUITING THE NEXT GENERATION

On a different front, Mercury Systems is also involved in efforts to bring the next generation of engineers into the RF/microwave industry. Beals recounted some of the industry's history. "In the early 1980s, there were many new college graduates entering the RF/microwave world. But then the Department of Defense (DoD) slowed down in the late 1980s and early 1990s. For about 10 years, no engineers were coming into the DoD arena because there was no demand."

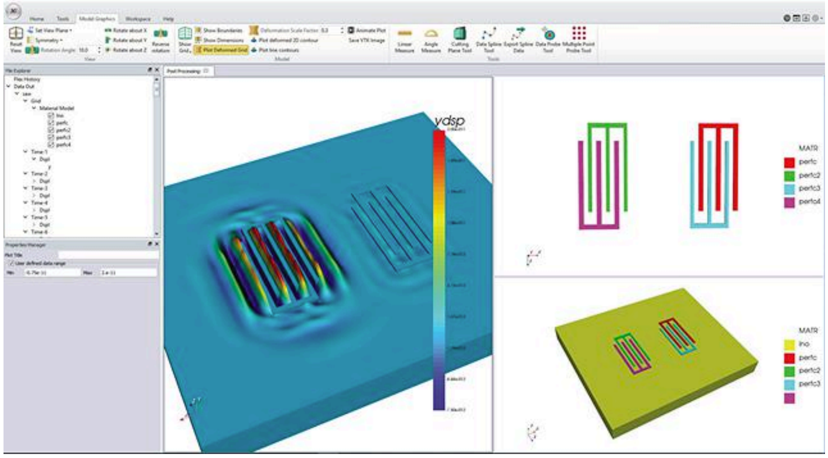
Beals explained how there was a big gap in the RF/microwave world, as commercial narrowband wireless technology elicited a much greater demand for engineers in comparison to the defense realm. "However," he added, "that has turned around in the last few years." Mercury Systems now has an internship program that's designed to create relationships with universities that have strong microwave programs. "This year, we had students reach out to us for internships," said Beals. The effort to attract young engineers will be essential, as more colleagues near the retirement stage. ■

STARTUP COMBINES CAE with the Cloud

FOUNDED EARLIER THIS YEAR, OnScale *(www.onscale.com)* is a startup company with a unique approach: Merge computer-aided engineering (CAE) software tools and multi-physics solvers with cloud high-performance computing (HPC). According to the firm, its solution can be described as an “on-demand scalable cloud CAE tool.” It can also be described as a “CAE in the Cloud” architecture that utilizes a pay-as-you-go subscription pricing model.

With OnScale’s cloud HPC platform, engineers are not limited to using CAE solvers that run on fixed on-premises computers. OnScale instead enables engineers to solve problems by taking advantage of multi-physics solvers with as many cloud HPC resources as needed. One can simply download OnScale and then begin to use it without having to buy CAE tools, pay for maintenance and support, procure HPC hardware, or wait for IT to deploy and maintain CAE systems.

OnScale’s targeted applications include biomedical, advanced driver-assistance systems (ADAS), Internet of Things (IoT), and 5G communications. With respect to 5G, the company is focused on RF filters and microelectromechanical-systems (MEMS) RF switches. In terms of filters, the design capabilities encompass TC-SAW, FBAR, and SMR filters *(see figure)*. Various filter design examples can be downloaded and then simulated within OnScale.



This OnScale analysis of a SAW-based filter illustrates electrodes, materials, and surface-wave behavior.

As mentioned, OnScale has a pay-as-you-go subscription pricing model; several subscription options are offered. The free subscription provides 10 core-hours (CHs) a month to a single user. The Professional subscription costs $300 per month, offering a single user with 50 CHs per month. The third option is the Team subscription, which costs $1,000 per month. This option supports as many as 10 users and provides 200 CHs per month. ■

JAGM SYSTEM PASSES DEFENSE Acquisition Board Review

LOCKHEED MARTIN’S JOINT Air-to-Ground Missile (JAGM) system has successfully passed its Defense Acquisition Board review and achieved milestone C. This enables the missile system to enter into (low-rate initial production (LRIP). The JAGM system is a multiple-sensor air-to-ground missile meant to succeed the HELLFIRE Romeo and HELLFIRE Longbow missile systems.

The JAGM system is backward compatible with all rotary-wing and fixed-wing aircraft capable of launching the HELLFIRE family of missiles. It features a multiple-mode guidance system for enhanced performance in the field. The guidance system combines laser and millimeter-wave-radar sensors for precision strike and fire-and-forget capability against moving and stationary targets on land and at sea.

The milestone C decision is a result of extensive flight testing *(see figure)*. Those tests revealed that the system is reliable and combat ready to provide high levels of performance even under adverse environmental conditions. The JAGM system hardware, with 95% reliability for in-flight testing, is built on the active HELLFIRE missile family production line by the same team that has produced over 75,000 missiles with a fielded reliability exceeding 97%.

Work on the JAGM system stems from a 24-month contract for the Engineering and Manufacturing Development (EMD) phase of the JAGM program from the U.S. Army and Navy. This contract included JAGM production, test qualification, and integration on the AH-64E Apache and AH-1Z Viper attack helicopters. The EMD phase also established an initial low-rate manufacturing capability in support of three follow-on LRIP options, with U.S. Army Initial Operational Capability expected early 2019. ■

In-flight testing of the JAGM system was performed late last year on board the AH-1Z helicopter. *(Courtesy of Naval Air Systems Command, NAVAIR)*

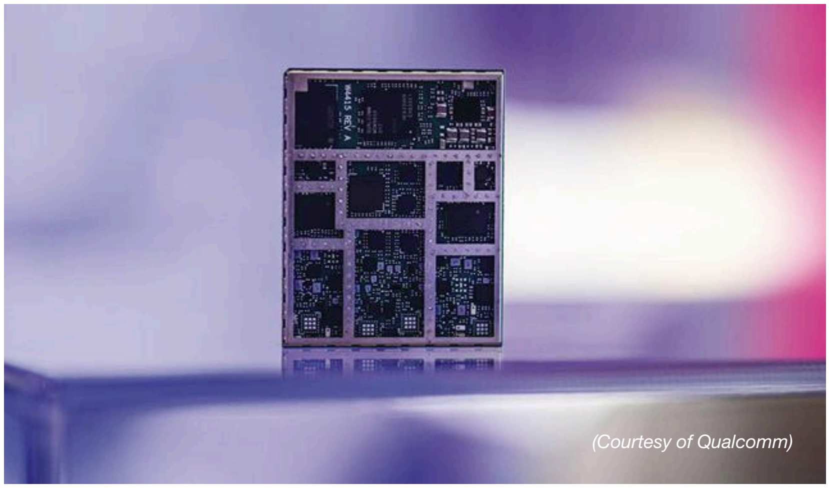
DRONE DETECTION SYSTEM Supervises Summit Meeting

THE RECENT SUMMIT MEETING of North Korea's Kim Jong Un and U.S. President Donald Trump was protected from rogue unmanned aerial vehicles (UAVs) by an AARTOS Drone Detection System produced by Aaronia AG. The system employs artificial intelligence (AI) and sensitive RF/microwave receivers to detect and track the radio-frequency signals used by drone aircraft for remote control and surveillance and provides a live situational awareness display including three-dimensional (3D) plots of drone flight patterns.

The AARTOS system *(see figure)* provides 360-deg. detection coverage with 1-deg. accuracy over a relatively long range of 10 to 15 km. Concerning this use of the system, the Chief Executive Officer of Aaronia AG (Strickscheid, Germany), Thorsten Chmielus, said, "We're overjoyed to be part of this historical and unique event to provide protection against drones. We are pleased that once again the inimitable capabilities of the AARTOS Drone Detection System are gaining in importance internationally."

The AARTOS Drone Detection System, shown here in a Singapore application, is capable of detecting and tracking UAVs and their users.

The AARTOS system features a model SPECTRAN V5 ultrawideband (UWB) real-time RF/microwave receiver, a patented AARONIA ISOLOG 3D Tracking Array Antenna, and AI-based tracking software. It detects and tracks RF emissions, even frequency-hopping patterns, not only of drones but also of nearby RF sources such as cellular telephones and other wireless devices within its UWB frequency range (as wide as 20 MHz to 20 GHz). It is capable of detecting even drones based on Fourth-Generation (4G) cellular telephone control systems. In addition to detecting the position of a drone by its RF/microwave signals, the user controlling the drone will also be detected by the radio signals of the remote control. ■


(Courtesy of Qualcomm)

QUALCOMM ESCAPES EXPENSIVE Regulatory Battle in Taiwan

THREE YEARS AGO, when Chinese regulators fined Qualcomm a billion dollars for gouging customers licensing its trove of wireless patents, the company escaped without having to make sweeping changes to its licensing business, its most profitable. Qualcomm was given the green light to charge royalties based on the wholesale price of a smartphone—a core part of its business model.

Now it seems that the San Diego, Calif.-based firm has escaped another regulator relatively unscathed. The company said it had resolved its dispute with Taiwan's Fair Trade Commission, which imposed $773 million in penalties on Qualcomm for choking competition in the country. The agency said that it would keep the $93 million Qualcomm has already handed over but waive the rest.

Last year, the agency accused Qualcomm of using its dominance in wireless modems to overcharge for patents, holding its chip supply hostage to stop customers from protesting unfair deals, echoing the issues regulators in Europe, South Korea, and the United States have had. It was also accused of refunding fees to major customers like Apple that used its modems and no one else's.

Under the terms of the deal, the fine is cut down significantly. Instead, the company said that it would to invest $700 million in Taiwan's technology sector and research over the next five years, including the development of 5G technology, and build new operations and manufacturing facilities in the country. Qualcomm also vowed to negotiate fair licensing contracts with customers in Taiwan.

Taiwan also tossed out requirements that would have pressured Qualcomm to switch its core business model over to chip-level patent licensing. That would mean charging companies to use its cellular technologies based on the cost of the components instead of the entire smartphone, possibly cutting into its profitability. But the settlement makes sure its business model is safe.

"This settlement directly addresses concerns raised by the Taiwan Fair Trade Commission, regardless of disputed positions, and builds on our foundation of collaborative, long-term business relationships in Taiwan," said Alex Rogers, president of the company's licensing business unit, which represents most of its profits, in a statement.

We are happy to reaffirm our commitment to licensing our valuable intellectual property under principles of fairness and good faith," he added. "With the uncertainty removed, we can now focus on expanding our relationships that support the Taiwanese wireless industry and rapid adoption of 5G technology." ■

DEVELOP AUTOMATED TESTING for Autonomous Vehicles

Autonomous, "self-driving" vehicles are heading this way, being preceded by vehicular electronic guidance and safety systems such as advanced driver-assistance systems (ADAS) technologies. Of course, with the functionality provided by these safety systems comes the need to develop effective test methods to evaluate them under a wide range of operating conditions.

Gathering large amounts of data is an important part of any measurement process. For example, no test procedure can possibly review the operation of a vehicle's ADAS equipment under all operating conditions and potential accident situations. But automated test solutions should try to anticipate the majority of single-vehicle, multiple-vehicle, and pedestrian combinations potentially involving ADAS and other types of autonomous-vehicle systems to ensure safe, reliable operation under the widest sets of conditions possible.

An innovator in developing automated test methods for ADAS and autonomous vehicles, the French firm UTAC CERAM, has counted on AB Dynamics and its Torus steering robots to perform automated steering testing on ADAS-equipped vehicles. Some of the steering robots have been designed specifically for ADAS development, since the demand for ADAS testing has been growing steadily in recent years.

In most cases, the ADAS vehicle dynamics measurements are short enough in duration that the robotics testers can collect sufficient results during these automated measurements to fully validate autonomous-vehicle operation. In some cases, when autonomous-vehicle testing may involve more complex street scenes and complex testing, the measurement systems are modified to meet the specific requirements with repeatable test results.

Measurement-equipment suppliers such as AB Dynamics are being challenged to produce automated, robotically controlled vehicular steering test systems during a time when the complexity of both the vehicular driving systems and the measurement systems used to characterize them is increasing. They have succeeded in making their measurement systems accessible, usable, and repeatable, much to the benefit of vehicle designers and manufacturers attempting to integrate ADAS and other automated driving approaches into commercial vehicles. Such tight control of autonomous-vehicle testing results in the collection of meaningful data and higher-quality, safer ADAS-based vehicles for all users.

See "Autonomous Vehicles and the Burden of Testing," NASA Tech Briefs, Vol. 42, No. 7, July 2018, p. 55, *www.techbriefs.com.*

WAVEGUIDE-BALANCED NbN/GaN Mixer Reaches 1.3 THz

ENVIRONMENTAL AND CHEMICAL research has benefitted from the continuing development of terahertz-frequency mixers, such as waveguide-balanced components capable of operation above 1 THz. For example, submillimeter-wave and terahertz heterodyne receivers have provided a great deal of insight into many different chemical processes. Analysis is typically performed at frequencies to about 1.6 THz.

Researchers from Sweden, France, and Russia teamed on the design and fabrication of a waveguide-balanced, phonon-cooled NbN hot-electron-bolometer (HEB) mixer on a GaN buffer layer. The mixer was used in a double-sideband (DSB) receiver operating at a local-oscillator (LO) frequency of 1.3 THz with extremely low noise temperatures for analysis of signals across wide bandwidths at terahertz frequencies.

While such NbN-on-GaN mixers have been developed previously for THz applications, compared to mixers on silicon (Si) substrates, little has been documented on the noise performance of such THz mixers. These researchers used the Y-factor technique to characterize mixer integrated circuits (ICs), which were fabricated by photolithography and mounted within a THz waveguide receiver assembly, and subsequently measure the receiver noise temperature.

Measurements were performed by evaluating black-body emitters held at different hot and cold temperatures, such as a hot temperature of 296 K and a cold temperature of 78 K. A commercial spectrum analyzer is then used to gauge the intermediate-frequency (IF) power spectrum of the receiver for hot and cold loads across an IF range of 500 MHz to 8 GHz, utilizing a local oscillator (LO) source tuned from 1.25 to 1.39 THz. The researchers were able to determine excellent gain-bandwidth and noise performance for the mixer, with much credit due to the mixer's use of a GaN buffer layer mounted atop a thin Si semiconductor wafer.

See "Noise and IF Gain Bandwidth of a Balanced Waveguide NbN/GaN Hot Electron Bolometer Mixer Operating at 1.3 THz," *IEEE Transactions on Terahertz Science and Technology*, May 2018, Vol. 8, No. 3, p. 365.

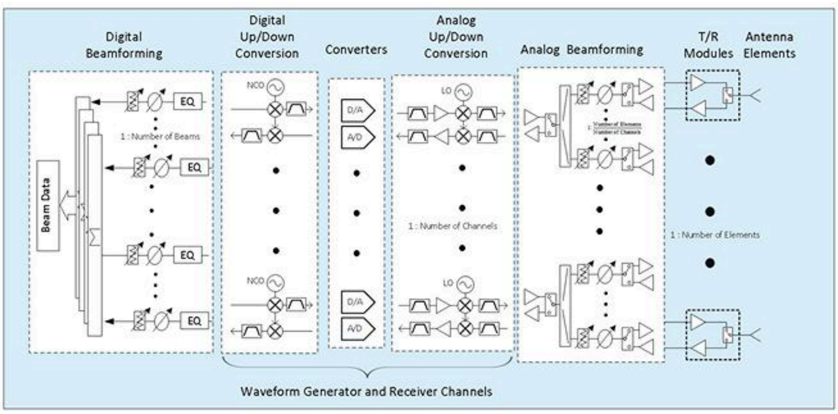

RF OUT
PASTERNACK

CHRIS DeMARTINO | Technical Engineering Editor

Radar Technology Beams Toward the Next Frontier

What's going on in today's rapidly transforming radar market? An industry expert breaks down the latest trends and key factors changing the face of this technology.

While radar certainly has a long history, tech developments over the last few years have catapulted modern radar systems to new levels of capability. Major advances include gallium-nitride (GaN) technology and high-speed converters. Other significant factors involve digital beamforming, as well as the push for more flexible platforms that can satisfy multiple missions. This article dives into the current radar landscape, examining these topics and more.



1. Shown is a generic analog/digital beamforming phased-array signal flow.

TUBES, GaAs, AND GaN

Peter Delos is a systems engineer in the aerospace and defense group at Analog Devices *(www.analog.com)*. With years of experience in developing radar-system architectures, he can provide valuable insight into today's radar market. But before speaking about the current market, Delos first offered a historical perspective of radar.

"If we go back to the history of radar, it primarily started in the World War II timeframe," said Delos. "There were big power tubes and rotating dishes. Then the phased-array world came into fruition, which started in a couple phases. The tubes stayed, but then there were phase shifters and large arrays. That was done all throughout the last century."

Delos explained when the radar landscape began to change. "Around the late 1990s or so, gallium arsenide (GaAs) came together and the T/R modules came together. That was the first transition to replace tubes in phased-arrays. The radar back-end processing was similar, but the T/R modules flooded the front ends of the phased-array world. That was the first definition of a solid-state array."

Solid-state technology has continued to advance in recent years. Specifically, as many may already know, GaN technology is now a major factor in today's radar-system development. "As the power-amplifier (PA) technology improved, the world migrated to GaN," noted Delos. "We see that as a dominant force going into the future. We're working actively in that area in terms of PAs and low-noise amplifiers (LNAs)."

While the primary benefits of GaN technology have been well-publicized, other benefits exist that may not receive as much attention. These benefits are significant as well, according to Delos. "There are some secondary benefits of GaN that are really enablers for many customers," he said. "At the LNA side, there is a higher breakdown voltage. That translates into higher survive power, which can translate into the removal of limiters. That translates to better overall noise figure for the system, which is a big factor. We have GaN LNAs coming out now, as well as some in development that are going to have much higher survive power."

It's no secret that GaN PAs play a major role in radar systems. Delos mentioned how these PAs require less current at higher voltages, thereby simplifying the power distribution. Gate switching is another point of interest. He added, "In the past, there was a lot of effort in drain switching to turn the PAs on and off in pulsed-radar applications. Circuits allowed for switching on the drain side. We worked out how to do that on the gate side. Less current drive is needed, and it can simplify and miniaturize some of the circuitry. That's built into our beamforming integrated circuits (ICs)."

PHASED ARRAYS

Another critical aspect of modern radar systems is phased-array technology. "Most radars now utilize phased arrays," explained Delos. "In terms of trends, we see that there is a large quest toward digital beamforming. At the lower frequencies, people are trying to enable every element digitally. That's enabled by our converters and other electronics. As you go up in frequency, the spacing between elements, or what's called the lattice spacing, goes down. So, the size, weight, and power (SWaP) constraints become very difficult. Therefore, there's going to be some upper frequency where analog beamforming is necessary.

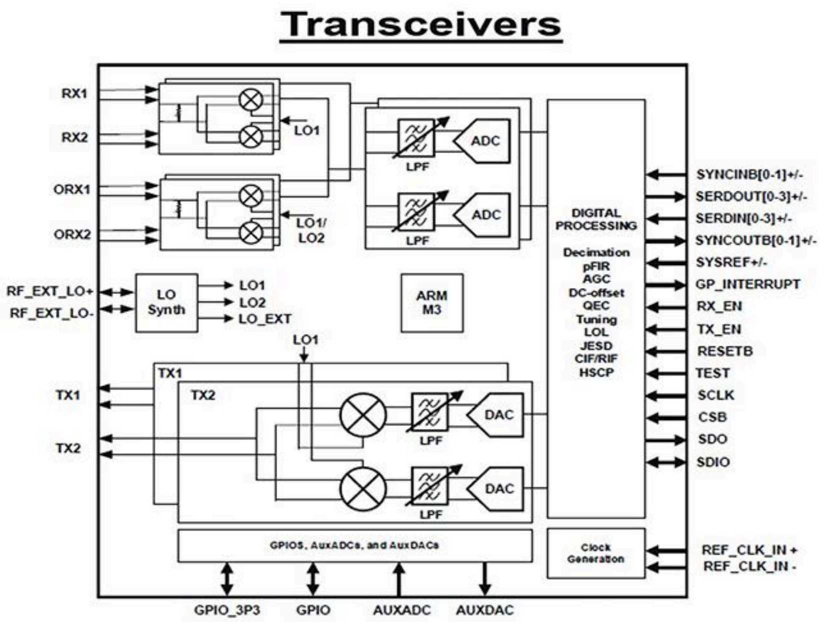
"Analog beamforming could be utilized for the whole array," he continued. "Or it could be utilized for subarrays, which is what many call hybrid beamforming. In those cases, you would combine several channels and then go on to digital receivers and waveform generators *(Fig. 1)*."

Along these lines is the recently released ADAR1000, which is a four-channel X-/Ku-band beamforming chip. It offers a 31-dB gain adjustment range and a full 360-deg. phase adjustment range. "The ADAR1000 enables digital beamformed arrays where there's a four-to-one subarray," noted Delos.

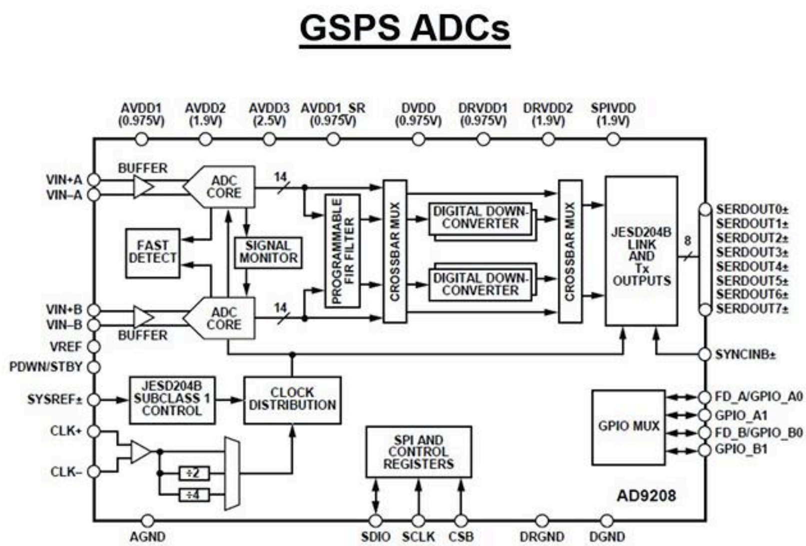
In terms of future radar applications, what scenarios will be better suited for analog beamforming as opposed to digital beamforming? And vice versa? "When it comes to analog versus digital beamforming," explained Delos, "I think a lot is going to come down to the number of beams. If a single beam is needed, it's still quite efficient to utilize an analog beamforming solution. If there are multiple beams, the economics of digital beamforming, along with its benefits and flexibility, become very attractive."

MULTI-MISSION SYSTEMS

When discussing today's radar systems, one important factor is the greater flexibility required to satisfy multiple missions. "In the past, there was a large set of disparate systems that both American and European governments were making," said Delos. "But the cost of doing that is no longer palatable. So, there's a large quest toward multi-mis-



2. Transceivers, such as the one illustrated here, are playing an essential role in radar applications.



3. This block diagram reveals details of a gigasample-per-second ADC.

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sion systems. Essentially, people are trying to get the most flexibility out of any platform. That leads to a system that can handle radar, electronic warfare (EW), and comms."

However, building these multi-mission systems comes it with its share of challenges. "The next challenge surrounds the somewhat disparate hardware requirements of these different systems when you really break them down," explained Delos. "At the high level, it may seem like I have this programmable antenna and I can do all these things. But it does lead to challenges, as each of these different systems have some performance differences.

"In terms of the heritage of the companies that make these systems," continued Delos, "some of them have been doing the same types of things for decades. They may have some tribal knowledge or their own style of doing things—and it's different in the radar world, the EW world, and the comms world."

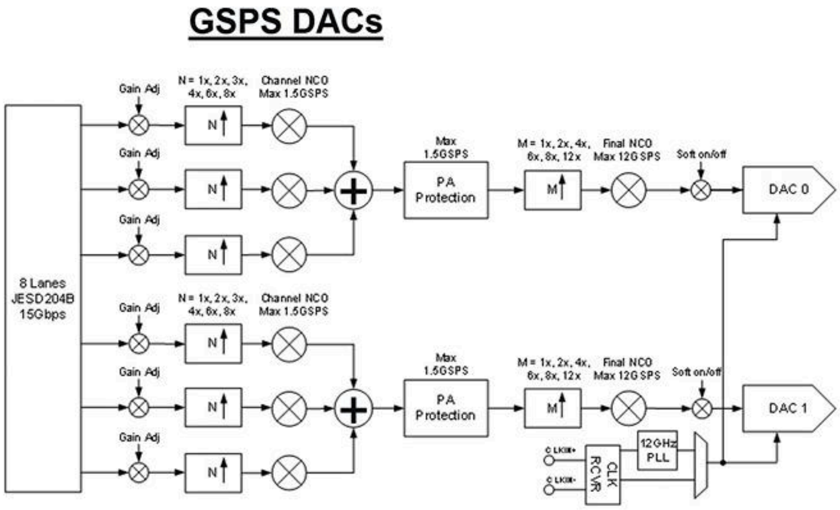
Delos added, "Trying to navigate hardware that can be used in all those domains is a challenge. At Analog Devices, we're right in the middle of that because our converters and transceivers feed into all those applications and we work directly with the engineers to try to pull the next set of electronics together *(Fig. 2)*."

HIGH-SPEED CONVERTERS AND MORE

Delos mentioned the converters being utilized today. No doubt, the latest high-speed analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) are enabling factors for next-generation radar systems *(Figs. 3 and 4)*. "Our converter speeds continue to go up," noted Delos. "The latest ADCs achieve 10 gigasamples per second. That gives us a 5-GHz Nyquist band to work with—that's really an enabler for wideband systems. A dual 3-GHz ADC is available, and there's going to be another batch." According to Delos, these ADCs can essentially make possible wideband systems in miniaturized platforms. Radar, EW, and comms applications are all targets.

Delos further explained the significance of higher converter rates. "In a sense, the converter is the center of the picture because the RF is defined based on the operating band. As the converter speeds increase, the IF frequencies go up and the RF electronics changes—and in most cases really simplifies. Now, you can go directly to L-, S-, and C-band without a mixing stage. A whole RF step has essentially been eliminated."

One additional point brought up by Delos is the difference in how evalua-



4. Here's a closer look at the inner workings of a gigasample-per-second DAC.

tion (eval) boards are characterized. "If you think historically, we would make an eval board for an ADC and an eval board for an amplifier. We would then hand these off. Now, we make an eval platform that's a full single chain, so data goes in and RF comes out. That's one dimension.

"The next dimension is going across channels," he continued. "We're making multichannel RF demos to demonstrate coherency and calibration to show that our electronics can fit elegantly into a phased-array solution. We can enable the customers with the demos, as well as learn from the multichannel platforms, since there are little details that we continue to fold into our products."

CONCLUSION

This article highlighted some of the activity in today's radar world. It's clear that technology has enabled radar systems to undergo a transformation, with GaN PAs and LNAs, as well as high-speed ADCs and DACs, being major driving forces. Digital beamforming is another critical factor. On top of that, the desire for multi-mission systems is redefining the radar market. It would be wise for those involved with radar systems to keep a close eye on what's coming next in these hotbed areas. mw

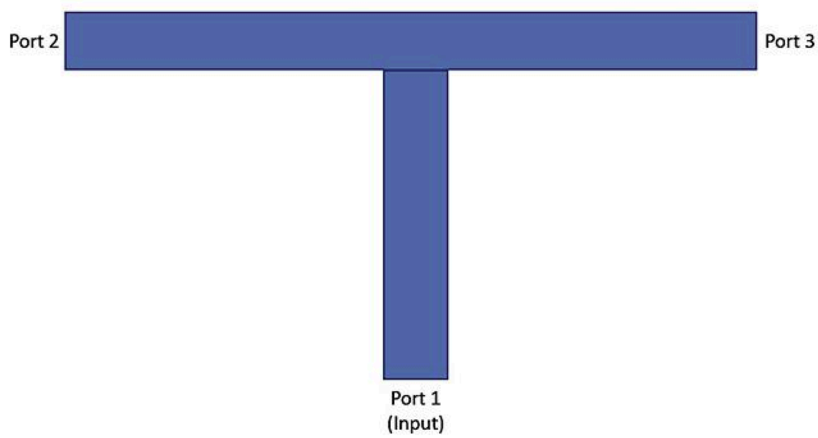
STEVEN PONG | Product Manager, Pasternack
www.pasternack.com

Power Dividers: Basic Tools Designers Can't Live Without

Upon first inspection, power dividers appear to be simple devices that require little knowledge on the part of designers. Nothing could be further from the truth.

When input power must be split among multiple transistors in an amplifier, the amplifiers themselves, antennas, or in an enormous number of other scenarios, power dividers are the answer. Not surprisingly, they are manufactured by dozens of companies throughout the world and represent a significant portion of the RF and microwave passive-component market. At first glance, RF and microwave power dividers appear simple. But each type has unique characteristics, so choosing the best one for a particular application can be confusing. This article will hopefully help to alleviate that problem.

For anyone not familiar with power dividing and combining, some of the confusion is caused by terms that tend to be used haphazardly over time. For example, power dividers are sometimes referred to as splitters—which is true. But the industry has deemed that power dividers should be called splitters when they are the simplest and least expensive devices, such as those used in home coaxial-cable systems. In addition, although the term coupler and power divider are often used interchangeably, key differences between the two exist.



1. The T-junction represents the basic idea of power division.

COUPLER OR DIVIDER?

Directional couplers are designed to "sample-off" a relatively small amount of power into one port for purposes like monitoring. Another factor to remember is that while the insertion loss of most passive components is simply the total attenuation from input to output, when applied to a power divider, it refers to the additional loss above that created by the splitting process itself.

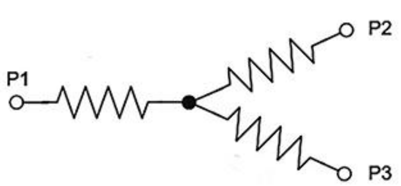
Furthermore, power dividers can also be power combiners, but this does not mean that their specifications will be the same nor that every type of power divider is equally suited for use as a combiner. As noted, there's more than meets the eye when it comes to power dividers.

A power divider splits an input signal into two or more outputs that are usually, but not always, equal in amplitude and phase. Regardless of its type, the goal of every power divider is to have the greatest port-to-port isolation, lowest insertion loss and voltage standing wave ratio (VSWR), and least amplitude and phase imbalance over the entire frequency range of the device.

The most basic type of power divider is the T-junction *(Fig. 1)*, which if mechanically symmetrical will divide a signal applied to its input into two outputs that are equal in amplitude and phase. It's basically just three transmission lines connected at a single point. The T-junction satisfies the basic purpose of dividing an input signal into two separate transmission paths, but it suffers from two very important deficiencies: There's no way to match impedance at all ports or any means of providing isolation between them. Although these limitations have always been important, the increasing sophistication of multichannel receivers, along with other applications, has relegated them to obscurity.

RESISTIVE POWER DIVIDER

There are two basic types of power dividers: resistive and reactive. The resistive type *(Fig. 2)* is symmetrical and arguably the least complicated, has the greatest bandwidth, and allows the desired system impedance (typically 50 Ω) to be maintained. It's a star configuration that has no dedicated input port. Therefore, every path has equal loss and an input at any port will distribute the signal equally to every other port. This allows them to function as "hubs" that are well-suited for connecting multiple receivers, transmitters, or transceivers, as well as for measurement purposes.



2. The resistive power divider is simple and broadband but lossy.

The resistive power divider's simplicity also makes it smaller than other types, since it's composed only of resistors. In addition, they are the only type that can have a minimum frequency down to dc. They achieve their wide operating bandwidths because there are no frequency-dependent components, i.e., reactive components.

However, since the resistors used as the dividers absorb power, resistive dividers have comparatively high insertion loss, making them unacceptable for use in many types of systems. For example, the typical insertion loss from one port to another in a 2-way resistive divider is 6 dB, while the loss in a 2-way reactive divider is 3 dB.

The star construction also means there's no port-to-port isolation. The power-handling capability of resistive power dividers is also limited by the reactance of the resistors; therefore, high-power versions are not practical. Resistive power dividers do not provide isolation between ports, which is a critical factor in applications such as communications systems plagued by crosstalk.

A variant of the resistive type produces an output impedance that's different from the system impedance. This is typically used in various types of measurement systems. For example, a simple resistive divider is often utilized with network analyzers in which the divided signal is split equally between the network under test and the reference channel. They also can be used to calibrate power sensors and other instruments.

REACTIVE POWER DIVIDER

Reactive power dividers are asymmetrical, essentially quarter-wave transmission lines matched to divide an input signal evenly to multiple output ports. They feature very low insertion loss, provide about 20 dB of port isolation, and are extremely rugged because they don't include resistors that can burn up, making them well-suited for demanding applications.

Long the choice for use in the distribution of signals in some antenna arrays, they also find homes in coax-based in-building systems such as legacy distributed antenna systems (DASs). In short, reactive power dividers are efficient, cover reasonably wide bandwidths, handle high RF power levels, and can be fabricated using waveguide, stripline, microstrip, transformers, and other technologies.

The basic advantage of reactive power dividers over other types is that they have very low loss, operate at high frequencies, and provide significant isolation between output ports. They are often fabricated coaxially with an air dielectric in which a 50-Ω input impedance is changed to 25 Ω at the outputs by varying the ratio of inner and outer conductors, with each output in parallel at 50 Ω.

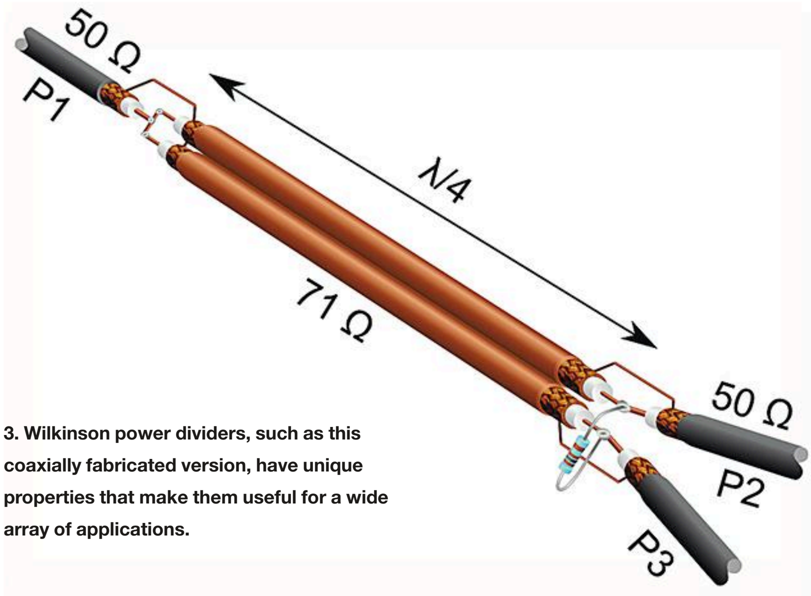
WILKINSON POWER DIVIDER

This is a good place to mention one of the most important contributors to the power-division domain: Ernest Wilkinson, whose "N-way hybrid power divider," details of which were published in "Institute of Radio Engineers (IRE, now the IEEE) Transactions on Microwave Theory and Techniques" in 1960. This achievement ensured Wilkinson a place in RF engineering history because it solves basic problems associated with the T-junction, which has made the reactive Wilkinson power divider a staple of RF and microwave design ever since they first became commercially available.

The Wilkinson power divider *(Fig. 3)* was created in part as a solution to the problems of matching and isolation that are inherent in a typical T-junction divider, in which a large amount of the power reflected from port 2 enters port 3 and thus provides little isolation. The Wilkinson power divider employs quarter-wavelength transformers to divide the input signal. But to understand why Wilkinson's creation is important, remember that network theory dictates no three-port device can be simultaneously matched, lossless, and reciprocal.

The Wilkinson power divider covers two of these bases, as it's inherently matched and reciprocal, but not lossless. So, its creator placed a resistor between the output ports, which not only dramatically reduces loss (if both of these ports are also well-matched) but provides isolation as well. That is, assuming both arms of the divider are the same, the signals will also be in phase. Therefore, the resistor will draw no current and thus add very little loss (ideally none, but this is not an ideal world).

So, while loss is not eliminated, it can be very low, reciprocity is maintained, and isolation is provided—all through the addition of one component. A good example of a Wilkinson power divider is Pasternack's PE2021 *(Fig. 4)* that operates from 7 to 12.4 GHz. The PE2021 can handle as much as 10 W of continuous-wave (CW) input power. It has 1 dB of insertion loss and achieves 16 dB of isolation. Furthermore, the PE2021 maintains an amplitude balance of ±0.3 dB and a phase balance of ±6 deg.



3. Wilkinson power dividers, such as this coaxially fabricated version, have unique properties that make them useful for a wide array of applications.

Wilkinson's creation has other benefits as well. For example, it's comparatively simple and can be implemented using printed components as well as with lumped inductors and capacitors. When fabricated in microstrip on a board, its cost is extremely low, too.

The initial implementations of the Wilkinson power divider were limited in bandwidth, but an enormous amount of work has been conducted over the years to improve on this metric, and

today much greater bandwidths are achievable. It can be configured as an N-way (more than two output) device, although it's primarily used for 2-way power division. Common division ratios are 2- through 8-way, although other division ratios, such as 5- and 10-ways, can be realized as well.

Countless variations of the Wilkinson power divider have been designed and constructed, particularly in recent years because of the availability of simulation software and improved fabrication techniques. Some Wilkinson designs allow for unequal division with large division ratios, as well as dual and broadband frequency operation. Designs that take advantage of coupling between the quarter-wave transmission lines to reduce layout size while maintaining a good bandwidth have also been developed.

Furthermore, it's possible to create Wilkinson power dividers with unequal (i.e., asymmetric) splitting ratios. These dividers, which are often used with array antennas and several types of receivers, consist of two quarter-wave segments of different impedances that realize the desired power division.

4. Pasternack's PE2021 4-way Wilkinson power divider operates from 7 to 12.4 GHz and handles 10 W of input power (CW).

This discussion covers some—but far from all—of the fundamental information about coaxial power dividers. A more thorough discussion requires considerable editorial real estate. Fortunately, many textbooks are available that discuss power division and power combining from the fundamentals through various configurations (of which there are many), as well as couplers and implementations in waveguide. mw

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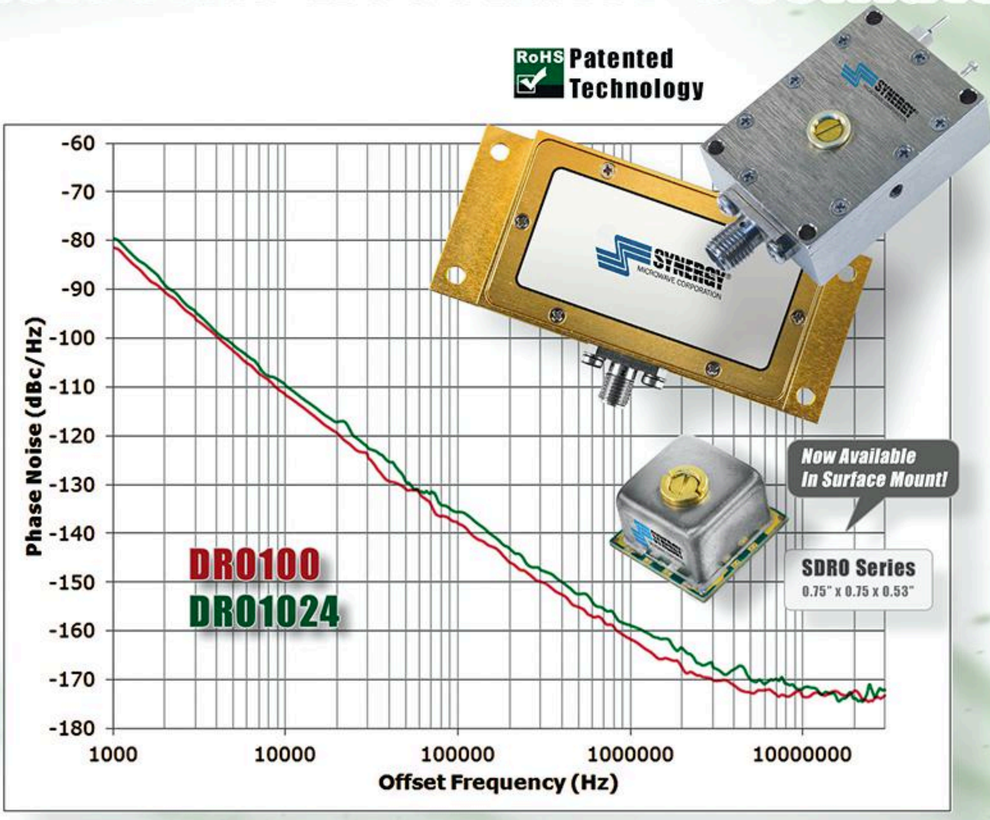

Model	Frequency (GHz)	Tuning Voltage (VDC)	DC Bias (VDC)	Typical Phase Noise @ 10 kHz (dBc/Hz)
Surface Mount Models				
SDRO1000-8	10	1 - 15	+8 @ 25 mA	**-107**
SDRO1024-8	10.24	1 - 15	+8 @ 25 mA	**-111**
SDRO1250-8	12.50	1 - 15	+8 @ 25 mA	**-105**
Connectorized Models				
DRO100	10	1 - 15	+7 - 10 @ 70 mA	**-111**
DRO1024	10.24	1 - 15	+7 - 10 @ 70 mA	**-109**

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www.keysight.com

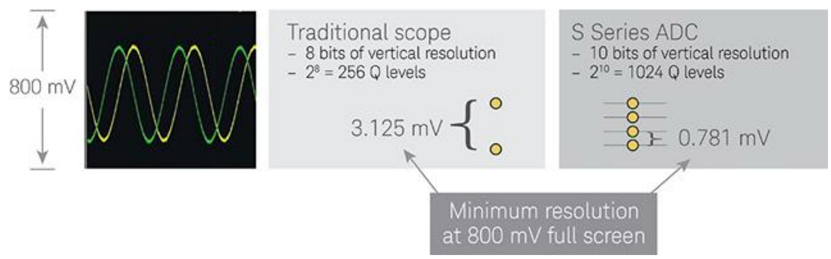
How to Evaluate Oscilloscope Signal Integrity

Oscilloscope signal integrity impacts signal shape and measurement values. This article is intended to help you assess the signal integrity of your oscilloscope and make trustworthy measurements.

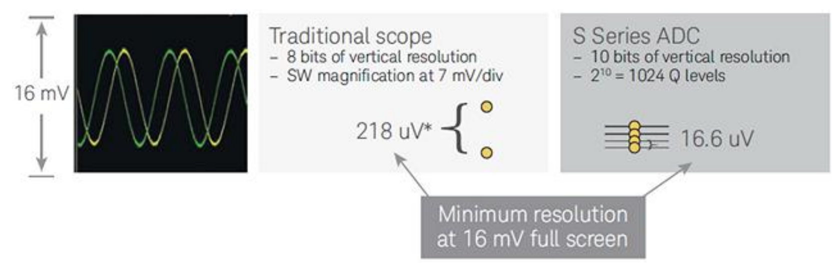
Signal integrity is the primary measure of signal quality. Its importance increases with higher signal speed, oscilloscope bandwidth, the need to view small signals, or the need to see small changes on larger signals. Signal integrity impacts all oscilloscope measurements. Oscilloscopes themselves are subject to the signal-integrity challenges of distortion, noise, and loss.

Oscilloscopes with superior signal-integrity attributes offer better representations of your signals under test, while representations provided by those with poor signal-integrity attributes will be inferior. This difference impacts an engineer's ability to gain insight and to understand, debug, and characterize designs.

Thus, selecting an oscilloscope that has good signal-integrity attributes is important; the alternative is increased risk in terms of development-cycle times, production quality, and the components chosen. To evaluate oscilloscope signal integrity, we will look at analog-to-digital converter (ADC) bits, vertical scaling, noise, frequency, phase response, effective number of bits (ENOB), and intrinsic jitter.



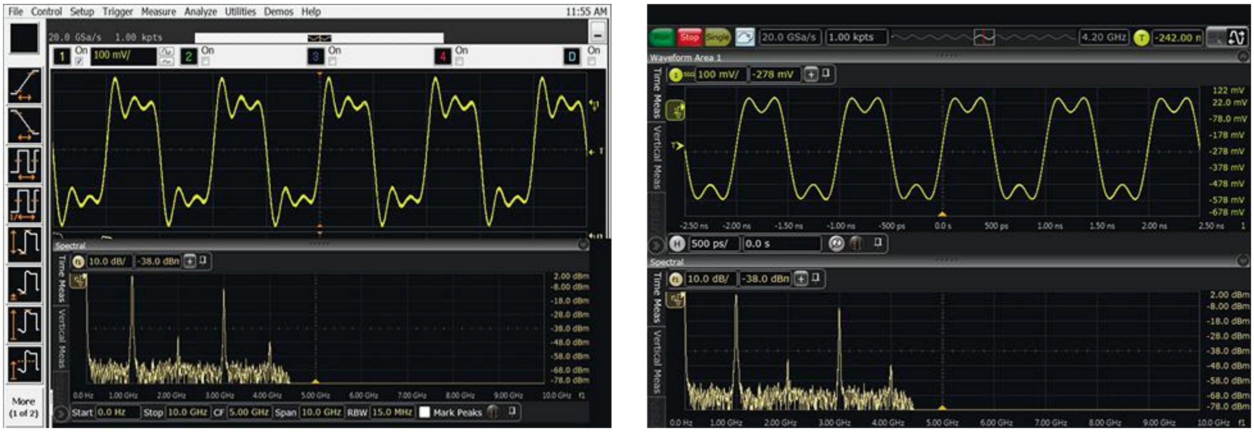
1. Resolution is an important signal-integrity attribute. More ADC bits and proper vertical scaling are two ways to increase resolution.



2. The minimal vertical setting an oscilloscope supports in hardware will be important for seeing small signal detail.

ADC BITS

Resolution is the smallest quantization (Q) level determined by the ADC in the oscilloscope. The higher the number of ADC bits, the greater the resolution. For example, an 8-bit ADC can encode an analog input to one in 256 different levels (since $2^8 = 256$), while a 10-bit ADC ideally provides four times the resolution of that (2^{10} = 1024 Q levels).



3. Two oscilloscopes having identical bandwidth rating, sample rate, and other settings were connected to an identical signal. The difference between the two is the one on the right uses hardware DSP correction filters to produce a flat magnitude and phase response, while the one on the left does not.

VERTICAL SCALING

Since the ADC operates on the full-scale vertical value, proper vertical scaling also helps increase oscilloscope resolution. *Figure 1* shows a full screen of 800 mV (8 divisions × 100 mV/div).

An oscilloscope with an 8-bit ADC has a resolution of 3.125 mV (800 mV/256 Q levels), while a 10-bit ADC has a resolution of 0.781 mV. Each oscilloscope can only resolve signals down to the smallest Q level.

To get the best resolution, use the most sensitive vertical-scaling setting while keeping the full waveform on the display. Scaling the waveform to consume almost the full vertical display makes full use of your oscilloscope's ADC. If a signal is scaled to take up only half or less of the vertical display, you will lose one or more ADC bits.

The combination of the ADC, the oscilloscope's front-end architecture, and the probe used determine the limit of vertical scaling supported by the oscilloscope hardware. At a certain point, each family of oscilloscopes cannot go to a lower vertical scale. Vendors will often refer to this as the point where the oscilloscope moves into software magnification. Turning the oscilloscope's vertical scale to a smaller number simply magnifies the displayed signal but doesn't result in any additional resolution.

Figure 2 gives an example of two oscilloscopes evaluating a small signal. The signal's magnitude is such that a vertical scaling of 16 mV full screen allows the signal to consume almost the entire vertical display height. The traditional 8-bit oscilloscope goes into software magnification at 7 mV/div, resulting in a minimum resolution of 218 μV (7 mV/div × 8 div/256 Q levels). A 10-bit oscilloscope, such as the Keysight Infiniium S-Series, stays in hardware all the way down to 2 mV/div, giving a minimum resolution of 15.6 μV (2 mV/div × 8 div/1024 Q levels)—14 times the resolution of the 8-bit oscilloscope.

NOISE

Noise impacts horizontal as well as vertical measurements. The lower the noise, the better signal integrity you can expect. If noise levels are higher than ADC quantization levels, you won't be able to take advantage of the additional ADC bits. Having an oscilloscope with low noise (high dynamic range) is critical if you want to see small currents and voltages, or small changes on larger signals.

Noise can come from a variety of sources, including the oscilloscope's front end, its ADC, and the probe or cable used to connect the device. The ADC itself has quantization noise, but this typically plays a lesser role in overall noise contribution than the front end.

Most oscilloscope vendors will characterize noise and include these values on their product datasheet. If not, you can ask for the data, or find out yourself. The measurement is easy and takes only a few minutes. Each oscilloscope channel will have unique noise qualities at each vertical setting. Disconnect all inputs from the front of the oscilloscope and set it to the 50-Ω input path (you can also run the test for the 1-MΩ path).

Turn on a decent amount of acquisition memory, such as 1 Mpoint, with the sample rate fixed at a high sample rate to ensure you are getting the full oscilloscope bandwidth. You can view

Signal integrity metric	Scope technology block	Where can you find the answer?
Resolution	ADC bits	Product datasheet
Noise	Front-end	Most vendors include in product datasheet.
Vertical scaling supported in HW	ADC/front-end	Datasheets don't always specify when SW magnification starts. Some vendors BW limit at small sensitivities.
Frequency response flatness	Analog filters and correction filters	Not typically included in product datasheets. You will need to ask the vendor to see a magnitude and phase response for the model you are evaluating.
Time scale accuracy	Time base	Product datasheet
Amount of intrinsic jitter	Time base	Some vendors include, others don't. If not in the datasheet, ask the vendor.
ENOB (Effective Number of Bits)	Combination of both vertical and horizontal scope system	Some vendors include, others don't. If not in the datasheet, ask the vendor.

These seven signal-integrity attributes should be considered when choosing an oscilloscope.

the noise visually by looking at waveshape thickness, or quantify it by measuring Vrms ac. By using these methods, you will know the amount of noise each oscilloscope channel has at each vertical setting.

FREQUENCY RESPONSE

Uniform and flat oscilloscope frequency response is highly desired for signal integrity. Each oscilloscope model will have a unique frequency response that's a quantitative measure of the oscilloscope's ability to accurately acquire signals up to the rated bandwidth. Three oscilloscope must-have requirements to accurately acquire waveforms are:

1. A flat frequency response.
2. A flat phase response.
3. Captured signals must be within the bandwidth of the oscilloscope.

A flat frequency response indicates that the oscilloscope is treating all frequencies equally. A flat phase response means the signal is delayed by precisely the same amount of time at all frequencies. Deviation from one or more of these requirements will cause an oscilloscope to inaccurately acquire and draw a waveform.

Some scopes have correction filters that are typically implemented in hardware digital-signal-processing (DSP) blocks and tuned for a family of oscilloscopes. *Figure 3* shows how correction filters can improve signal integrity of the measurement by creating a flat magnitude and phase response. The oscilloscope on the right shows a waveform that accurately matches the spectral content of the signal, while the one on the left does not.

Your oscilloscope's overall frequency response will be a combination of the oscilloscope's frequency response and the frequency response of any probes or cables connected between the device under test (DUT) and the instrument. If you put a BNC cable that has 1.5-GHz bandwidth on the front of a 4-GHz oscilloscope, the system's overall bandwidth is limited by the BNC cable and not the oscilloscope. Make sure your probes, accessories, and cables aren't the limiting factor for a precision measurement.

EFFECTIVE NUMBER OF BITS (ENOB)

ENOB is a measure of the oscilloscope's dynamic performance expressed in a series of bits-vs.-frequency curves. Each curve is created at a specific vertical setting while frequency is varied. The resulting voltage measurements are captured and evaluated. In general, a higher ENOB (expressed in bits) is better.

While some vendors may provide the ENOB value of the oscilloscope's ADC separately, this figure has no value. ENOB of the entire system is what's important. The ADC could have a great ENOB, but poor oscilloscope front-end noise would dramatically lower the ENOB of the entire system. Engineers who look exclusively at ENOB to gauge signal integrity should be cautioned. ENOB does not consider offset errors or phase distortion that the oscilloscope may inject.

An oscilloscope doesn't just have one ENOB number. Rather it has different ENOB values for each vertical setting and frequency.

INTRINSIC JITTER

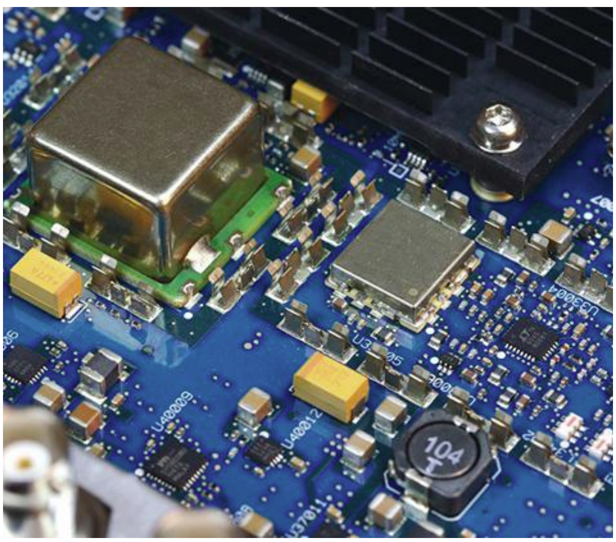
Jitter describes deviation from the ideal horizontal position. It's measured in ps rms or ps peak-to-peak. Jitter sources include thermal and random mechanical noise from crystal vibration. Traces, cables, and connectors can further add jitter to a system through intersymbol interference.

Oscilloscopes themselves have jitter. The term "jitter measurement floor" refers to the jitter value reported by the oscilloscope when it measures a perfect jitter-free signal. The jitter-measurement-floor value is comprised not only of the sample clock jitter, but also of vertical error sources, such as vertical noise and aliased signal harmonics. These vertical error sources affect horizontal time measurements because they change the signal of threshold crossings.

Excessive jitter is bad, as it can cause timing violations that result in incorrect system behavior or poor bit error rates (BER) in communication systems that result in incorrect transmissions. Measurement of jitter is neces-

Your oscilloscope's overall frequency response will be a combination of the oscilloscope's frequency response and the frequency response of any probes or cables connected between the device under test (DUT) and the instrument.

sary to ensure high-speed system reliability. Understanding how well your oscilloscope will make those measurements is critical to interpreting your jitter measurement results *(Fig. 4)*.



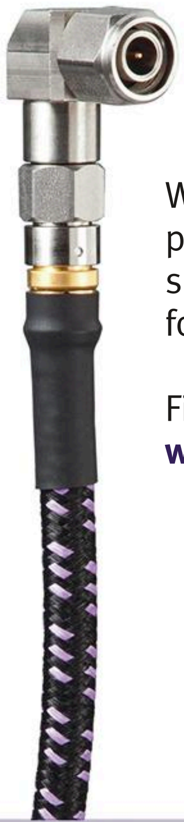
4. Keysight's Infiniium S-Series oscilloscopes include a new time-base technology block. Its clock accuracy is 75 parts per billion. Intrinsic jitter for short record lengths is less than 130 fs.

SUMMARY

While each attribute is important, the most overall accuracy will be seen in the oscilloscope that has a better overall composite of the seven attributes as listed in the table. Looking at only a single signal-integrity attribute in the absence of others can lead to false conclusions of the quality of your oscilloscope, which can then lead to unnecessary risk in getting your products to market or meeting product performance. mw

FOR MORE detailed information, please download the Keysight application note: https://literature.cdn.keysight.com/litweb/pdf/5991-4088EN.pdf?cmpid=72329

Proven Performance



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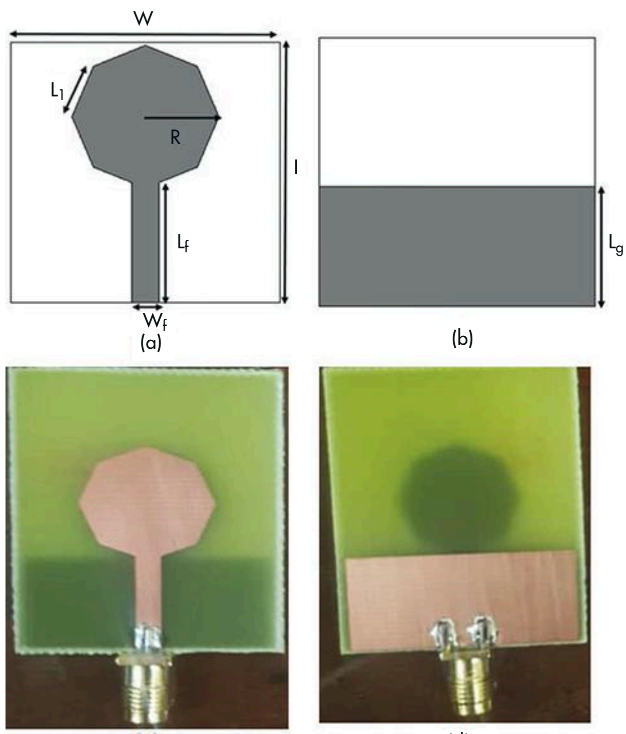
Planar UWB Antenna Includes Two Notches

This compact UWB antenna includes two frequency notches for suppression of interference occurring in WiMAX and WLAN frequency bands without the addition of filters.

Ultrawideband (UWB) communications technology makes use of broad expanses of frequency spectrum, transferring information at high data rates using low-energy pulses. While UWB signals are designed not to interfere with existing narrowband communications systems within the same frequency range, they are subject to interference from narrowband communications signals.

To overcome that interference problem, an UWB antenna was designed with a bandwidth of 3.1 to 11.5 GHz and with two notches; thus, the antenna doubles as a band-reject filter. The notches are designed to prevent interference from larger signals in such applications as WiMAX systems and wireless local-area networks (WLANs). The experimental antenna was fabricated on low-cost FR4 printed-circuit-board (PCB) material to demonstrate the effectiveness of the design.



(a) (b) (c) (d)

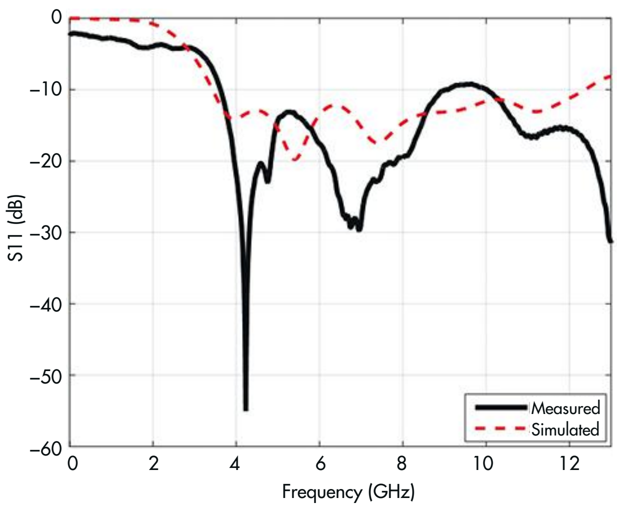
1. The geometry of the dual-notch UWB antenna can be seen from these (a) front and (b) rear views of the layout as well as from (c) front and (d) rear views of the fabricated prototype.

A LOOK AT UWB

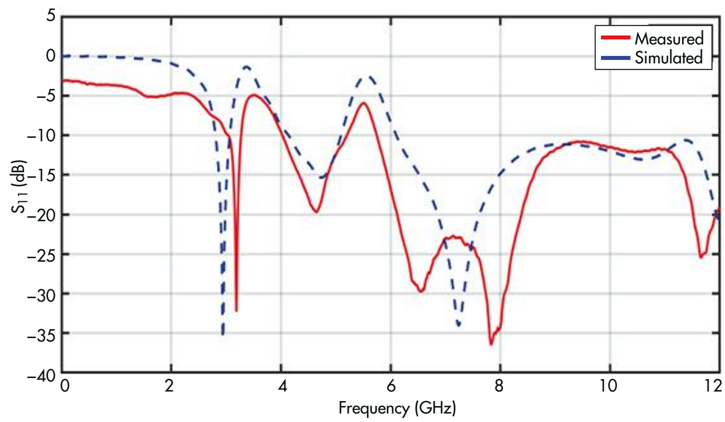
Although UWB technology has existed for some time for radar applications, the Federal Communications Commission (FCC) increased interest in the frequency range from about 3.1 to 10.6 GHz for short-range, high-data-rate commercial communications.[1] Many components have been designed for UWB use, including antennas based on various topologies.[2-13]

For UWB applications, planar antenna structures appear to offer advantages over other configurations for their simple structures, ease of fabrication, small size, low profiles, and low cost. UWB communications systems provide many benefits, such as enabling high data rates, increased security, low power consumption, and simple hardware requirements

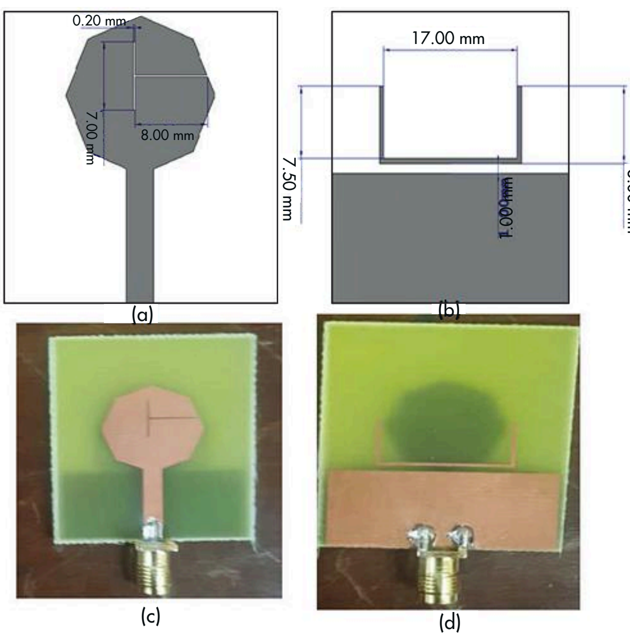
The UWB antenna can be fabricated on low-cost circuit-board material with good performance. It operates from 3.1 to 12.0 GHz with a compact footprint and, without additional hardware, can suppress interference occurring in the frequency bands of 3.3 to 3.9 GHz and 5.2 to 5.9 GHz.



2. The plots illustrate the two notches for the simulated and measured responses of the UWB antenna.



4. More detailed than Fig. 2, these plots depict the two notches in the response of the UWB antenna.



3. These images show similar but more detailed information than Fig. 1 for the (a) front and (b) rear views of the layout as well as from (c) front and (d) rear views of the fabricated prototype.

in practical applications.[2] For UWB systems to be effective, however, antennas for those systems must meet several requirements, including small size; omnidirectional radiation patterns; high, stable gain across a wide frequency range; and compatibility with other required components, such as filters and amplifiers.

Of course, signals occupying the UWB frequency range must coexist with many well-established narrowband communications systems, such as IEEE 802.11a and HIPERLAN/2 WLAN systems operating in the 5- to 6-GHz range. In some European and Asian countries, WiMAX service occupies the frequency range from 3.3 to 3.6 GHz. UWB antennas have typically functioned with the addition of filters to suppress narrowband signals that might interfere with UWB operation. As an alternative approach, portions of the UWB spectrum can be notched out by developing antennas with band-notch characteristic.[10-17]

BUILDING THE TWO-NOTCH ANTENNA

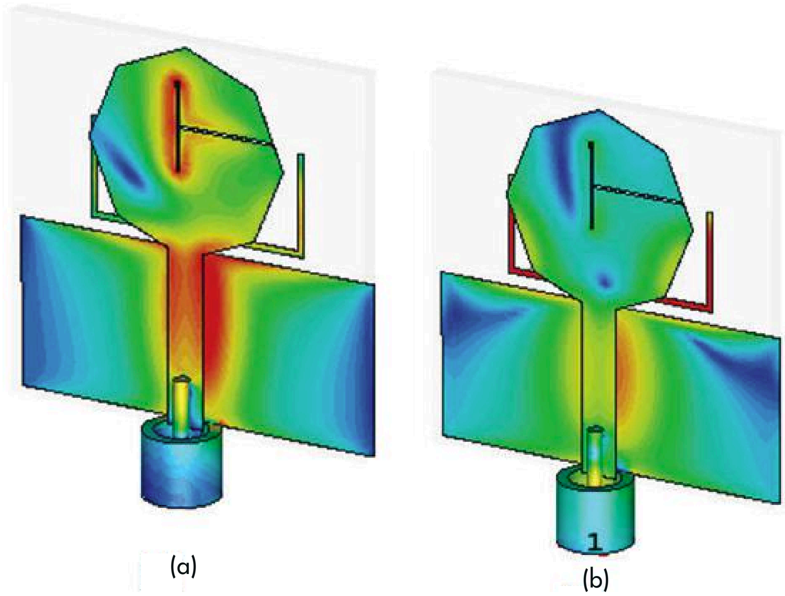
To demonstrate this design approach, an UWB antenna with two notched frequency bands was developed. Two techniques were used to achieve the notches. In one, a T-shaped slot was formed in the radiating patch on the current path of the antenna. In the other, a U-shaped parasitic strip was added above the antenna ground plane. The first notch is intended to reduce interference in the frequency band from 3.3 to 4.1 GHz. The second notch is to eliminate interference within the frequency band of 5.1 to 6.0 GHz.

CST Studio three-dimensional (3D) electronic design automation (EDA) software from Computer Simulation Technology was used in the design and simulation of the antenna.

Figure 1 (page 45) shows the basic antenna structure. It's composed of an octagonal-shaped radiator with radius (r) of 8.2 mm. This radiator is interconnected with the microstrip transmission line with a line width, W_f, of 3 mm to achieve a characteristic impedance of 50 Ω; the transmission has a line length (L_f) of 13.8 mm. As may be apparent from *Fig. 1b*, the antenna has a partial ground plane with length (L_g) equal to 13.4 mm to achieve the desired impedance bandwidth required for UWB applications. The width (W) of the antenna is 30 mm and the length (L) is 30 mm.

A prototype of the planar antenna was fabricated on low-cost FR4 PCB material *(Figs. 1c and 1d)*. The FR4 circuit material exhibits relative permittivity (ε_r) of 4.4 and thickness of 1.6 mm. *Figure 2* shows the simulated and measured return loss of the planar UWB antenna with two frequency notches. The antenna was simulated from 3.3 to 12.0 GHz with better than 10-dB return loss. From the measured results, the measured return loss is better than 10 dB from 3.3 to 10.0 GHz, showing good agreement with the simulated data.

Figure 3 presents the structure of the proposed UWB antenna with the two notched frequency bands to reduce interference from other wireless applications operating within the UWB frequency range. The two notches are obtained by adding the T-shaped slot and the U-shaped parasitic strip. The T-shape slot is inserted in the radiating patch to reduce interference from



5. The simulated current distributions for the antenna are shown at (a) 3.6 and (b) 5.5 GHz.

WiMAX applications from 3.3 to 4 GHz, while the U-shaped parasitic strip decreases interference from WLAN applications from 5.2 to 5.9 GHz. The length of the U-shaped parasitic strip is calculated by means of Eq. 1:

$$L_{total} \approx \lambda_g/2 = c/(2f_{notch}(\varepsilon_{eff})^{0.5} \qquad (1)$$

where

$$\varepsilon_{eff} \approx (\varepsilon_r + 1)/2$$

and c is the speed of light in a vacuum, and ε_r is the relative permittivity of the PCB material.

Figures 3c, 3d, and 4 offer different views of the dual-notched-band UWB antenna prototype, which was characterized with the aid of the ZVB 20 vector network analyzer (VNA) from Rohde & Schwarz. The network analyzer is capable of high-resolution S-parameter measurements to 20 GHz. *Figure 4* shows measurements made with the VNA, along with simulated return loss for the proposed UWB antenna with dual notched bands.

THE VERDICT

Examining the simulated results, the antenna operates from 3 to 12 GHz with return loss of better than 10 dB except from 3.3 to 4.0 GHz, which is a notch intended to suppress signals from WiMAX applications, and from 5.2 to 6.0 GHz, which is a notch aimed at WLAN applications, where the return loss is about 3 dB. From the measurements, it's apparent that the return loss is better than 10 dB from 3.2 GHz to about 12 GHz except for the two notched frequency bands. The measurements show good agreement with the simulated performance plots.

However, there are some discrepancies between the simulated results and the measured performance of the prototype, resulting from losses due to soldering and the antenna fabrication process. The simulated current flow is primarily concentrated around the T-shaped slot at 3.6 GHz *(Fig. 5a)*, which is the center frequency of the notch intended to reduce interference from WiMAX applications.

It's also apparent that current flow is concentrated around the U-shaped par-

(Continued on page 92)

Design Feature

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Perform Cost-Effective Antenna Radiation Measurements

Measuring antenna radiation is no longer in the exclusive domain of high-end test laboratories—it can be performed with a compact system that has all of the hardware.

Antenna designers and researchers have often wished for better measurement tools to check their work. Even as computer-aided-engineering (CAE) simulation tools[1-3] have improved over time, true validation of a design ultimately comes from fabricating and testing a prototype. Typical (or minimum) measurements of antenna characteristics include S-parameters and radiation patterns with further information on the antenna gain and efficiency, which usually calls for costly test equipment that may be outside the range of a designer's budget. Fortunately, affordable antenna measurements are becoming more practical and readily available.

S-parameters can be measured in a limited fashion with a scalar network analyzer (SNA) and more completely with a vector network analyzer (VNA).[4,5] Until recently, VNAs have been rather expensive test instruments, although smaller, less-costly units are emerging from several commercial suppliers.

Still, for full antenna characterization, some form of radiation pattern analyzer will also be needed and, fortunately, more affordable antenna radiation pattern analyzers have also entered the commercial market.[6-8] For effective antenna radiation pattern measurements, the analyzer usually must be supported by an anechoic chamber and two antenna masts, for transmit and receive antennas, with the capability of rotating 360 deg.

1. This is how the MegiQ Radiation Measurement System (RMS) appears when it's fully assembled and ready for testing antennas.

Today, antenna designers can perform a wide range of antenna radiation measurements with the aid of a radiation measurement system (RMS) from the Netherlands-based firm MegiQ.[9] Two versions of the RMS *(Fig. 1)* are available, for 0.6 to 4.0 GHz or 0.6 to 6.0 GHz. These frequency ranges cover many commercial wireless-communications applications.

The RMS enables quick, easy measurements of three-dimensional (3D) radiation patterns (single-axis measurements are an option), as well as measurements of antenna gain, directivity, total efficiency, effective isotropic radiated power (EIRP), total radiated power (TRP), and field strength. Values can be measured for multiple frequencies during the single rotation of an antenna under test (AUT), simultaneously measuring horizontal (H) and vertical (V) radiated field components.

This capability to measure simultaneous H and V radiation field components can greatly speed the measurement process, either for studying two orthogonal patterns of cross-polarization measurements or for a dual-polarization antenna measurement. The analyzer can control the rotation of an AUT's turntable with 2-deg. angular resolution and with measurement speed of 30 s/rotation. Integrated PC software provides a simple user interface to control the measurement functions, allowing a user to define various attributes: measurement distance; cable characteristic (either a total loss or a complete frequency characteristic by importing a Touchstone file); transmitter power; rotation control; how the results are displayed; data storage; or even the generation of a simple report.

The measurement distance between the transmit and receive sides is ranges from 0.8 to 3.0 m. For popular wireless frequencies (e.g., the 2.4-GHz band) and small antennas, very dependable results (confirmed by a comparison to results obtained by high-grade anechoic chambers and instruments[10]) are obtained at a separation distance of 90 to 110 cm even without an anechoic chamber. And that's even with surrounding objects present in the measurement room, which can be seen in the enclosed figures.

Results are displayed on the computer screen in real time. As soon as a measurement is completed, it's possible to see the radiation patterns for the chosen output parameters (i.e., field strength in dBμV/m or EIRP in dBm or antenna gain in dBi) as well as the maximum realized gain and antenna efficiency. Measured values for every measurement point can be also seen in the graphs.

For those not satisfied with the default plots, measurement results can be easily exported to a text file and then imported into a popular spreadsheet program for post-processing by the user and plotting in a user-preferred style. A user can choose between rotational measurements (single axis or three axes) that are then performed at a single (or multiple) discrete frequency or gain measurement. During this time, the turntable does not rotate, but the RMS tester performs frequency sweeping to analyze AUT characteristic as a function of a designated frequency range.

WHAT'S IN THE BOX

The RMS is equipped with several items that are often left as accessories by other instrument suppliers. Included with each analyzer *(Fig. 2)* are small parts that help simplify the assembly of the system and the measurements: a 3-m measuring tape; a screwdriver of an optimal length and size; a sticky (tesa) tape to fix the AUT to the turntable; and a roll of "TFR" stickers that are instrumental for proper orientation of an AUT on the turntable. These accessories enable a buyer to assemble a measurement system from the ground up a short time after opening the box.

2. A variety of accessory parts are shipped with each RMS tester in a small box.

Inclusion of the box of accessories with each RMS is indicative of the thoughtful design that went into the model RMS0640 used for antenna measurements. The PC software is extremely user-friendly and enables AUT measurements even without an anechoic chamber. The system is well thought out, even to the intelligent rotation of the turntable, which prevents overstretching of the interconnecting cables. All assembly instructions lead to the construction of an automated system fully capable of producing genuine antenna 3D radiation patterns.

The two sides of the RMS can be referred to as the antenna unit and the turntable unit *(Fig. 1, again)*. The antenna unit contains an antenna base box (which stands on the floor) with inputs and outputs for power supply and data and control cables (communications links to a PC and the turntable unit, respectively), and carries a telescopic antenna mast (adjustable in height from 100 to 170 cm), on top of which a user mounts a pyramidally shaped measurement head and a MegiQ dual-channel receiver. The whole assembly of this side is carried out by two plastic pipes that provide the necessary height of the head and carry the antenna and the dual-channel receiver.

The measurement head contains a dual-polarization antenna such that the RMS can simultaneously measure the horizontal and vertical polarization of an AUT. Matching that, the dual-channel receiver mounted just behind the measurement head measures the two polarization components received by the dual-polarization antenna. In this way, a user instantly has information on the cross-polarization of a linearly polarized antenna or the axis ratio of a circularly (or elliptically) polarized antenna.[11]

By adding an optional generator output to the dual-channel receiver, the measurement system can generate test signals from the test receiver and measure passive devices under test (DUTs), such as passive antennas. Otherwise, test signals must be provided from an additional third-party signal generator. For an active device, the PC software enables a user to designate an external source as the RF test signal source for the measurements.

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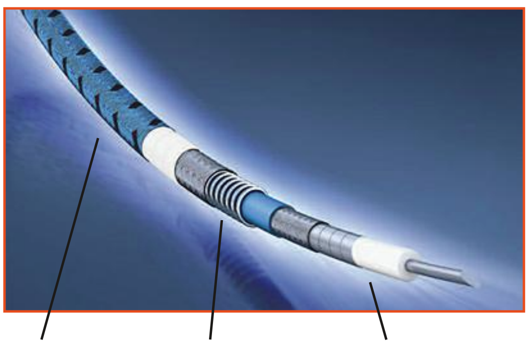

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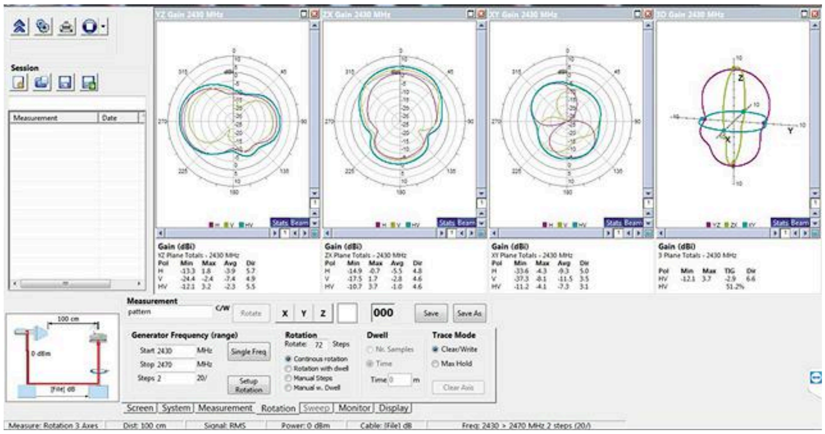
The other side of the RMS *(Fig. 1, again)* contains a turntable unit box (on the floor), a plastic pipe-based antenna mast (two-piece construction, to enable height adjustment from 70 to 130 cm), a rectangular 28- × 28-cm table punched with an array of holes through it (to accommodate a DUT with as much as 7.5-kg load), and a (small) object platform that's being plugged into some of the base table holes. The purpose of the latter is to allow for easy placement of a DUT in a correct orientation, as defined by the RMS instructions.

The turntable unit contains a stepper motor that's controlled by the PC software via the antenna unit box and USB and control cable that connect the PC, antenna unit, and turntable unit. The stepper motor achieves a full 360-deg. rotation in about 30 s, has smooth acceleration and deceleration, and quiet operation. For those testing heavier DUTs, MegiQ offers a heavy-duty table of 100- × 50-cm size, which can carry loads as large as 30 kg.

The RMS, as declared, will help a user have comfortable measurements when a distance between the two RMS masts is in the range from 0.8 to 3 m. The author has used the RMS for measurements at separation distances between 90 and 150 cm with good results. The separation adjustment, the antenna alignment, and the turntable "reference turn" could be completed quickly and easily.

To complete the measurement setup, a user will need a good-quality coaxial cable about 5 m long and 5 mm in diameter to connect the dual-channel receiver and a DUT. The cable passes through the predefined holes in the plastic pipes for the two masts. Such a cable is not included with the shipment of the RMS, but is available separately from MegiQ.



3. PC software is included with each RMS tester to control the radiation measurement procedure.

SOFTWARE SIDE

PC software that comes with the RMS controls the measurement procedure for characterizing an antenna's radiation pattern. The software contains simple and intuitive commands to control major steps of the measurement *(Fig. 3)*. Using tabs at the bottom of the PC control screen, the user sets different options and input values. These include the "Measurement" tab for choice of measurement type, i.e. a single rotation (for a single pattern) or 3-axis rotation (for a 3D pattern and antenna parameters derived from it), or the "Sweep" (for gain vs. frequency). By choosing such tabs, test variables are selected, including the measurement distance between the two antennas and the source of the RF signal, the output power that will be used in a measurement, and the cable loss value (in dB) or the cable loss as a function of frequency as a Touchstone file.

For example, the "Rotation" tab establishes the desired test frequencies and the characteristics of the AUT rotation (i.e., the number of sample points and the choice between the continuous rotation and rotation with dwell time as well as the rotation in manual steps). The "Display" tab contains the frequencies at which results will be displayed using the "Addgraph," "Update," "Close Graphs," or "Clear Data" buttons. Finally, an "Export" button opens an interface to quickly export results into a file for later customized processing. The windows with the plotted patterns currently have limited capabilities in rotating patterns, but this will be upgraded in future versions of the software.[10]

Another convenience is that the most-popular beam parameters are automatically displayed underneath the display graphs as soon as the final rotation is completed. At that point, a user is presented with the most relevant parameters: directivity, maximum realized gain (as well as the direction of a specific gain value, if desired, by hovering the mouse over any graph point), the realized efficiency, or the 3- and 10-dB beamwidths—all in just a few mouse clicks for any of the measured frequencies from the list.

While a few other tabs and buttons contain additional convenient features, this review focuses on the most important features. During the radiation pattern measurements, all tabs contain the "X Y Z" buttons, which are instrumental in instructing the software which rotational plane is to be measured. Closely related to that is the need for the user to correctly set a DUT on the table using the small object platform. This can pose the greatest challenge in learning to use the RMS properly and optimally, but can be learned within a few days.

EVALUATING EXAMPLES

To understand the capabilities of the RMS, it was used to characterize a few commercial and prototype designs. The commercial antennas were a 2.45-GHz monopole from TP-Link and a log-periodic HyperLOG 7060 from Aaronia for use from 0.7 to 6.0 GHz.[12]

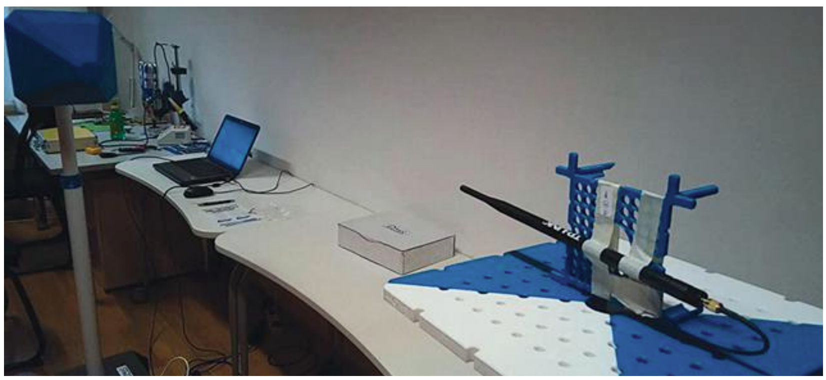
The two prototypes were developed in the laboratory: a 2.45-GHz rectangular microstrip patch antenna and a circularly polarized textile antenna for ISM-band use. These antennas represent a diversity of types for the RMS, with differences in size, polarization, and frequency range. For precision, a VNA-created .s2p Touchstone file was imported to describe the characteristics of the coaxial cable between the transmitter and receiver. The cable was a 5-m-long SMA coaxial cable from Delock *(www.delock.com)*.

The 2.45-GHz monopole was measured first. It was placed on the object platform and the turntable for one measurement plane *(Fig. 4)*. A video of its rotation can be found at *https: //photos.app.goo.gl/pYNLIo0N8MdZVfoy2*. To measure its gain over a wider frequency range (2.3 to 2.5 GHz), it was placed in a vertical orientation and the RMS was set to measure antenna gain from 2.3 to 2.5 GHz. The measurement results are shown in *Fig. 5*, which shows gain of 8.88 dB at 2.45 GHz. This closely matches the antenna's specified gain of 8 dB. Since the RMS receiver simultaneously measures and plots both the horizontal (H) and vertical (V) field component, as well as the total (HV) component, the HV curve is relevant for the total gain.

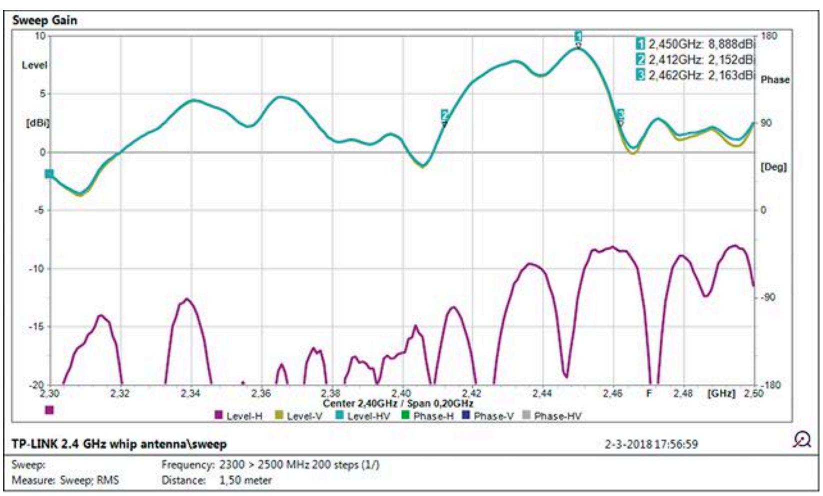
Three markers were placed to show the gain values around the operating frequency: marker 1 at the maximum gain and markers 2 and 3 at the gain of frequencies below (to the left) and above (to the right) of the maximum gain. Their values appear in the upper-right-hand corner of the plot window. In this version of the RMS software, the curves have predefined colors, while in upcoming software upgrades, it's expected that the user will have the option of choosing the color for each curve.[10]

Next, the model HyperLOG 7060 log-periodic antenna from Aaronia[12] was tested. It's designed for use from 700 MHz to 6 GHz *(Fig. 6)*. An auxiliary sticker placed on the top of the antenna helps a user correctly orient the antenna prior to the measurement of each cut-plane, which is essential while performing a 3D pattern scan with the RMS. The arrows and letters on the sticker indicate the necessary orientation of each axis label.

Although users can set their own coordinate system for a given DUT, it's important to set the proper constellation of the axes, so that the orientation of the DUT corresponds to the settings in the measurement software for correct interpretation of the results. The swept antenna gain for this antenna was measured from 700 to 1500 MHz



4. This was the setup for measuring the commercial 8-dB, 2.45-GHz monopole antenna from TP-Link.



5. The measured gain-versus-frequency responses for the commercial 8-dB, 2.45-GHz monopole antenna shows a good agreement with antenna specifications. from TP-Link.

6. This commercial log-periodic antenna was tested on the RMS from 700 MHz to 6 GHz.

(Fig. 7), with gain varying between 5 and 7 dB (6 dB average). These results are about 1-dB higher than the specifications listed on the antenna's data sheet.

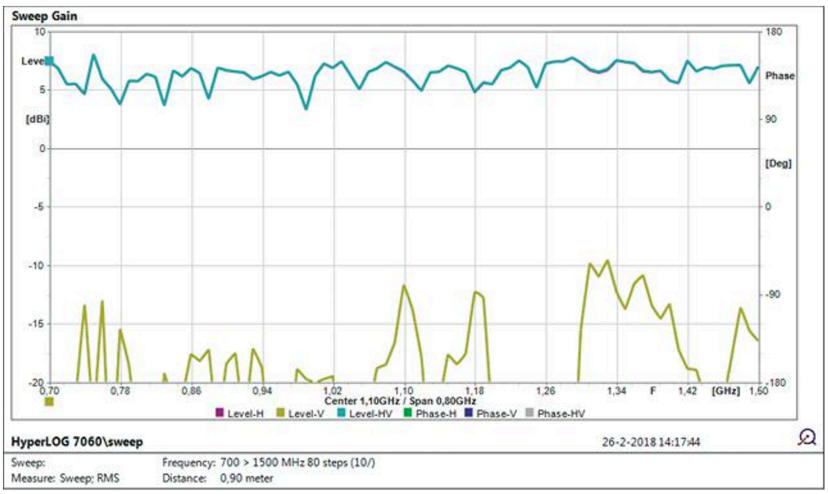
This antenna's radiation pattern was measured at 1500 MHz with patterns obtained in three orthogonal cut-planes *(Fig. 8)*. The yz and xy planes correspond to the two major cut planes, which are the H and V axes, respectively (the x-axis is orthogonal to the antenna top plate, pointing upward, while the y-axis points forward through the tip of the antenna). The third cut-plane, the zx-plane, was measured to complete the procedure before the antenna parameters were evaluated.

Although antenna efficiency is not listed in the product datasheet, these measurements revealed efficiency of 61.8%. The horizontal and vertical major 3-dB beamwidth lobes were measured at 60 and 80 deg., respectively, which are in close agreement with the values that can be derived from the patterns on the datasheet plotted for 1800 MHz, where they also have 3-dB beamwidths of about 60 and 80 deg. wide, respectively.

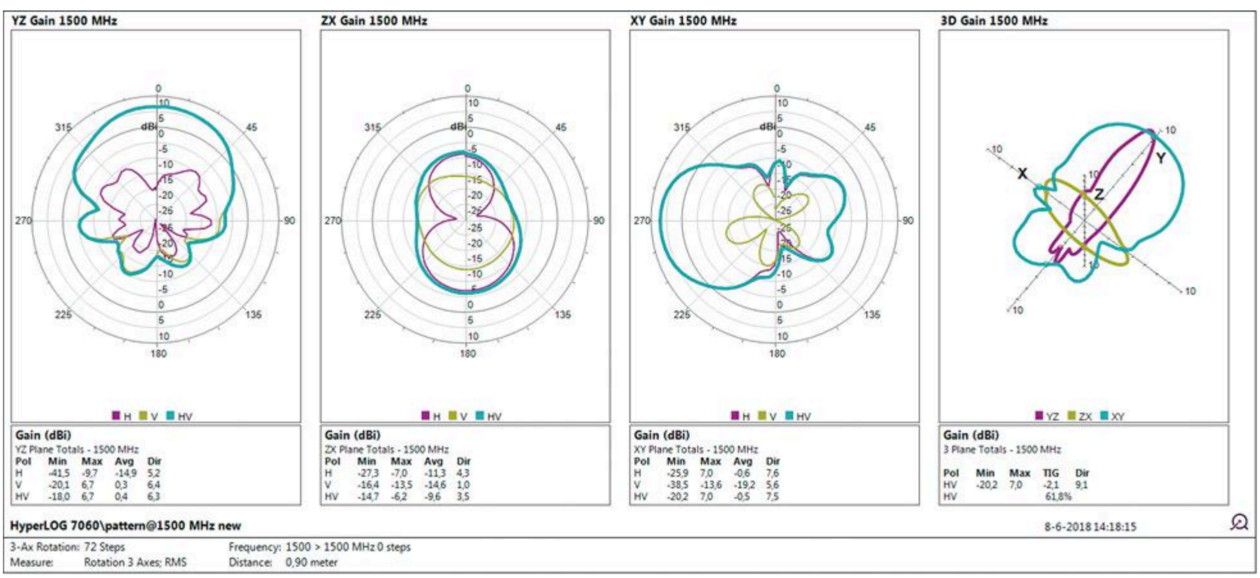
The third test example deals with a homemade, rectangular-patch, microstrip 2.45-GHz WLAN antenna *(Fig. 9)*. A "Top-Right-Front" orientation sticker was placed on the antenna's top surface to help with the correct orientation of the antenna with respect to the RMS rotation sequence and the control software. *Fig. 10* shows the results at three frequencies (2.33, 2.43, and 2.53 GHz), measured simultaneously during a single procedure, which is extremely efficient.

Using this extremely efficient measurement system has been a tremendous benefit in the design and evaluation of a novel, circularly polarized wearable antenna under development *(Fig. 11)* for use within the ISM band.[13] *Fig. 12* shows radiation pattern measurements for this wearable antenna at 2430 MHz.

In addition to total directivity, gain, and efficiency displayed under the 3D gain plot (the first plot from the right), beam statistics are available by clicking on the beam button on the RMS display. Statistics for H and V radiated field components as well as for total field components (computed as the vector sum of the H and V measurements) include



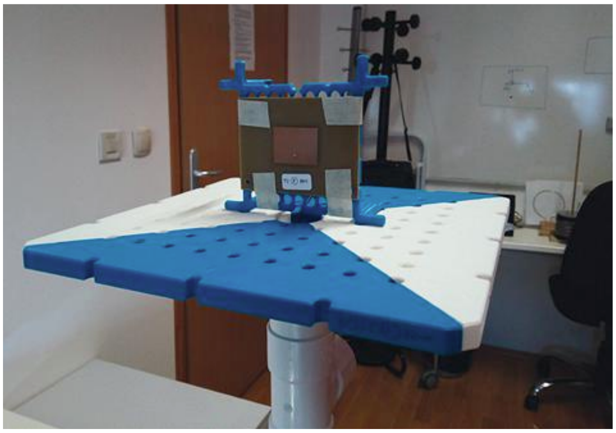
7. These plots show the measured gain from 700 to 1500 for the log-periodic antenna.



8. These radiation patterns were measured for the three cut-planes of the commercial log-periodic antenna at 1500 MHz.

maximum gain level, direction of maximum gain, 3-dB beamwidth, direction of the 3-dB beam center, 10-dB beamwidth, direction of the 10-dB beam center, and front-to-back ratio. Minimum, maximum, and average values for gain and directivity can also be displayed.

Simultaneous measurement of both the H and V antenna radiation field components, especially for a linearly polarized antenna, has the benefit of instantly showing the effect of the cross-polarization in both major cut-planes of interest. However, since H and V radiation field components are measured



9. This test setup on the RMS measured the 2.45-GHz WLAN microstrip patch antenna.

11. This is a prototype wearable sleeve-badge antenna being developed with the help of the RMS tester.

10. These radiation patterns were measured simultaneously at three different frequencies for the 2.45-GHz WLAN microstrip patch antenna.

(Continued on page 87)

JACK BROWNE | Technical Contributor

Block EMI/RFI with Shields and Filters

EMI/RFI shields and filters are both effective in controlling electromagnetic-based interference, although they work in different ways.

1. Lightweight silver/polyamide mesh shielding materials are capable of 50 dB or more shielding. *(Courtesy of AaroniaUSA)*

Noise can start from inside or outside an RF/microwave circuit or system, but it's controllable when adding filters and shields that target electromagnetic interference (EMI) and radio-frequency interference (RFI). Both types of components provide reasonable noise suppression and, with proper planning, add little to the size and cost to a design. But why use one noise-suppressing component rather than another—what's the difference? Some suppliers offer EMI/RFI filters as well as shielding materials and may even recommend using both at the same time. So, when does one noise blocker make more sense than the other?

EM shields are meant to prevent radiated emissions of EM fields propagating beyond a certain point, such as outside an equipment cabinet or enclosure. EM energy that propagates beyond that threshold can act as interference for other equipment (e.g., cell phones and radios), preventing their proper operation. By surrounding an EM field with a conductive barrier, such as a copper or stainless-steel gasket that seals an equipment enclosure, the EM field can be contained, and interference minimized.

When an EM wave strikes an EMI/RFI shield, two things happen. Most of the energy from the EM wave is reflected by the conductive surface of the shield, in different directions, depending on the material qualities and the phase of the WM wave at the point of impact. Some of the energy from the EM wave is also absorbed by the shield—it will be converted into heat energy that, depending on the power levels, may require additional thermal management. Some EMI/RFI shielding materials are formulated to double as shields and thermal-management materials, and can be used as both shields and heat sinks.

An EMI/RFI shield also works in both directions. It can contain EM radiation within an area described by the shielding material, but also prevents EM radiation from sources outside of the shielding protection, such as cell-phone signals and radio broadcast signals, from reaching within the area (and its circuits and components) defined by the shields. In contrast, EMI/RFI filters control EM energy traveling through conductors, such as wires and connectors, and are added to specific points along a circuit with the intention of controlling current flow at different frequencies.

Shielding materials, such as thin sheets of copper or aluminum, require good ground connections for effective EM field containment. EMI/RFI shields may also require openings in the metal sheets to release heat generated in higher-power electronic circuits, especially for shielding materials that absorb rather than reflect EM fields. The sizes of the openings should not relate to the wavelengths of the EM waves that are being contained, otherwise it will minimize the shielding effectiveness (SE) of an EMI/RFI shield.

Several parameters are instrumental when sorting through shielding materials, including material conductivity, thickness, weight, and tooling costs. Increased SE is typically a function of material thickness, with the tradeoff that thicker shielding materials also tend to add weight to a design.

Most shielding-material suppliers provide measured SE values at different frequencies across the usable frequency ranges of their materials. Designers thus can compare the weights and densities of different shielding material solutions with the amount of shielding (typically in dB) that they provide. Additional parameters when choosing an EMI/RFI shielding material include compression force (when using the material as a gasket), volume resistivity, operating temperature range, and elongation with temperature.

In contrast to traditional EMI/RFI shielding materials, such as sheets of copper, aluminum, and stainless steel, newer composite materials include fabrics and meshes that often combine a metal and a polyester material. For example, AaroniaUSA *(www.aaroniausa.com)* offers a variety of commercial EMI/RFI shielding materials, including lightweight silver/polyamide mesh materials capable of 50 dB or more shielding, copper/nickel/polyester materials with 70-dB shielding, and copper/polyester materials with 100-dB shielding *(Fig. 1)*.

Those materials are extremely flexible for ease of installation in product housings and enclosures, but do not lack for SE across RF/microwave frequency ranges. Of course, when formed in sufficiently thin sheets, such as 2 mil thick, traditionally used materials like aluminum can also be made into shields with enough flexibility for most EMI/RFI shielding applications *(Fig. 2)*.

Thin sheets of shielding materials supplied as fabrics or in mesh form are useful not only for shielding around PCBs in an equipment cabinet or enclosure, but are being applied in what might be referred to as "secondary shielding" applications, such as for healthcare protection. Due to the growing reliance of RF energy in wireless radio networks, some healthcare concerns are mounting over the long-term exposure to low levels of RF/microwave radiation. As a result, some of these thin-mesh shielding materials are being formed into window screens—screens that can provide more than 50-dB shielding around a living area while still allowing light to pass through.

FILTERING OUT NOISE

EMI/RFI shields can provide shielding for entire circuits and designs, whereas EMI/RFI filters target specific noise sources, such as high-speed motor drives or power-switching devices. The fast switching of currents in a circuit can cause fundamental- and harmonic-frequency noise later in the circuit, which can degrade the overall performance of the circuit. Insertion of an EMI/RFI filter at the point of noise generation can enable the passage of desired currents while attenuating the unwanted noise. In contrast to shields that target radiated EMI/RFI emissions, EMI/RFI filters are designed to suppress conducted noise. EMI/RFI filters also provide a means of controlling noise from known noise sources, to achieve electromagnetic-compatibility (EMC) standards for EMI/RFI noise for a product in a geographic area.

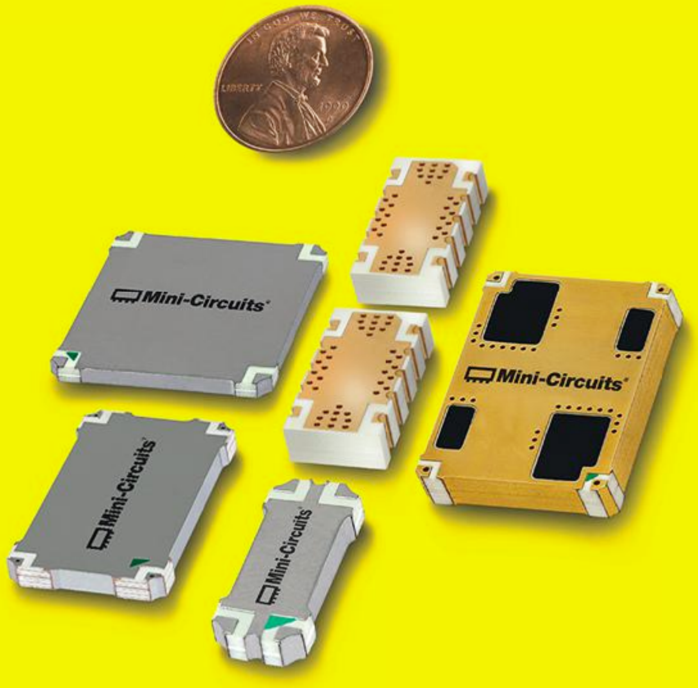
As with shielding materials, when specifying an EMI/RFI filter, several performance parameters can be compared for choosing the best filter for an application. EMI/RFI filters are available from several suppliers for single- and three-phase power sources *(Fig. 3)* and for different current ratings. While EMI/RFI filters may have different maximum voltage ratings, such as 600 V per a commercial standard like Underwriters Laboratories (UL) in the U.S. and the CE mark in Europe, any filter for a given application should be rated for the proper voltage. However, it should be sized according to the maximum current requirements of the application.

The list of suppliers for EMI/RFI shielding materials and filters is long and includes AaroniaUSA, Coilcraft *(www.coilcraft.com)*, CTS Corp. *(www.ctscorp.com)*, EMI Solutions Inc. *(https://4emi.com)*, Leader Tech *(www.leadertechinc.com)*, Mouser Electronics *(www.mouser.com)*, MTE Corp. *(www.mtecorp.com)*, Murata *(www.murata.com)*, Tech-Etch *(www.tech-etch.com)*, TE Connectivity *(www.te.com)*, WaveZero, and Zippertubing *(www.zippertubing.com)*.

2. Traditional shielding materials such as aluminum can be formed in sufficiently thin sheets to achieve a great deal of flexibility. *(Courtesy of Zippertubing)*

3. These EMI/RFI filters screen noise from single-phase power supplies. *(Courtesy of TE Connectivity)*

The cost of EMI/RFI shielding and filtering must be carefully considered when developing a netlist for a circuit or a bill of materials for a new design. Of course, the cost of failure due to EMI or RFI can be prohibitive and can be effectively prevented through proper application of EMI/RFI shields and filters, sometimes using both. For those interesting in learning more about EMI/RFI filters and shields, Murata offers an excellent 13-chapter tutorial course, "Noise Suppression Basic Course," available on the firm's website at *https://www.murata.com/en-us/products/emc/emifil/knowhow/basic/chapter01-p1.* mw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defense electronics

A Special Section to INFORMA'S DESIGN ENGINEERING & SOURCING GROUP SEPTEMBER 2018

Portable Antenna System Supports Battlefield MANETs

JACK BROWNE | Technical Contributor

PERSISTENT SYSTEMS, LLC has developed a portable antenna system for mobile ad hoc networks (MANETs) in the battlefield. The Auto-Tracking Antenna System, a portable ground-to-air antenna based on the firm's Wave Relay MANET technology, is designed to incorporate aircraft and their pilots into a MANET. The easy-to-assemble antenna system supports the mobile battlefield network.

"The Auto-Tracking Antenna System represents a major step towards achieving the vision of a truly networked battlefield," says Herb Rubens, CEO of Persistent Systems. "The tracking antenna rotates to follow air assets, keeping them connected to the MANET. The air platforms orbit over our users on the ground, extending the MANET bubble and keeping soldiers connected to the enterprise. High-throughput, low-latency connectivity empowers the warfighter and decreases the dependence on SATCOM, which both reduces cost and increases network availability."

The Auto-Tracking Antenna System can be assembled and deployed in less than 15 minutes. The portable, lightweight design is completely collapsible, with the main 5-ft.-diameter parabolic dish breaking down into eight individual petals. The large parabolic dish enables video streaming out to distances of 130 miles (over 200 km) while maintaining high throughput and strong signal strength.

The entire system fits into most standard-sized sport utility vehicles (SUVs)

This portable antenna system uses interchangeable antenna feeds for operation at S-, L-, and C-band frequencies. *(Courtesy of Persistent Systems, LLC, www.persistentsystems.com)*

for easy transport and compact storage. It has interchangeable S-, L-, and C-band multiple-input, multiple-output (MIMO) antenna feeds that allow for coverage of all frequency bands handled by radio modules from Persistent Systems. The antenna feeds twist-lock into place for quick and simple installation. An automatic heading system enables the tracking antenna to self-calibrate prior to operation for greater precision and better than 1-deg. pointing accuracy.

"Our customers require a system that is simple to put together, turn on, and works," says Louis Sutherland, vice president of

(Continued on page 64)

Congress Passes $716 Billion Defense Bill

PRESIDENT DONALD TRUMP'S call for a bigger, stronger military was met by a recent Senate vote of 87 to 10 in favor of the John S. McCain National Defense Authorization Act (NDAA). The $716 billion defense policy bill, which has passed annually for more than 50 years, authorizes U.S. military spending, but it's also used for other policy matters. After having been passed by the House of Representatives and the Senate, the bill is sent to the president, who is expected to sign it into law.

The fiscal 2019 NDAA was named to honor McCain, the Armed Services Committee chairman, war hero, long-time senator, and former Republican presidential nominee, who recently lost his battle with brain cancer. The bill imposes some controls on government contracts with Chinese companies ZTE Corp. and Huawei Technologies Co. Ltd. because of national security concerns.

However, the restrictions on the Chinese companies are weaker than in earlier versions of the bill, which angered some lawmakers. Those lawmakers wanted to reinstate tough sanctions on ZTE to punish the company for illegally shipping products to Iran and North Korea, nations hostile to the U.S. de

The Expanding Role of the Essential Radar

JACK BROWNE | Technical Contributor

RADAR HAS BEEN part of the electronic battlefield for some time, detecting unseen troops in the distance during WWII. Those early, vacuum-tube-powered radar systems have come a long way from the 1940s. Today's lighter, transistorized radar systems warn aircraft pilots about potential threats or are transported across different battlefields to provide an invaluable awareness of enemy troops. Few present-day military personnel would like their chances in any conflict without some kind of radar system in front of them.

That protection from radar is not just for the battlefield, though. All who rely on the weather for their livelihoods also rely on a radar system of some form for early warnings of significant storm fronts and other weather patterns. Especially in recent years, as weather patterns have seemingly grown more severe and violent, warnings of hurricanes and tornadoes have become essential to the health and well-beings of millions of civilians.

The NOAA's National Weather Service manages the country's thousands of weather radar systems, far more than the typically larger military systems. Weather radars are mostly pulse Doppler systems that detect precipitation in the distance, to provide warning of significant storm fronts. With the uncertainty of weather, such radar systems can be life-saving.

Life-saving will be the role of many radar systems in the automotive field, too, as civilians purchase vehicles with the latest advanced driver-assistance systems (ADAS) electronic equipment. Many newer vehicles include ADAS hardware with front-looking cameras and front- and rear-looking mmWave collision-avoidance radar systems to provide safety functions based on data coming from the vehicle's many sensors.

Companies like Texas Instruments have made tremendous efforts at developing and integrating different technologies with radar into ADAS vehicle solutions, including LiDAR, optical cameras, and ultrasound sensors. Most drivers are probably unaware of the amount of ADAS sensors that protect an autonomous vehicle from front to rear. Many older drivers may poke fun at this use of sensor tech to create a "self-driving" car. But those who have been cut off by drivers running red lights or passed on narrow roads by reckless drivers may welcome the "sanity" of autonomous vehicles and their ADAS protection. de

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CMA-84+	DC-7	24	21	38	5.5	5	8.95
CMA-62+	0.01-6	15	19	33	5	5	7.45
CMA-63+	0.01-6	20	18	32	4	5	7.45
CMA-545+	0.05-6	15	20	37	1	3	7.45
CMA-5043+	0.05-4	18	20	33	0.8	5	7.45
CMA-545G1+	0.4-2.2	32	23	36	0.9	5	7.95
CMA-162LN+	0.7-1.6	23	19	30	0.5	4	7.45
CMA-252LN+	1.5-2.5	17	18	30	1	4	7.45

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Portable Antenna System Supports Battlefield MANETs

(Continued from page 61)

business development at Persistent Systems. "They want to extend the Wave Relay MANET out to aircraft and achieve high data rates and reliable HD video transmission. The Auto-Tracking Antenna System truly delivers." The antenna is IP67-rated and built to endure harsh environments and weather, so it can be setup and left out for as long as needed for the mission at hand. de

Energy Harvesting Extends UAV Flight Times

SOLAR SOARING, an energy-harvesting technology developed by the U.S. Naval Research Laboratory (NRL), enables unmanned aerial vehicles (UAVs) to handle longer flight times without heavier batteries. By drawing power from the sun and the atmosphere, UAVs with Solar-Soaring technology can fly for more than 12 hours without carrying extra weight in batteries.

"One of the common complaints that we hear across industry and the warfighters is that they want aircraft to fly longer," says Dr. Dan Edwards, senior aerospace engineer in NRL's Tactical Electronic Warfare Division. "One great way to do this is to capture atmospheric wind energy or solar energy to extend the endurance."

Edwards explains that by using thermals in the manner of a bird in flight, a UAV can use the heated air to gain altitude and save energy: "Sunlight heats up the surface of the Earth, which in turn heats the lowest layer of air. That warm air eventually bubbles up as a rising air mass called a thermal, which the airplane can use to gain altitude." Solar cells on the UAV are also used as energy sources to recharge the UAV's onboard battery cells.

Improvements in solar-cell technology have made the energy sources efficient enough to justify adding their weight to a UAV. "For a long time, even though there has been solar aircraft since the 1990s, the efficiency of the solar cells wasn't high enough to pay the mass penalty, meaning you weren't getting enough energy to justify the additional mass," says Phil Jenkins, head of the Photovoltaics Section in NRL's Electronics Science & Technology Division. "But over the last 10 years, that has really changed. The cells have gotten more efficient and lighter."

This combination of technologies, which NRL refers to as "Solar Soaring," is enabling long-distance surveillance missions for UAVs and many other longer-duration applications once considered not possible because of limited battery life. "In the case of Solar-Soaring, we're demonstrating the techniques to fly aircraft with a higher endurance," says Edwards. "These techniques are portable to a lot of the programs of record, like the small-size Raven or potentially the larger Predator, so it's a pretty broad application space." ■

Solar Soaring is a combination of techniques applied by the NRL to extend the flight times of UAVs. *(Courtesy of the Naval Research Laboratory, www.nrl.navy.mil)*

L3 Technologies Realigns Organization

MAJOR DEFENSE CONTRACTOR

L3 Technologies *(www.l3t.com)* has realigned its business segments for improved integration of capabilities, forming the new Intelligence, Surveillance & Reconnaissance (ISR) Systems segment from the formerly separate Sensor Systems division and Aerospace Systems and Sensor Systems division. In addition to ISR technologies, this branch of the contractor will focus on signal-intelligence (SIGINT) solutions.

The ISR Systems part of the company, which is expected to post 2018 sales of $4.7 billion, will be led by Jeffrey A. Miller, corporate senior vice-president and president of Sensor Systems. Once this business transition is complete, Mark R. Von Schwarz, president of Aerospace Systems, will retire from the company. This transition will not affect L3's Electronic Systems and Communication Systems business segments. ■

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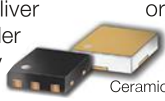

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FLIR Receives Delivery Order for Biodetector

FLIR SYSTEMS *(www.flir.com)* has received a delivery order for FLIR IBAC 2 biological agent detector systems to support the U.S. Forces Korea (USFK). The delivery order is under a 10-year, indefinite-delivery/indefinite-quantity (IDIQ) contract in support of the Joint USFK Portal and Integrated Threat Recognition (JUPITR) program led by the Joint Program Executive Office for Chemical and Biological Defense (JPEO-CBD). Deliveries for the order, which is valued at $4 million, are already scheduled to begin.

The FLIR IBAC 2 real-time air monitor *(see figure)* is designed to warn users in 60 seconds or less when an airborne biothreat has been detected, such as spore, viral, cellular, and protein toxins. It collects, preserves, and transmits data about the detected toxin to command and control centers. With more than 1,500 operating units worldwide, the FLIR IBAC 2 is the most widely deployed biological trigger on the market today.

One of the world's most widely deployed airborne biodetectors now supports U.S. forces in Korea. *(Courtesy of FLIR Systems)*

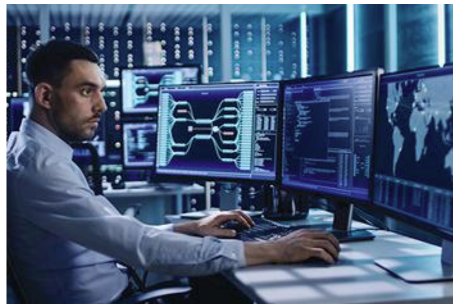
"We are proud to support our U.S. militaries with reliable products that ensure accurate analysis of biological threats for safe and fast response," says David Ray, president of the Government and Defense Business Unit at FLIR. "This order supports our mission to provide solutions that save lives and livelihoods, equipping U.S. soldiers with technology that gathers, interprets, and communicates actionable information, reducing decision time in support of our national security." ■

DARPA Eyes BAE to Detect Cyber Threats

MODERN COMMUNICATIONS AND computer technologies bring with them great convenience, but at the risk of cyber threats. To help protect large networks against cyber threats, the Defense Advanced Research Projects Agency (DARPA) has selected BAE Systems to develop data-driven, cyber-hunting tools that detect and analyze such threats. BAE Systems intends to automatically detect and overcome aggressive cyber threats by combining advanced machine learning with cyber-attack modeling. The contract for Phases 1, 2, and 3 of the program is valued at approximately $5.2 million.

DARPA's Cyber-Hunting at Scale (CHASE) program has been instituted to develop, demonstrate, and evaluate new automated cyber-defense tools for use across large enterprise networks. Current cyber-protection tools typically lack the scale necessary to provide full protection for large-sized enterprise networks. By coming up with a guard against cyber attacks, data and resource security is expected to improve across commercial networks. The CHASE-driven technology is also thought to be able to protect military and government data networks.

"Today, advanced cyber attacks within many enterprise networks go entirely unnoticed among an overwhelming amount of network data, or they require intensive manual analysis by expert teams," says Anne Taylor, product line director for the Cyber Technology group at BAE Systems. "Our technology aims to alleviate resource constraints to actively hunt for cyber threats that evade security measures, enhancing the collective cyber defense of these networks." BAE Systems' work for the program builds on previous cyber-security efforts for the Army, Navy, and DARPA. The work will be performed in Arlington, Va. ■



BAE Systems is developing a defense against enterprise network cyberattacks as part of the CHASE program. *(Courtesy of BAE Systems)*

JACK BROWNE | Technical Contributor

Radar Now Travels with the Troops

Various radars, including weather radars, are becoming more portable thanks to solid-state power, which enables systems to be designed with smaller footprints.

RADAR HAS been a defensive electronic weapon for some time, usually served by large, heavy systems, although the technology is being fit into smaller and lighter packages. Radar transmitters once relied on large vacuum tubes along with their associated full-sized power supplies to power their pulses. The large sizes and weights of these components limited the portability of radar systems in the battlefield.

However, the tide is steadily changing with increased use of solid-state semiconductor technologies such as gallium-nitride (GaN) transistors on silicon (Si) and silicon-carbide (SiC) substrates. As solid-state device technologies gain in power and frequency, high radar output power can be reached with much smaller devices and system packages, making true portability possible. The same radar system that provides a warning from a distance can sit alongside the troops.

One of the larger and "more visible" of these portable radar systems is the AN/TPS-78, a transistorized S-band air-surveillance radar system from Northrop Grumman. The Air Force uses the Doppler radar system for long-range detection, even with the system's capabilities of rapid assembly and disassembly. It can detect high- and low-altitude targets even when they are surrounded by heavy ground clutter and sea clutter.

By operating at S-band frequencies, the system can work with smaller antennas and electronics than at lower frequencies (longer wavelengths). Along with the antenna, transmit electronics, and receive electronics, the full system can be housed in a compact ISO shelter that's then transported in a single C-130 aircraft or helicopter and deployed in less than 30 min. It can also be deployed by means of a single all-wheel-drive vehicle *(Fig. 1)*.

1. The AN/TPS-78 is a transistorized, transportable S-band air-surveillance radar system that uses Doppler processing for long-range detection. *(Courtesy of Northrop-Grumman)*

The same contractor supplies the Highly Adaptable Multi-Mission Radar (HAMMR), which is a derivative of the Ground Based Fighter Radar (GBFR) developed for use by troops on the move. The HAMMR system is a lightweight ground configuration of the lightweight active electronically scanned array (AESA) antenna technology used in airborne fighter aircraft (and in a growing number of autonomous, self-driving commercial vehicles). An AESA antenna provides a full 360-deg. coverage on either an airborne or ground-based vehicle with rapid transport capability.

The HAMMR system is optimized to detect both fixed- and rotary-wing aircraft, cruise missiles, and unmanned aerial vehicles (UAVs) in a relatively small footprint that can serve civil as well as military applications. The modular system, which is adaptable to many different vehicle types for ease of transport, can deliver real-time situational awareness at large public gatherings in addition to providing a protective RF shield around troops in the field.

EARLY PORTABILITY

One of the first man-portable ground surveillance radar systems, the Vietnam War era AN/PPS-5 (dating from 1966), is still one of the most widely used ground surveillance radar systems in the world. Commonly known as a man-portable surveillance and target acquisition radar (MSTAR) system, the lightweight Doppler radar is designed to acquire targets at night and in bad weather. It operates at I- and J-band frequencies and can detect individuals to 5,468 yds (5 km) and groups of soldiers or small vehicles to 10,936 yds (10 km).

The radar system transmits at a pulse repetition frequency (PRF) of 4 kHz and receives reflected returns across 50 channels. It features moving-target-indication (MTI) processing to highlight activity in the field, and the MTI functionality can be turned off to focus on fixed targets.

Designed to be an "assemble it in the field" radar, the system can be made to appear and disappear as needed. It can be bundled into two or three packages, each of which would be carried by a soldier. The radar operates from 8.0 to 8.9 GHz in I-band and 16.0 to 16.5 GHz in J-band, with magnetron-based amplification in earlier systems. Upgrades of MSTAR systems are shrinking with time, with solid-state devices replacing vacuum tubes and their power supplies for transmit amplification.

2. The AN/TPS-75 is a transportable radar system with long-range capabilities used by the Air Force.

3. The FLIR Ranger R1 is a ground-based perimeter surveillance and tracking radar system. *(Courtesy of FLIR Systems)*

4. The E7000XD Doppler weather radar embraces solid-state technology and advanced mechanical design for small size and portability. *(Courtesy of EWR Weather Radar)*

With its considerable history, AN/PPC-5 MSTAR systems have been viewed by military-system specifiers as "legacy" equipment, with improvements made through upgrades. One of those upgrades was in the form of the AN/PPS-5B man-portable radar system, which boosted the personnel detection range to more than 12 miles for Army in-field users. Another, the AN-PPC-5C, was a low-power variant of the radar system with detection range extended to nearly 15 miles. The British army is and has been a regular user of AN/PPS-5 MSTAR radar systems, continuing to upgrade older systems rather than replace them with new systems.

The Air Force has had its own favorite transportable radar system, the AN/TPS-75 radar system *(Fig. 2)*. It can cover a 240-nautical-mile area and providing real-time long-range data while communicating via radio, satellite, or microwave link. Data from this mobile ground radar system can be combined with data from other radar systems for a fully integrated battlefield picture. The system is transportable via plane, helicopter, or truck.

GROWING SMALLER

Newer radar systems designs are taking advantage of the power and efficiency of solid-state transmitters to achieve portability without sacrificing performance. By leveraging device technologies such as SiC and GaN, transistor amplifiers can provide the peak output powers for long-distance target detection with high resolution while running on battery power.

As an example, the B202 Mk 2 radar from Blighter Surveillance Systems Ltd. is a compact radar unit weighing only about 35 lbs. and measuring a mere (approx..) 18.7 × 17.4 × 6.2 in. (474 × 442 × 157 mm). Designed to operate about 12 hours on 12-V vehicle batteries, the medium-range ground surveillance radar uses electronic scanning (e-scan) methods to detect moving vehicles and personnel via simultaneous Doppler and frequency-modulated continuous-wave (FMCW) scans.

A wide vertical elevation beam and passive electronically scanned array (PESA) technology enables the B202 Mk 2 system to detect targets that are close to the radar as well as at some distance. In fact, using only 1-W transmit power at Ku-band frequencies, the ground surveillance radar system can detect moving targets at distances to 8 km. The wide beam enables the system to scan uneven terrain without tilting the radar or its antennas.

Smaller often means less range, or more systems needed for a certain area of coverage, and such is the case with the FLIR Ranger R1 ground-based perimeter surveillance and tracking radar system from FLIR Systems *(Fig. 3)*. It's small but can accurately detect personnel and vehicles as far as 700 m away. It scans 360 deg. every second, covering areas as large as 1.5 km^2 (0.6 miles^2). When more coverage is needed, more units are added, such as a mid-range FLIR Ranger R2 radar, and networked to create an overlapping security array.

CHECKING WEATHER

Radar technology is benefitting both military and commercial users when it comes to keeping track of the weather. Companies such as EWR Weather Radar invest in the latest technologies in support of smaller, more portable radar systems, as well as take part as an industry partner of the collaborative adaptive sensing of the atmosphere (CASA).

The firm has succeeded in developing small, lightweight radar systems such as the E7000XD Doppler weather radar *(Fig. 4)*. The E7000XD is extremely portable and compact due to mechanical and solid-state design *(Fig. 5)*. Rather than vacuum-tube transmitters, it uses solid-state transmitters with pulse compression techniques to send out longer pulses at lower power levels to illuminate a target.

The company also supplies a portable, non-Doppler weather radar, the E600 Tactical Weather Radar. It provides the capability to determine the location of precipitation cells, the intensity of the coming precipitation, the direction of the weather cell movements, and the speed of the weather cells. Originally developed for use in harsh military environments, the system has become widely embraced by agricultural and industrial users as well.

The latest addition to the company's 700 series of portable weather radars is the model E750. Its rugged design is well-suited for mobile, temporary, or tactical applications, using dual polarization and a narrow beam width for high resolution in challenging terrain. It can also be used as part of an in-field network of radar systems in which multiple pulses are used to fill gaps in the detection. It employs a solid-state transmitter for portability without lack of resolution, operating at X-band frequencies. The E750 includes a complete suite of meteorological products, including all Vaisala/Sigmet IRIS and EWR/Nexrad Level III products.

AESA antennas are steering many radar designs into smaller packages. In addition to the adoption of solid-state electronics, AESA technology is instrumental in the miniaturization of modern radar systems. Not only does electronic beamsteering shrink the size of the radar antennas, it also eliminates moving parts in older antennas and increases reliability.

Widespread adoption of AESA technology in military radar systems is an ambitious goal of the Spectrum Efficient National Surveillance Radar (SENSR) cross-agency program. Here, industry partners are working closely with the military to consolidate and modernize this country's aging (and oversized) radar systems.

5. Portable and transportable, the E7000XD Doppler weather radar can be managed by small crews. *(Courtesy of EWR Weather Radar)*

One of those industry partners is Raytheon, which is working to replace over 600 legacy ground-based radar systems with more versatile, multiple-mission radars capable of supporting air traffic control, air defense and surveillance, border protection, and weather forecasting. Such upgrades are being performed with the simultaneous goals of freeing frequency bandwidth for other applications, such as high-speed communications. Adoption of newer technologies such as AESA not only shrinks the size of the radar systems, but also improves performance. In the case of weather forecasting, severe storms can be identified in seconds rather than minutes, benefiting both civilian and military users. de

JACK BROWNE | Technical Contributor

HIGH-RELIABILITY RF CABLES: Not Just for the Military!

RF/microwave cable assemblies, critical components in many systems, are essential for providing high-frequency signal interconnections—with no room for failure.

COAXIAL-CABLE assemblies are indispensable, signal-routing components in many RF/microwave systems, although they are often specified and added as an afterthought. For military applications, the durability of high-reliability (hi-rel) cables can mean the difference between life and death. In deep-space missions, such as for communications or surveillance satellites, cable failure is not an option. But military and aerospace are no longer the only application areas for hi-rel cables and connectors. More commercial and industrial users come to depend on long operating lifetimes from cables installed in such applications as communications systems and manufacturing equipment.

Choosing a hi-rel RF/microwave cable assembly may be essential to the completion of a system design, whether it's for commercial, industrial, or military applications. But it's not just a simple matter of looking up a few specifications and making a cable fit a set of requirements. It's important to understand how reliability is defined for different applications. Once defined, one must figure out how to achieve reliability with different types of RF/microwave cable assemblies, and that it stands the test of time and whatever an application can throw at it.

Coaxial RF/microwave cables *(Fig. 1)* have many uses in high-frequency applications. They range from "set-and-forget" interconnections in commercial or military communications equipment to applications in test systems that endure constant changes in cable positions and connections.

WHAT CONSTITUTES RELIABILITY?

Reliability is often defined in terms of product failures and lifetimes in the shape of a "bath-tub" curve as a function of time, with three different failure rates over a product's lifetime. The first is a period of decreasing failures, followed by a period of constant failures, with a third period of increasing failures during the wear-out stage of the product. High-reliability cables are designed and assembled for a minimum number of failures along the bath-tub curve and lifetime of the cable assemblies, so that subsequent system failures do not result from the failing interconnects.

Reliability refers to receiving the expected levels of performance from a cable assembly every time it's used, without degradation or loss in performance for the full lifetime of the application. Failure of a cable assembly can be expected when it exceeds the mechanical or electrical or environmental limits set for it, such as forming a flexible cable into a bend radius smaller than the recommended minimum. Another failure case would involve applying RF/microwave power levels higher than the rated maximum or operating the cable assembly at temperatures exceeding the specified operating temperature range.

1. Low-loss cable assemblies such as these are often used for interconnections in high-reliability systems.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The definition of reliability becomes more complex when limits are set for performance degradation that's acceptable over time. The performance of a coaxial cable assembly can be described by many different parameters, such as insertion loss, VSWR, and phase stability.

The reliability of a cable assembly may be linked to maintaining tight control on just one or two performance parameters or on a full set of parameters. The required tolerances for what describes a hi-rel cable assembly can differ from one application to another. For example, a variation of ±2 dB in insertion loss over certain temperature and frequency ranges may constitute excellent reliability for a system requiring ±3-dB insertion-loss stability, but may result in the failure of a system requiring ±0.5 dB insertion-loss stability. The reliability of a coaxial cable assembly is very much a function of an application and its operating environment.

MILITARY SPECIFICATIONS

The reliability of cables and connectors for military and aerospace applications is guided by many different military standards, such as MIL-DTL-17 coaxial cables and MIL-PRF-39012 RF coaxial connectors. MIL-DTL-17 covers many different applications, operating environments, and sets of performance specifications for different coaxial cables, with much attention paid to the center conductor dimensions and the materials chosen for the center conductor (e.g., tin, silver-coated copper, and copper-clad steel conductors).

Coaxial connectors for military and aerospace applications must often meet the standards contained within MIL-PRF-39012, which is used by all departments and agencies of the U. S. Department of Defense (DoD). It covers general requirements and test methods for characterizing RF connectors used with flexible and semirigid coaxial cables for military applications, and applies to many types of connectors, including field-serviceable and non-field-serviceable connectors.

The reliability of these connectors is defined by critical interface materials and finishes, such as PTFE dielectric material, silver-plating thickness on brass-bodied connectors, passivation for steel-bodied connectors, and the thickness of gold plating on the connector center contacts. MIL-PRF-39012 even details the use of recycled, recovered, or environmentally friendly materials in the manufacture of military-grade connectors whenever possible and visual means of checking when connector pairs are properly mated.

EXTENDING BEYOND MILSPACE

Applications for high-rel cable assemblies include interconnections not just in military systems and subsystems, but in commercial, industrial, and a growing number of medical electronic systems relying on electromagnetic (EM) energy for treatment. These systems may have limited access, such as on a battlefield or in space, and the cost of failure (whether due to a cable or any other component) is prohibitive.

In many cases, reliability is important for maintaining service, such as in a wireless cellular communications network. The lack of reliability could lead to a costly loss of service in a high-frequency RF/microwave network. Hi-rel cable assemblies are often used in applications in which performance degradation is unacceptable, such as in test-and-measurement facilities and in automatic-test-equipment (ATE) systems. In these cases, the accuracy and reliability of the system's measurements are part of the quality assurance used by a high-frequency component manufacturer to validate the performance of products before shipping them.

For such applications as satellites or other space-based equipment, cable assemblies can be specified according to what are known as "S-level" requirements, characterized by extensive environmental mechanical and electrical testing to ensure the high reliability needed in space-based applications. S-level reliability is considered the highest level of reliability possible for a tested product. It's usually achieved by performing life-testing of a component, such as a coaxial-cable assembly, in an environmental chamber. Here, the component can be operated and tested over the full range of environmental conditions, such as the full temperature range or the full shock and vibration range.

The level of reliability provided by S-level cable assemblies may be unmatched by any other military standard, but it's not without a price for the extensive processes and testing required to produce such failure-free cables. The price tag for such high reliability is considerably higher than for standard-grade cables, although when compared to the cost of failure in a space-based application, the investment in S-level reliability is worth it. This leads to the question: What makes one cable assembly more reliable than another? It's due to several factors, including product design, choice of materials, the processes applied, and the level of process control maintained on those processes.

WITHSTANDING THE CONDITIONS

As noted earlier, a cable assembly's application and operating environment can have a great impact on its reliability, requiring that an RF cable be designed specifically for optimum long-term reliability. For example, a cable assembly lacking proper EMI shielding can provide a pathway to interference in a system with high sensitivity, such as a surveillance or radar receiver.

Recent applications for RF cable assemblies, e.g., surveillance unmanned aerial vehicles (UAVs), have demanding requirements for environmental specifications, such as temperature, shock, and vibration. When equipped with standard-grade cable assemblies rather than hi-rel cables, these assemblies are more likely to fail. At the same time, to ease the load requirements on a UAV, cable

assemblies for UAV applications should be as compact and light in weight as possible, while still achieving the durability required for hard landings and takeoffs.

Depending on the application, such as a cable assembly that may require constant movement, the assembly must be designed specifically for the needs of the application and with proper conductor, shield, and jacket materials. High-quality materials, including high-conductivity metals and low-loss dielectric materials, can deliver excellent performance in a cable assembly, but in themselves will not ensure high reliability.

The connectors, cable, and cable-connector interfaces must be well designed to maintain high reliability under harsh operating conditions. Moreover, the manufacturing processes that assemble those different materials and components into a cable assembly must be well controlled and repeatable. On top of that, when specialty materials are used in producing a cable assembly for an application, the manufacturer must have tight control over the supply chain to maintain adequate inventory of the required materials.

TEST PHASE

While testing is widely referred to as a "non-value-added" part of component manufacturing, testing and measurement results are critical for improving product reliability. A manufacturer will not know how reliable its product is if measurements are not being made. Furthermore, manufacturers of high-rel cable assemblies are frequently working to improve reliability. This entails new ideas, new processes, and experiments. The testing is critical and will ultimately help determine if the new processes are yielding benefits or inadvertently causing problems.

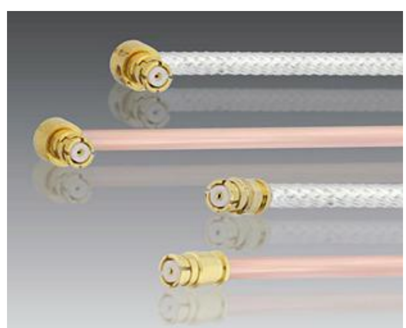
Typical measurements include insertion loss, return loss (VSWR), phase stability with flexure and over temperature, and thermal cycling performed on ATE systems built around a microwave vector network analyzer (VNA) with suitable frequency range for the cable assemblies under test. Analysis of the measured data reveals a great deal about the reliability of the cable assemblies. And a review of the historical test data provides insights into the efficiency and effectiveness of the manufacturing process, especially when attempting to create a process that provides the highest reliability possible for all combinations of RF/microwave coaxial cables and connectors. These include semirigid and flexible cables and TNC, BNC, Type N, SMA, and BMA connectors *(Fig. 2)*.

2. BMA connectors have long been used for high reliability cable assembly applications where blind mating and RF performance are critical.

Regular measurements and analysis of test results are critical parts of any process for building components with ever-improving reliability, but they are also essential contributors to the product design process. The analyses combine together with three-dimensional (3D) electromagnetic (EM) simulation software to develop new connector and cable configurations with higher reliability and improve performance at higher frequencies, as commercial, industrial, and military cable and connector specifiers seek ever-lower interconnection losses at signal frequencies reaching into the millimeter-wave frequency range. The use of modern computer simulation software tools provides experimental looks at new connector, cable, and interface configurations under any number of operating conditions, as might be needed for high-reliability applications. Access to high-performance test systems and reliable test data helps to validate and refine those connectors and cable models.

Growing dependability on electronic devices at RF, microwave, and even millimeter-wave frequencies puts the onus on manufacturers of high-frequency components such as RF/microwave cable assemblies to deliver products with acceptable reliability, and this applies to many different environments and operating conditions. While the breakdown of a wireless base station due component failure may lead to lack of cellular communications service for customers in the area around that base station for some time, it can be reached and eventually repaired with a replacement part—even if it happens to be a coaxial-cable assembly. Using a cable assembly with proven track record for reliability in the base station will minimize the need for a repair due to cable failure.

In contrast, should a cable assembly in an orbiting satellite fail, the repair is not quite so routine (or inexpensive). Because of the difficulty and cost of repairing the satellite, it's an application that truly calls for the state of the art in reliability for an RF/microwave coaxial cable assembly—cables designed, manufactured, and tested to S-level qualification. These are cable assemblies for applications where failure is not an option *(Fig. 3)*, and where the added cost of this cable rating and qualification is insignificant compared to the cost of a cable failure.



3. Semirigid cable assemblies with SMP connectors are often used for high-reliability applications requiring weight reduction and high RF isolation.

Two-Way, 90-deg. Power Splitter Handles 50 W from 8 to 12 GHz

Model QCH-123+ is a two-way, 90-deg. power splitter that handles power levels to 50 W from 8 to 12 GHz. Insertion loss is no more than 0.40 dB and typically only 0.25 dB across the full frequency range. Isolation between ports is at least 18 dB and typically 23 dB across the full frequency range. Well-suited for use with balanced amplifiers and antenna feeds in commercial and military applications, it maintains typical amplitude unbalance of ±0.35 dB and typical phase unbalance of ±6 deg. The compact splitter measures only 0.2 × 0.25 × 0.069 in. with wraparound terminations for good solderability and easy visual inspection.

MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-003; (718) 934-4500, www.minicircuits.com

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Dual Directional Coupler Handles 250 W to 1 GHz

Model C10561 is a "mismatch-tolerant" 50-dB dual directional coupler designed for use from 20 to 1000 MHz. The compact, surface-mount component is conservatively rated at 250 W CW power. It maintains very low heat dissipation because insertion loss is less than 0.1 dB. The dual directional coupler provides better than 25-dB directivity.

WERLATONE INC., 17 Jon Barrett Rd., Patterson, NY 12563; (845) 278-2220, FAX: (845) 278-3440, E-mail: sales@werlatone.com, www.werlatone.com

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GaN-on-SiC Transistor Powers IFF Systems

The IGN1011L120 is a GaN-on-SiC high-electron-mobility transistor (HEMT) designed for Class AB linear operation in identify-friend-or-foe (IFF) avionic applications. It delivers more than 120 W peak pulsed output power from 1030 to 1090 MHz with +50 V dc bias and 6.4% duty factor (32 μs on and 18 μs off). The rugged power transistor achieves 17-dB power gain with drain efficiency of 75% under Mode S pulsed conditions (6.4% duty cycle). The gold-metallized, depletion-mode device is supplied in a metal-based package sealed with a ceramic-epoxy lid.

INTEGRA TECHNOLOGIES INC., 321 Coral Circle, El Segundo, CA 90245-4620; (310) 606-0855, FAX: (310) 606-0865, www.integratech.com

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Solderless Connectors Support High-Speed Networks

These solderless vertical-launch connectors are well-suited for high-speed networking, high-speed computing, and telecommunications applications to 50 GHz with VSWRs as low as 1.30:1. The connector launches feature a reusable clamp attachment that works with microstrip or stripline transmission-line technologies. Both male and female versions are available, covering SMA, 2.4-mm, and 2.92-mm connector interfaces. All models provide solderless installation. The removable vertical launches are equipped with a stainless-steel outer conductor, gold-plated beryllium-copper center contact, and polyetherimide (PEI) insulators.

PASTERNACK ENTERPRISES, 17802 Fitch, Irvine, CA 92614; (866)-PASTERNACK, (866) 727-8376, (949) 261-1920; E-mail: sales@pasternack.com, www.pasternack.com

SCRUTINIZE YOUR Eutectic Die-Attachment Process

The latest gallium-nitride (GaN) and gallium-arsenide (GaAs) die parts can deliver higher power levels than previous-generation solutions. When working with such devices, precision and consistency must be maintained throughout the die-attachment and assembly process. But many challenges are associated with the die-attachment process, such as contamination and the quality of pickup collets. In the tech brief, "Eutectic Die-Attach of GaN and GaAs MMICs," SemiGen examines key factors that help determine if a eutectic die-attachment process is acceptable.

GaAs and GaN technology are essential for today's applications. While GaAs and GaN die attachment can be performed using various methods, eutectic die attachment is one of the preferred approaches. The eutectic die-attachment process allows for a very reliable mechanical connection and an optimized thermal and electrical connection. These qualities are essential for the power and heat produced by the latest GaN power amplifiers (PAs) and maximize grounding for electrical performance.

SemiGen,
54 Grenier Field Rd.,
Londonderry, NH 03053;
(603) 624-8311;
www.semigen.net

Next, the tech brief explains some key die-attachment factors, leading off with a discussion on thermal considerations. The document notes the importance of having a matching coefficient of thermal expansion (CTE) of the die, solder, and substrate, as that helps to prevent mechanical damage during thermal cycling.

The scrubbing technique, which is commonly used with eutectic die attachment, is also touched upon. This process involves the die being held with some force by a pickup collet. The bonder performs its "scrubbing" action while the solder is in its liquid state. Scrubbing can help to ensure a conformal solder layer and greater solder adhesion between the die base layer and the substrate/spreader. Key factors for a successful scrub include head force, scrub direction and path, scrub cycles, and scrub time, as well as the point in the reflow process where the scrub is performed.

The document examines the pitfalls of eutectic die attachment, such as die contamination. In addition, the plating of the die and die carriers must maintain integrity to ensure adequate wetting and adhesion quality. The tech brief concludes with a discussion on pickup collets.

SETTLE IN YOUR MIND How to Measure Settling Time

FREQUENCY HOPPING IS a method that's commonly utilized to help avoid interference and increase security. Since data throughput is a key parameter for wireless systems, an important metric is the time needed for a frequency change or hop. Frequency-settling-time measurements are therefore essential for frequency synthesizers. In the application note, "Frequency and Phase settling time measurements on PLL circuits," Rohde & Schwarz provides an overview of these types of measurements, followed by an explanation of how such measurements can be performed with modern phase-noise analyzers.

Rohde & Schwarz,
Mühldorfstrasse 15, 81671
Munich, Germany;
(410) 910-7800;
www.rohde-schwarz.com

Since a frequency hop impacts data throughput, its execution time is limited. Understandably, then, quick frequency settling is a key characteristic. Furthermore, complex test setups have been required to determine the settling time of a frequency hop. The application note points out, though, that communication-system developers now require an easy and efficient method due to time pressures.

The document next presents some theoretical information. Frequency settling is typically measured during the development of components for modern communication applications, such as mobile phones and radar systems. It can be quantified as the time needed to hop from one frequency to another. Only after settling on the new frequency can data transmission begin.

In most communication systems, the internal frequency oscillators are frequency-locked to a common frequency reference via a phase-locked loop (PLL). The PLL's loop filter greatly affects the amount of time required by the system for frequency and phase settling after a frequency or channel change.

While past frequency-settling-time measurements involved a frequency discriminator, an alternative method involves signal analyzers with digital sampling. High-speed analog-to-digital converters (ADCs) can sample an input signal and then save the measurement data. The bandwidth and sampling rate of the ADCs, along with the available memory, determine the acquisition time, possible frequency resolution, and the range at which frequency settling can be measured.

Also discussed in the document is how modern phase-noise analyzers can measure frequency- and phase-settling time. It wraps up by revealing measurements performed with the FSWP phase-noise analyzer.

CHRIS DeMARTINO | Technical Engineering Editor

SPECTRUM ANALYZER Packs a Powerful Punch

We get to take a test drive with a new high-performance spectrum analyzer from a company known for its compact test equipment.

Any RF engineer or technician knows that the spectrum analyzer is one of the most essential test instruments—no test lab is complete without one. Today, spectrum analyzers range from more traditional benchtop instruments to portable USB-based versions. In addition, purchasing a spectrum analyzer requires one to have certain knowledge in terms of their characteristics, such as understanding the difference between swept-tuned and real-time spectrum analyzers. It should come as no surprise, then, that a wide variety of spectrum analyzers populate the market today.

One of the latest spectrum analyzers to arrive is Signal Hound's *(www.signalhound.com)* SM200A, which the company describes as a high-performance 20-GHz spectrum analyzer and monitoring receiver. Since Signal Hound was kind enough to loan me an SM200A, this article takes a hands-on look at the equipment, exploring some of its many features *(Fig. 1)*.

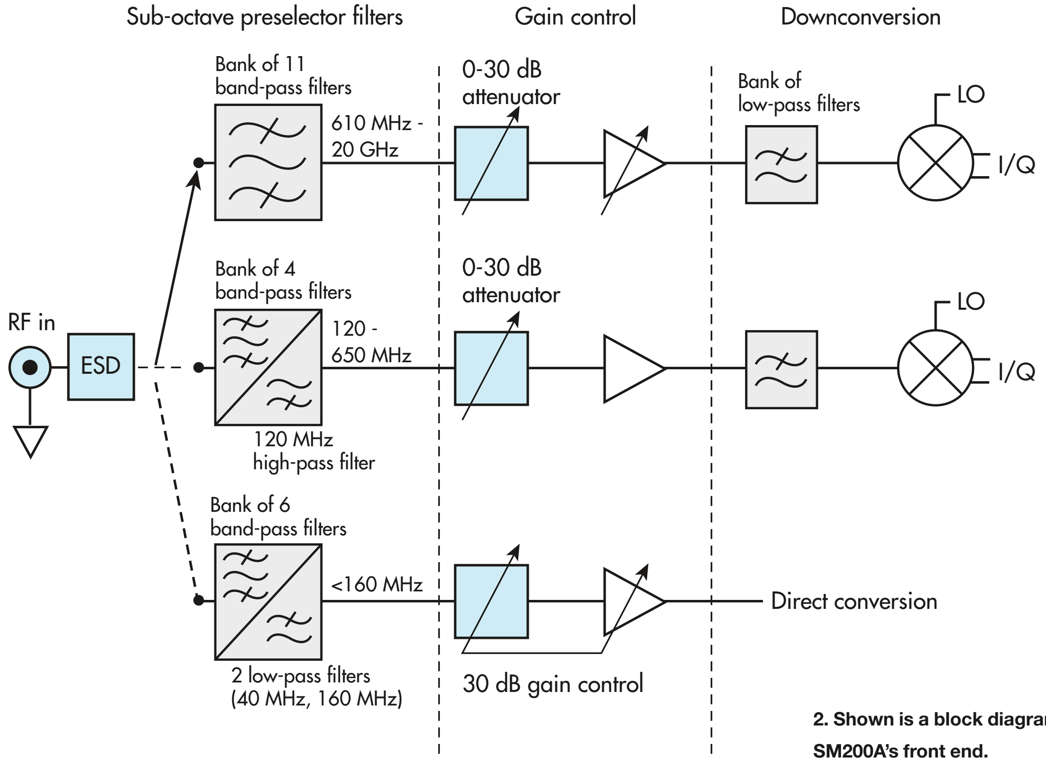
1. The SM200A is a 20-GHz spectrum analyzer and monitoring receiver.

AN INTRODUCTION TO THE SM200A

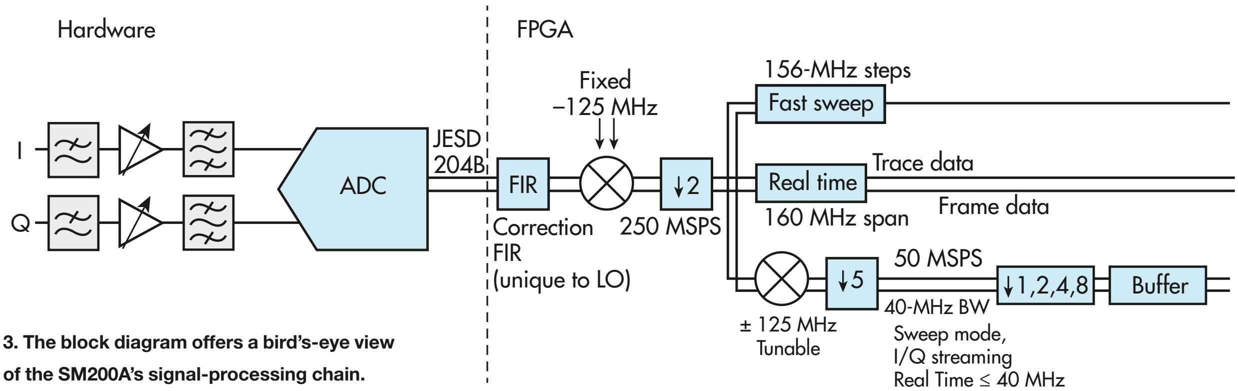
Although the SM200A was released earlier this year, it was actually a few years in the making. In fact, Signal Hound showcased the SM200A at IMS 2017 in anticipation of it being released before the end of last year. Of course, that didn't happen.

So why was the SM200A delayed? A blog post from Signal Hound, "Adventures in hardware development: the case of our 'missing' 20 GHz spectrum analyzer, the SM200A," provides the answers. It explains some of the challenges that arose along the way, as well as how the engineering team at Signal Hound overcame them. The company officially launched the SM200A in early 2018.

While Signal Hound had already been offering spectrum analyzers like the BB60C, the SM200A differs from those for several reasons. For one, it has a higher frequency range, operating all the way to 20 GHz. The SM200A is also substantially larger than the firm's other test instruments due to the performance



2. Shown is a block diagram of the SM200A's front end.



3. The block diagram offers a bird's-eye view of the SM200A's signal-processing chain.

capabilities that were built into its package. It measures 28 × 20 × 13 cm and weighs 3.93 kg.

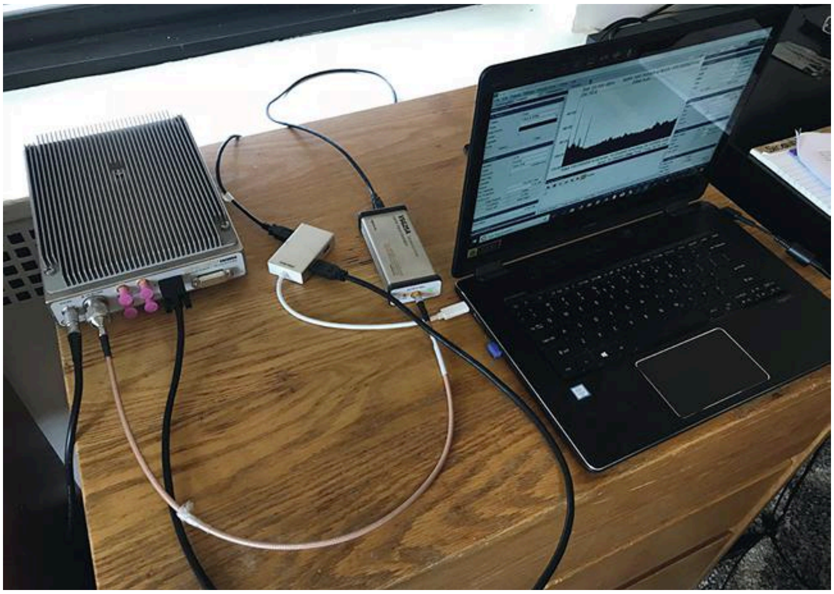
Another difference lies in how the SM200A is powered. Like Signal Hound's other instruments, the SM200A connects to an external PC via a USB cable. The PC displays the measurements and provides the user with the controls needed for operation via a software program. However, the SM200A is not USB-powered like other Signal Hound test instruments—it's powered separately.

The SM200A's overall frequency range extends from 100 kHz to 20 GHz. It achieves 160 MHz of instantaneous bandwidth along with 110 dB of dynamic range. One notable feature of the SM200A is its 1-THz/sec. sweep speed at 30-kHz resolution bandwidth (RBW).

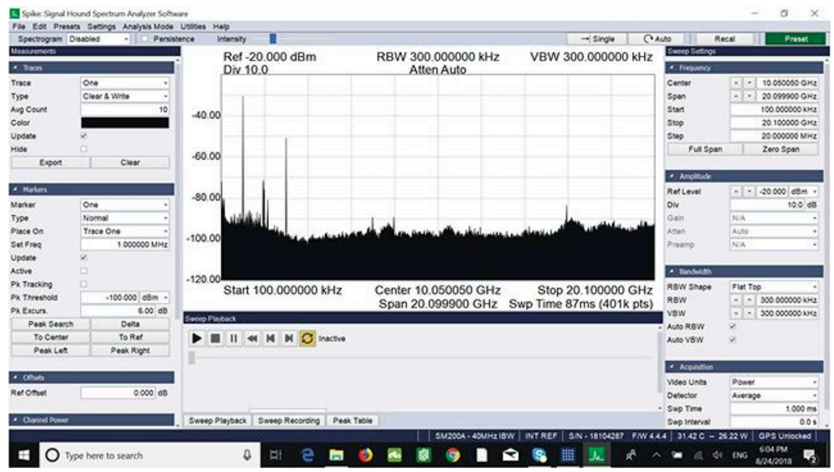
The analyzer can also measure phase noise, with performance that in Signal Hound's own words is "low enough to contribute less than 0.1% error to error-vector-magnitude (EVM) measurements and rival even the most expensive spectrum analyzers on the market."

Additional specifications are listed in the table. To get further perspective on what makes the SM200A tick, block diagrams of its front end and signal-processing functionality are revealed in *Figures 2 and 3*, respectively.

The SM200A is intended to be used with the Spike spectrum-analyzer software, which can be downloaded from the company's website. Those who have prior experience using any of Signal Hound's spectrum analyzers should already be familiar with Spike, since the software is used throughout its analyzer lineup.



4. This measurement setup featured the SM200A and VSG25A.



5. The *Sweep* analysis mode, which is essentially a traditional spectrum-analyzer measurement environment, is Spike's default analysis mode.

GETTING STARTED WITH THE SM200A

Now let's explore some of the analyzer's features. Signal Hound's VSG25A vector signal generator (VSG) is used to generate the signals that are being measured by the SM200A *(Fig. 4)*. As can be seen, both instruments are connected to a laptop via USB cables.

Figure 5 shows the Spike software when first starting the program. In this case, the SM200A is measuring a 1-GHz continuous-wave (CW) signal from the VSG25A. All of the typical spectrum-analyzer settings are depicted here.

Clicking on the *Analysis Mode* tab in the top menu reveals the various analysis options. When first starting Spike, the default analysis mode is *Sweep*, shown in *Fig. 5*. The *Sweep* analysis mode essentially represents a traditional spectrum-analyzer measurement environment in which the analyzer sweeps across a desired span. Additional analysis modes include *Real-Time, Zero-Span, Harmonics, Phase Noise, Digital Modulation Analysis, EMC Precompliance, Analog Demod*, and *Interference Hunting*. The wide array of analysis modes is what makes the SM200A such a versatile instrument.

MAKING PHASE-NOISE MEASUREMENTS

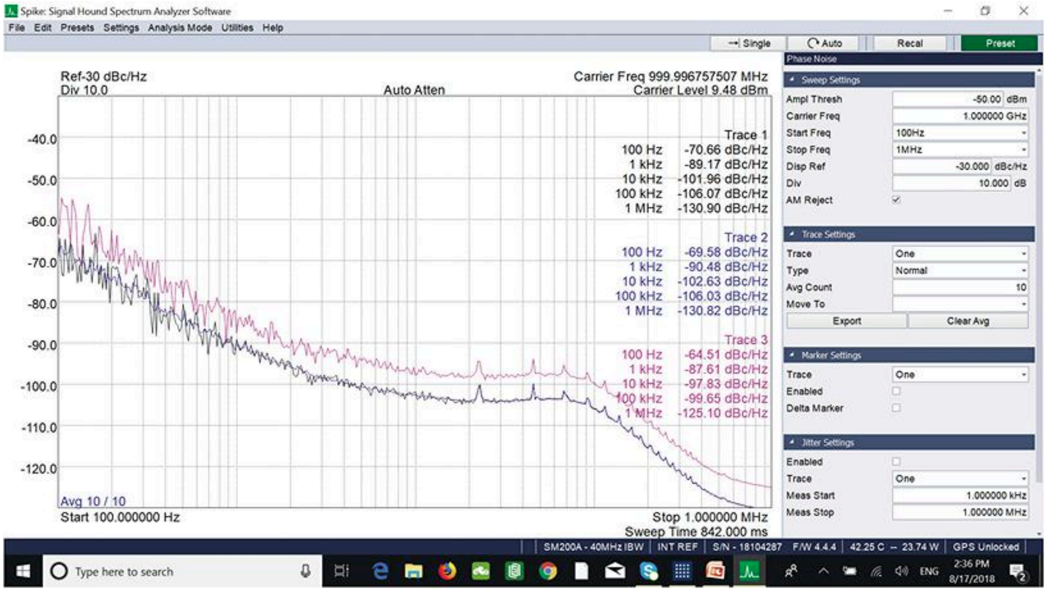
One significant aspect of the SM200A is its phase-noise measurement capability. To measure phase noise, one must simply click the *Analysis Mode* tab and then select *Phase Noise* from the subsequent dropdown menu.

Figure 6 reveals phase-noise measurements at two different carrier frequencies. Trace 1 (black) and Trace 2 (blue) depict phase-noise measurements of an active 1-GHz signal. Trace 1 represents a "normal" measurement, while Trace 2 represents an "average" measurement. For an "average" measurement, a user-specified number of traces are averaged to create an average phase-noise measurement trace. Users can specify the number of traces to average by entering a value for *Avg Count* in the *Trace Settings* area. In this example, *Avg Count* is set to 10, which is the default value.

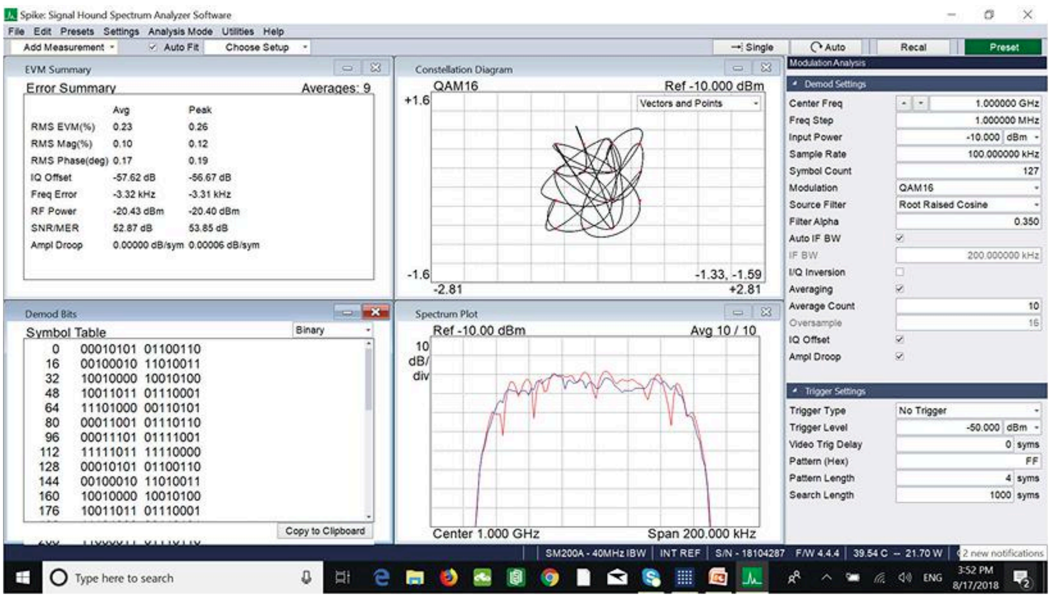
Trace 3 (pink) depicts a "reference" measurement. In this case, it represents a previous phase-noise measurement of a 2-GHz signal. That phase-noise measurement trace was then set to a "reference" trace, which is simply a trace that's not updated after each phase-noise sweep. This feature is useful for comparing the phase-noise performance of a source at two different frequencies, as is the case here. It could also help to compare the phase noise of two different sources. All traces can be configured in the *Trace Settings* area.

VECTOR SIGNAL ANALYSIS

One noteworthy analysis mode is *Digital Modulation Analysis*. With *Digital Modulation Analysis*, the SM200A can essentially function as a vector signal analyzer (VSA). The SM200A supports a very wide range of modulation for-



6. In this phase-noise analysis, the three traces represent measurements at two different carrier frequencies.



7. Digital modulation analysis was performed on a 1-GHz 16-QAM signal.

mats, including BPSK, QPSK, OQPSK, and 8PSK, among others. It also supports 16-QAM, 32-QAM, 64-QAM, and 256-QAM.

As an example, we'll look at a 1-GHz 16-QAM signal. *Figure 7* shows an analysis of this signal. Included is a constellation diagram along with an error summary, which displays a readout of various metrics like EVM, magnitude error, phase error, frequency error, and more. Here, the peak EVM is just 0.26%.

Also seen in *Figure 7* is a spectrum plot along with a table that displays the demodulated bits of the input signal. The number of demodulated bits shown is equal to the specified symbol count multiplied by the number of bits each symbol represents for the selected modulation type. In this case, a 16-QAM signal is being analyzed (4 bits per symbol). Since the signal count is set to 127, the total number of demodulated bits in this example is 508 (127 × 4).

Additional measurement options can be viewed by clicking the *Add Measurement* dropdown, which is shown in the upper left-hand area of *Fig. 7*. Options include *Eye Diagram, EVM vs Time, Mag Err vs Time, Phase Err vs Time,* and more. In essence, users can select the measurements to display to meet their specific needs.

ADDITIONAL CAPABILITIES AND CLOSING THOUGHTS

The SM200A offers plenty of other

measurement options, too, such as zero-span mode, analog demodulation analysis, and more. With zero-span analysis, users can record and playback I/Q waveforms. The sweep recording and playback capability, along with the sub-octave filters, makes the SM200A well-suited for spectrum-monitoring applications.

Of course, as its name implies, the SM200A is a real-time spectrum analyzer, which is critical for interference-hunting applications. And while the SM200A is equipped for such applications, a deeper look into that facet of the analyzer is probably worthy of its own article. Signal Hound has also published an application note, "Introduction to Interference Hunting with Spike." The document dives into the topic of interference hunting in greater detail, explaining how to configure the Spike software for such measurements.

In summary, the SM200A certainly packs a great deal of performance capabilities into a single instrument. With its array of analysis modes at a price tag of just $11,900, the SM200A can hold its own in today's market. It appears that Signal Hound may have a winner on its hands. mw

Calibrated Streaming I/Q	5 kHz to 40 MHz of selectable I/Q bandwidth
Resolution Bandwidths (RBW)	0.1 Hz (≤200-kHz span) to 3MHz (any span) using 40-MHz IBW; 30 kHz to 10 MHz using 160-MHz IBW
System Noise Figure (Typical)	11 dB over 700 MHz to 2.7 GHz; 14 dB from 2.7 GHz to 4.5 GHz; 18 dB from 4.5 GHz to 15 GHz;
Sweep Speed	1-THz/sec (1-MHz RBW); 1-THz/sec (100-kHz RBW); 1-THz/sec (30-kHz RBW); 160-GHz/sec (10-kHz RBW); 18-GHz/sec (1-kHz RBW);
Displayed Average Noise Level (DANL)	100 kHz to 700 MHz: -156 dBm/Hz; 700 MHz to 2.7 GHz: -160 dBm/Hz; 2.7 GHz to 4.5 GHz: -158 dBm/Hz; 4.5 GHz to 8.5 GHz: -153 dBm/Hz; 8.5 GHz to 15 GHz: -154 dBm/Hz; 15 GHz to 20 GHz: -149 dBm/Hz
SSB Phase Noise at 1-GHz Center Frequency	10-Hz offset: -76 dBc/Hz; 100-Hz offset: -108 dBc/Hz; 1-kHz offset: -123 dBc/Hz; 10 kHz offset: -132 dBc/Hz; 100-kHz offset: -136 dBc/Hz; 1-MHz offset: -133 dBc/Hz

(Continued from page 55)

simultaneously (i. e., they are in phase), the cross-polarization of a circularly polarized AUT cannot be obtained explicitly by this measurement but requires a post-calculation in a spreadsheet.[10] mw

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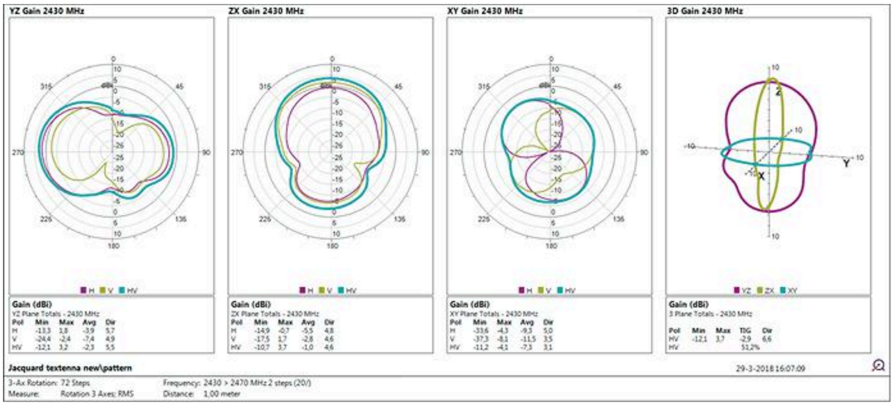
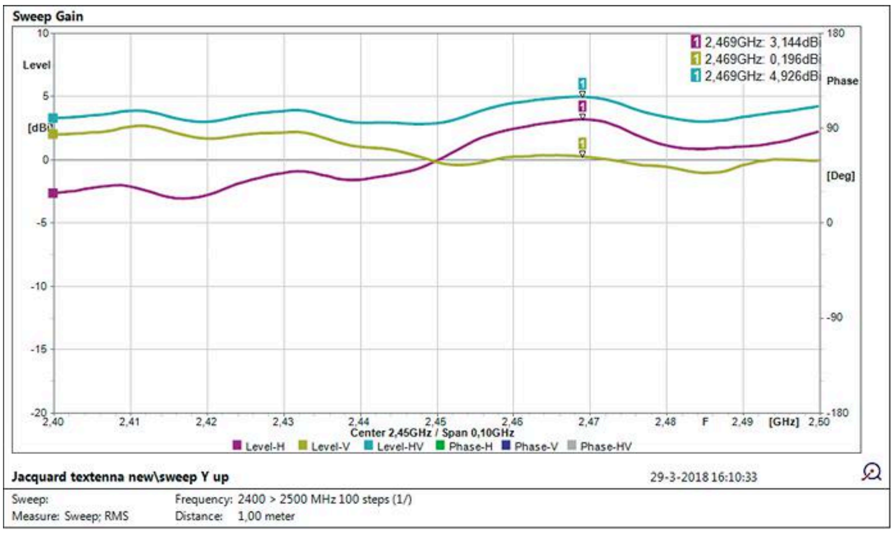


12. These radiation patterns were measured for the prototype circularly polarized wearable antenna.



13. These gain-vs.-frequency responses were measured for the prototype circularly polarized wearable antenna.

JACK BROWNE | Technical Contributor

Solid-State Amplifiers "Amp" Up the Power

Solid-state technology, mainly in the form of gallium-nitride transistors, is opening the door to more powerful, "tube-like" microwave power amplifiers.

High-power amplifiers (HPAs) for RF/microwave applications were once automatically associated with electron-tube devices such as klystrons or traveling-wave tubes (TWTs). While those devices still provide some of the highest output-power levels available at microwave frequencies, solid-state HPAs are pushing output-power performance higher, largely due to the capabilities of gallium-nitride (GaN) wide-bandgap transistors that enable HPAs with high output-power levels in smaller packages.

The physical sizes of these amplifiers are generally limited by the thermal characteristics of the devices, their associated printed-circuit boards (PCBs), and their enclosures. Although GaN and other power transistors are also gaining in efficiency, even a device with 50% efficiency still wastes one-half of its supplied energy as heat and other forms of energy losses.

Amplifier output power comes in many forms. An amplifier designed for linear Class A or Class AB use (with transistors remaining turned on) with continuous-wave (CW) signals will generally deliver less output power than the peak power levels possible with an amplifier developed for pulsed signals. An example of the latter is a Class D amplifier that switches on and off to save power and boost efficiency. Solid-state RF/microwave amplifiers exploit several different transistor technologies, including silicon (Si) lateral diffused metal-oxide-semiconductor (LDMOS) devices for lower frequencies and GaN and GaAs field-effect transistors (FETs) at higher frequencies.

Some designs, such as the innovative model 2154-BB52E-6ARR from Empower RF Systems *(www.empowerrf.com)*, combine semiconductor technologies, using Si LDMOS at lower frequencies and GaN for upper-frequency operation. The Class AB linear amplifier system comes in three rack-mountable enclosures, with a Si LDMOS amplifier for 20 to 1000 MHz and a GaN amplifier for 1 to 3 GHz that feature as much as 500 W CW output power over each frequency range. The third rack-mount enclosure carries power-supply, control, and monitoring circuitry for the two amplifiers. The amplifier, powered by a single-phase power supply, is equipped with forced-air cooling and an assortment of self-test functionality for protection.

As an example of the solid-state power levels that can be reached with pulsed signals, the firm offers the GaN-based rack-mount model 2213 power amplifier for applications from 2900 to 3500 MHz. It also operates under Class AB conditions, but with pulsed signals, and is capable of 10 kW peak output power with 2- to 100-μs pulses at duty cycles from 0.5 to 6.0%.

SMALLER BUT STRONGER

One recent trend in commercial solid-state HPAs involves the increased power levels from smaller amplifier housings. Diamond Microwave *(www.diamondmw.com)*, one of the leading proponents of the "smaller is better" school of solid-state RF/microwave amplifier design, offers sleek pulsed microwave amplifiers that boast hundreds of watts of output power.

The dominant position of the input connector on Diamond Microwave's X-band GaN HPA *(Fig. 1)* is a telltale sign of the small size of the housing, even with its rated 300-W minimum peak pulsed output power across a 2-GHz bandwidth. Belying its compact size, this "smart" amplifier has built-in monitoring and protection and front-panel Ethernet connection for remote control. The 300-W amplifier leverages innovations

1. This X-band GaN HPA produces 300 W minimum output power across a 2-GHz bandwidth, while following a trend of fitting into smaller enclosures than traditional HPAs. *(Courtesy of Diamond Microwave)*

2. This rack-mountable power amplifier can deliver 20 kW output power from 2 to 30 MHz with solid-state devices. *(Courtesy of Ophir RF)*

3. Model AGN/098-6060-P is a compact GaN HPA designed for 1-kW pulsed applications from 8.5 to 9.8 GHz. *(Courtesy of CPI)*

from the firm's higher-power model DM-X400-02 400-W pulsed HPA, which has been replacing traveling-wave-tube amplifiers (TWTAs) in some avionics and military communications applications.

In terms of pure power, higher solid-state output-power levels are still more common at lower frequencies. Model 4135 from Ophir RF *(https://ophirrf.com)* is a good example of what's possible from solid-state amplifiers at HF (2 to 30 MHz). The Class A linear amplifier is rated for 20 kW saturated output power across its frequency range. It features 75-dB minimum gain with ±3-dB gain flatness. Unlike the novel compact configuration of the Diamond HPA, however, this robust, "old-fashioned" power amplifier comes complete with internal heat sinks and weighs 600 lbs *(Fig. 2)*. It measures 19 × 60 × 36 in. and will fit a standard 19-in. rack. Internal forced-air cooling keeps its solid-state devices from overheating while providing those enormous output-power levels.

API Technologies *(www.apitech.com)* is another supplier of solid-state HPAs that makes the best use of available semiconductor technologies, including GaAs, GaN, and Si LDMOS. The firm offers HPAs in standard rack-mount enclosures and custom housings, including GaN power amplifiers at pulsed output levels to 1 kW and frequencies to 18 GHz. Many of their larger amplifiers are meant as solid-state replacements for larger, heavier TWTAs.

Some HPAs still fit into smaller packages even with large output-power levels. For example, a long-time supplier of compact microwave power amplifiers, CTT Inc. *(www.cttinc.com)*, developed the AGN/098-6060-P for pulsed applications from 8.5 to 9.8 GHz. It can deliver 1 kW output power but is designed for pulses of 100 μs or shorter at 10% duty cycles; longer duty cycles will damage the amplifier. Packed into a miniature metal housing *(Fig. 3)*, the robust little GaN amplifier offers 60-dB gain with ±3-dB gain flatness.

TURNING TO TUBES

What about the vacuum-tube amplifiers, such as TWT and klystron tube amplifiers, that these solid-state HPA are attempting to replace? What levels of power are they providing in the marketplace? For applications requiring generous amounts of RF/microwave power for transmitters, such as in satcom systems, HPAs are still based on klystrons and TWTs, typically in enclosures that are much larger than SSPAs. Among the suppliers of microwave vacuum tubes and tube amplifiers, Communications and Power Industries (CPI) *(www.cpii.com)*, provides HPAs for all common satcom frequency bands. They include its Gen IV klystron amplifiers with high efficiency and many user-friendly features, such as a large touchscreen control interface and built-in performance monitors and alarms.

CPI's klystron HPAs for X-band applications include tubes capable of 2.5, 3.0, and 3.3 kW output power from 7.9 to 8.4 GHz. Following signal combining and processing, the tubes result in amplifier output levels of 2.0, 2.4, and 2.7 kW, respectively, across the same frequency range. The lower-power (2.5 kW) klystrons drive 60-MHz instantaneous bandwidths, while the higher-power (3.0 and 3.3 kW) klystrons energize instantaneous bandwidths of 45 MHz. Although these klystron HPAs represent an older technology when compared to solid-state GaN amplifiers, they are still well-suited for many high-frequency transmit applications (e.g., satcom systems), and provide healthy minimum gain of 77 dB at X-band frequencies.

Many HPA suppliers, such as Teledyne Microwave *(www.teledynemicrowave.com)*, CPI, and Comtech Xicom Technology *(https://xicomtech.com),* provide both tube and solid-state power amplifiers. They offer specifiers a choice of frequencies, power levels, and technologies that can be compared to meet different size, weight, and power (SWaP) requirements for avionics applications versus ground-based systems.

As an example, Comtech Xicom Technology makes tube-based and solid-state power amplifiers for military and commercial satellite uplink applications, across bands from 2 to 51 GHz and at output-power levels from 8 W to 3 kW. Even in its klystron power amplifiers, evidence is clear concerning the efforts made to reduce size and weight compared to conventional klystron power amplifiers. Not to mention the bright, front-panel touchscreens that reveal these HPAs as powerful amplifiers with traditional technology but quite modern features. mw

CHRIS DeMARTINO | Technical Engineering Editor

Probing Systems Run on Their Own

This company recently introduced its new probing systems, as well as an autonomous RF measurement solution that can perform calibrations and measure RF devices without user intervention.

Probe systems are a specialty of FormFactor (*www.formfactor.com*), which demonstrated its latest advances at the recent IMS 2018. At the show, FormFactor highlighted a new line of 200-mm probing systems, dubbed SUMMIT200 (*Fig. 1*). The company also announced a new autonomous RF measurement capability that's intended to help meet faster time-to-market requirements of integrated circuits (ICs) for markets like 5G communications, autonomous vehicles, and next-generation Wi-Fi.

Jens Klattenhoff, senior director for systems marketing at FormFactor, attended IMS and spoke about the SUMMIT200 and more. "The SUMMIT200 is an engineering platform for high-end engineering, as well as niche production and high-volume engineering. We have added a loader to our SUMMIT200 platform, so it allows for faster time-to-data. You can put in two different cassettes, and it can be fully handled automatically. We have reworked our whole Summit platform, so it has high temperature stability and overall better performance."

Klattenhoff also mentioned the benefits in speed provided by the SUMMIT200, noting that it's five times faster than the current Summit system.

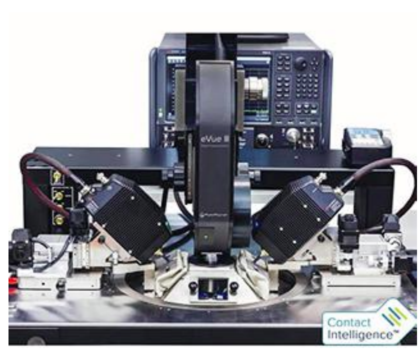
In addition, the SUMMIT200 platform supports FormFactor's Contact Intelligence technology, which leads to its major announcement at IMS. The company revealed that it has extended its Contact Intelligence technology to enable autonomous RF measurements. The autonomous RF measurement solution combines a probe system, advanced programmable positioners, and the WinCal XE and Velox software tools (*Fig. 2*). Both the SUMMIT200 and CM300xi probe systems support the Contact Intelligence solution.

FormFactor asserts that the Contact Intelligence solution allows customers to take advantage of "fully autonomous, hands-free calibrations and measurements of RF devices over multiple temperatures." An operator can begin a test and then let the system run on its own overnight or even over a weekend—no user intervention is required. The system will automatically realign the probes with the pads if they drift away from alignment.

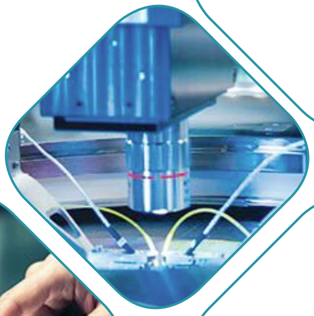
In addition, calibration is continuously monitored. If the calibration drift exceeds a predefined limit, the system will automatically perform a recalibration.

"With our brand new autonomous RF measurement system, the whole system will perform the measurement, recalibration, and wafer handling," noted Klattenhoff. "This gives you the freedom to concentrate elsewhere, as the machine will do the work for the whole shift. It will recalibrate over different temperatures from –40 to +125°C. Automatic positioners guarantee best contact at all times."

1. With the SUMMIT200 probing solutions, measurements can be performed manually, semi-automatically, or fully automatically.



2. This autonomous RF measurement solution can perform autonomous calibrations and measurements of RF devices over multiple temperatures.



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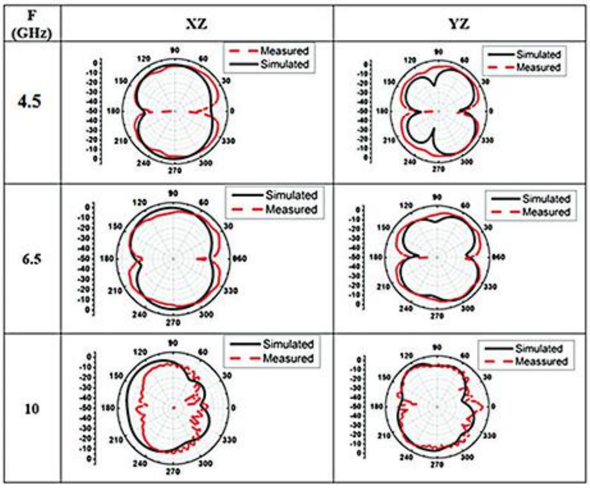
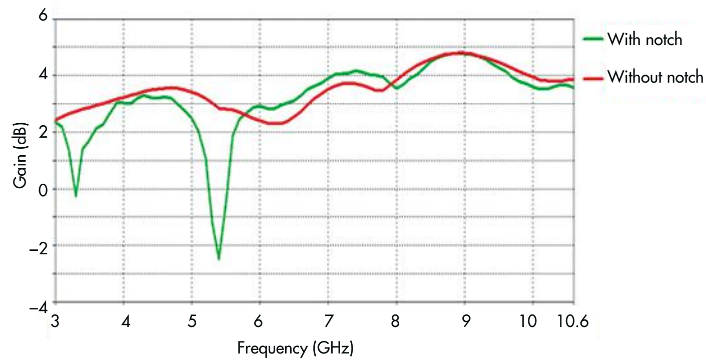


6. The measured and simulated radiation patterns for the UWB were plotted at 4.5, 6.5, and 10.0 GHz.



7. These traces show the simulated peak gain of the antenna, with and without the two notches.

asitic strip at 5.5 GHz *(Fig. 5b)*, which is the center frequency of the notch intended to reduce interference from WLAN applications. The radiation patterns of the UWB antenna prototype was measured while inside an anechoic chamber, at 4.5, 6.7, and 10.0 GHz for the main planes—the x-z and y-z radiation planes.

Figure 6 shows the simulated and measured radiation patterns at those three test frequencies, revealing that the antenna exhibits an omnidirectional radiation pattern in the y-z plane and a bidirectional radiation pattern in the x-z plane. As the plots in *Fig. 6* show, there's reasonable agreement between the simulated and measured results for the radiation patterns of the UWB antenna. *Figure 7* compares the simulated gain of the antenna, with and without the two notches. The average gain without the notches is about 3 dB. The simulated gains for the lower- and higher-frequency notches is about −2 and −1 dB, respectively.

In short, as the measurements on the prototype reveal, this UWB planar antenna with two built-in notches is promising as a means of simplifying UWB communications systems design, as it eliminates the need for at least two of those additional filters. The UWB antenna can be fabricated on low-cost circuit-board material with good performance. It operates from 3.1 to 12.0 GHz with a compact footprint and, without additional hardware, can suppress interference occurring in the frequency bands of 3.3 to 3.9 GHz and 5.2 to 5.9 GHz. mw

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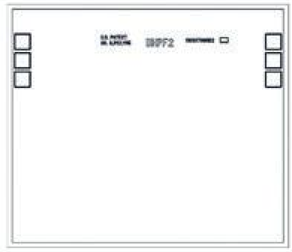
Splitter/Combiner Channels 1 to 100 MHz, 2.45 to 2.7 GHz

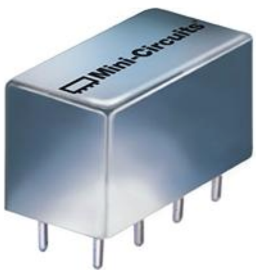
Mini-Circuits' model ZC8SC272-12DL+ is an eight-way, 0-deg., dual-channel splitter/combiner with a lowpass channel from 1 to 100 MHz and highpass channel from 2450 to 2700 MHz. It is well suited for distributing S-band intermediate-frequency (IF) and reference signals on the same line. It handles +37 dBm power over the highpass channel as a splitter and +27 dBm power over the lowpass channel as a splitter. The 50-Ω splitter/combiner has typical lowpass insertion loss of 0.5 dB and typical highpass insertion loss of 2.0 dB. The typical VSWR is 1.20:1 and typical isolation between ports is 22 dB. It is supplied in a rugged aluminum housing measuring 4.00 ×1.25 ×0.50 in. with SMA connectors.

Reflectionless Filters Pass 13.9 to 26.0 GHz



Mini-Circuits' X-Series of reflectionless highpass filters now includes two-section models with as much as 41-dB stopband rejection from DC to 7 GHz. The patented MMIC filters feature a topology that absorbs signals in the stopband rather than reflecting them back to a source. The RoHS-compliant, 50-Ω highpass filter die have stopband from DC to 9 GHz, frequency cutoff at 11.2 GHz, and passband of 13.9 to 26.0 GHz. The passband insertion loss is typically 1.4 dB from 13.9 to 15.0 GHz and typically 0.8 dB from 15.0 to 26.5 GHz. The reflectionless filters have an operating temperature range of -55 to +105°C.

Four-Way Splitter/Combiner Handles 0.5 to 400 MHz



Mini-Circuits' model PSC-4-1W-75+ is a four-way, 0-deg. power splitter/combiner for 75-Ω applications from 0.5 to 400 MHz. Well suited for use in HF/VHF radios and amateur radios, it handles as much as 1 W input power as a splitter. It has typical insertion loss (above 6-dB splitting loss) of 0.6 dB from 0.5 to 5 MHz, 0.4 dB from 5 to 100 MHz, 0.7 dB from 100 to 250 MHz, and 1.1 dB from 250 to 400 MHz. Isolation between ports is typically 24 dB from 0.5 to 5 MHz, 26 dB from 5 to 250 MHz, and 20 dB from 250 to 400 MHz. The RoHS-compliant splitter/combiner has an operating temperature range of -55 to +100°C and is supplied in a rugged, welded push-in package.

Digital Step Attenuators Control 15.5 dB to 4 GHz

Mini-Circuits' ZX76-15R5A-PN+ series of 50-Ω digital step attenuators provide control of 0 to 15.5 dB attenuation is 0.5-dB steps from DC to 4 GHz. Attenuation is adjusted by a 5-b serial/parallel interface and the attenuators can be powered by single possible or dual positive/negative supply line. Control lines are buffered by Schmitt Triggers to allow a wide range of control voltage levels. The attenuators feature high typical IP3 of +52 dBm and low VSWR of typically 1.30:1 with attenuation accuracy of typically 0.1 dB. The digital step attenuators are supplied in a rugged unibody case with SMA connectors. They are well suited for test and instrumentation applications.

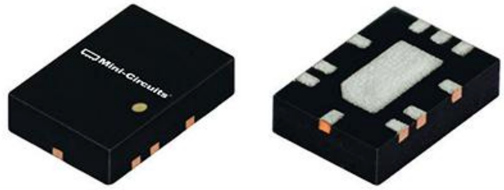
VCO Tunes from 3790 to 3970 MHz

Mini-Circuits' model ROS-39702PH19R+ is a voltage-controlled oscillator (VCO) that tunes from 3790 to 3970 MHz for satellite and point-to-point radio applications. The RoHS-compliant VCO provides +3.5 dBm typical output power across the range with -23 dBc typical harmonics. The phase noise is typically -70 dBc/Hz offset 1 kHz from the carrier, -98 dBc/Hz offset 10 kHz from the carrier, -119 dBc/Hz offset 100 kHz from the carrier, and -139 dBc/Hz offset 1 MHz from the carrier. The VCO has a tuning voltage range of 0.5 to 5.0 V and exhibits typical tuning sensitivity of 48 to 63 MHz/V. The RoHS-compliant oscillator is supplied in a metal housing measuring 0.5 × 0.5 × 0.18 in. for an operating temperature range of -55 to +85°C.

SP8T Absorptive Switch Tackles 1 to 6000 MHz

Mini-Circuits' model SPI-SP8T-6G is a single-pole, eight-throw (SP8T) absorptive switch with high isolation and fast switching speed from 1 to 6000 MHz. The RoHS-compliant switch features high linearity, with a typical third-order intercept point (IP3) of +50 dBm, and typical switching speed of 6 μs. Typical isolation is 85 dB or better across the full frequency range. Power and control are accessed via a Hirose DF11 connector while switching is controlled by a 3-wire SPI interface compatible with TTL and LVTTL voltages. The typical VSWR is 1.45:1 or better across the full frequency range. The switch is supplied in a rugged metal case measuring 3.68 ×3.27 ×0.40 in. with 9 SMP male connectors and two Hirose DF11 connectors.

MMIC Splitter/Combiner Commands 10 to 43.5 GHz



MODEL EP2KA+ is a GaAs monolithic-microwave-integrated-circuit (MMIC) power splitter/combiner suitable for wideband applications from 10.0 to 43.5 GHz. It features low insertion loss (above 3-dB splitting loss) of typically 0.9 dB or less from 10 to 30 GHz, 1.5 dB from 30 to 40 GHz, and 2.2 dB from 40.0 to 43.5 GHz. The isolation between ports is typically 17 dB from 10 to 20 GHz, 26 dB from 20 to 25 GHz, 22 dB from 25 to 30 GHz, 26 dB from 30 to 40 GHz, and 29 dB from 40.0 to 43.5 GHz. The splitter/combiner exhibits typical amplitude unbalance of ±0.57 dB or better across the full frequency range and typical phase unbalance of ±9.6 deg. or better across the full frequency range. The RoHS-compliant device, which has an operating temperature range of –40 to +85°C, comes in a compact housing measuring just 3.5 × 2.5 mm and handles as much as 1.25 W power as a splitter.
MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500, www.mini-circuits.com

Dividers/Combiners Extend to 18 GHz

A LINE OF coaxial two-way power dividers/combiners features models in bands from 5 kHz to 18 GHz capable of handling 20 W average power and 1 kW peak power. They control insertion loss to a maximum of 0.5 dB to 0.5 GHz, 0.3 dB from 0.5 to 4.0 GHz, and just 1.0 dB from 4.0 to 18.0 GHz. Minimum isolation between ports is 20 dB to 4 GHz and 16 dB to 18 GHz, while worst-case VSWR is 1.40:1 to 4.0 GHz and 1.60:1 from 4.0 to 18.0 GHz. The rugged dividers/combiners are housed in aluminum bodies with MIL-C-39012 SMA female connectors.
ARRA INC., 15 Harold Court, Bayshore, NY 11706; (631) 231-8400, FAX: (631) 434-1116; www.arra.com

Combiner/Divider Goes Three Ways to 500 MHz

MODEL D9866 IS is a three-way power combiner/divider rated to handle 750 W CW power from 30 to 500 MHz. It exhibits maximum insertion loss of 0.1 dB with maximum VSWR of 1.50:1 and minimum isolation between ports of 20 dB. The three-way combiner/divider maintains amplitude balance of ±0.35 dB and phase balance of ±5 deg. It's available with different configurations of Type N female, 7/16 female, and SC female connectors. The D9866 is designed for use in both commercial and harsh military environments.
WERLATONE INC, 17 Jon Barrett Rd., Patterson, NY 12563; (845) 278-2220, FAX: (845) 278-3440, E-mail: sales@werlatone.com, www.werlatone.com.

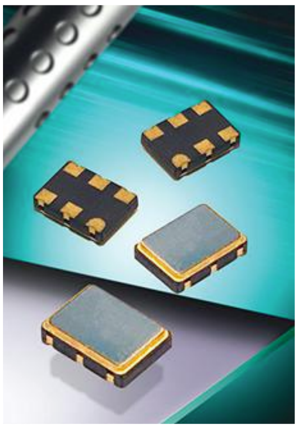
Wi-Fi FEM Combines Switches and Amplifiers

MODEL PE561221 IS a silicon-on-insulator (SOI), 2.4-GHz Wi-Fi front-end module (FEM) that's ideal for Wi-Fi gateways, routers, and set-top boxes in home and industrial applications. The high-performance module uses a smart bias circuit to deliver a high linearity signal and excellent long-packet error-vector-magnitude (EVM) performance. It integrates a low-noise amplifier (LNA), a power amplifier (PA), and single-pole, four-throw (SP4T) and single-pole, three-throw (SP3T) switches into a monolithic die housed in a compact 16-pin, 2- × 2-mm LGA package. It's well-suited as the main Wi-Fi device in a design or in larger 4 × 4 or 8 × 8 multiple-input, multiple-output (MIMO) modules. Based on pSemi's UltraCMOS technology, the PE561221 achieves 28-dB transmit gain and 14-dB receive gain from 2.4 to 2.5 GHz. The Wi-Fi FEM features low power consumption and a human-body-model (HBM) electrostatic-discharge (ESD) rating of 2 kV. It's designed for operating temperatures from –40 to +85°C.
pSEMI CORP. (FORMERLY PEREGRINE SEMICONDUCTOR), A MURATA COMPANY, 9369 Carroll Park Dr., San Diego, CA 92121; (858) 731-9400, FAX: (858) 731-9499; E-mail: sales@psemi.com, www.psemi.com

Two-Way Divider Spans 3 to 45 GHz

A LINE OF matched-line directional dividers (MLDDs) includes model 6030450, a two-way model with low dividing loss from 3 to 45 GHz. It maintains insertion loss of 2.10 dB or less to 36 GHz and to 2.80 dB or less to 45 GHz. Input VSWR is 2.30:1 or less and output VSWR is 1.80:1 or less from 3 to 45 GHz. Typical isolation between ports is 14 dB. Amplitude tracking is ±0.5 dB to 36 GHz and ±0.7 dB to 45 GHz, while phase tracking is ±10 deg. to 36 GHz and ±14 deg. to 45 GHz. The two-way divider comes with 2.4-mm female connectors.

KRYTAR INC., 1288 Anvilwood Ave., Sunnyvale, CA 94089; (408) 734-5999, (877) 734-5999, FAX: (408) 734-3017, www.krytar.com



Low-Jitter Oscillators Handle 50 to 700 MHz

A LINE OF stable frequency sources has been developed for low-jitter applications from 50 to 700 MHz. Based on high-speed current-steering logic (HCSL) technology, the oscillators exhibit phase jitter of no greater than 300 fs and typically only 150 fs. Suitable for low-voltage applications such as optical communications systems, they feature extremely low current consumption of no greater than 115 mA and typically only 94 mA. The EQJF series HCSL oscillators are available for supply voltages of 1.8, 2.5, or 3.3 V dc and frequency stability specifications of ±25, ±50, and ±100 ppm across commercial (–10 to +70°C) and industrial (–40 to +85°C) temperature ranges.

EUROQUARTZ LTD., Blacknell Lane, Crewkerne, Somerset, UK TA18 7HE; +44 (0)1460 230000; FAX: +44 (0)1460 230001; E-mail: info@euroquartz.co.uk, www.euroquartz.co.uk

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Wireless Standards 2018

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5G: WHERE WILL IT TAKE US?

5G COMMUNICATIONS: POTENTIAL WORLDWIDE 5G FREQUENCIES

Band	Downlink/Uplink (MHz)
n77	3300-4200
n78	3300-3800
n79	4400-5000
n257	26500-29500
n258	24250-27500
n260	37000-40000
n261	27500-28350

CELLULAR COMMUNICATION

LTE

FDD

Band	Uplink (MHz)	Downlink (MHz)	Bandwidth UL/DL (MHz)	Duplex Spacing (MHz)
1	1920 - 1980	2110 - 2170	60	190
2	1850 - 1910	1930 - 1990	60	80
3	1710 - 1785	1805 - 1880	75	95
4	1710 - 1755	2110 - 2155	45	400
5	824 - 849	869 - 894	25	45
6	830 - 840	875 - 885	10	45
7	2500 - 2570	2620 - 2690	70	120
8	880 - 915	925 - 960	35	45
9	1749.9 - 1784.9	1844.9 - 1879.9	35	95
10	1710 - 1770	2110 - 2170	60	400
11	1427.9 - 1447.9	1475.9 - 1495.9	20	48
12	699 - 716	729 - 746	17	30
13	777 - 787	746 - 756	10	-31
14	788 - 798	758 - 768	10	-30
17	704 - 716	734 - 746	12	30
18	815 - 830	860 - 875	15	45
19	830 - 845	875 - 890	15	45
20	832 - 862	791 - 821	30	-41
21	1447.9 - 1462.9	1495.9 - 1510.9	15	48
22	3410 - 3490	3510 - 3590	80	100
23	2000 - 2020	2180 - 2200	20	180
24	1626.5 - 1660.5	1525 - 1559	34	-101.5
25	1850 - 1915	1930 - 1995	65	80
26	814 - 849	859 - 894	35	45
27	807 - 824	852 - 869	17	45
28	703 - 748	758 - 803	45	55
29	N/A	717 - 728	11	N/A
30	2305 - 2315	2350 - 2360	10	45
31	452.5 - 457.5	462.5 - 467.5	5	10
32	N/A	1452 - 1496	44	N/A
65	1920 - 2010	2110 - 2200	90	190
66	1710 - 1780	2110 - 2200	70/90	400
67	N/A	738 - 758	20	N/A
68	698 - 728	753 - 783	30	55
69	N/A	2570 - 2620	50	N/A
70	1695 - 1710	1995 - 2020	15/25	300
71	663 - 698	617 - 652	35	-46
72	451 - 456	461 - 466	5	10
73	450 - 455	460 - 465	5	10
74	1427 - 1470	1475 - 1518	43	48
75	N/A	1432 - 1517	85	N/A
76	N/A	1427 - 1432	5	N/A
85	698 - 716	728 - 746	18	30
252	N/A	5150 - 5250	100	N/A
255	N/A	5725 - 5850	125	N/A

TDD

Band	Uplink and Downlink (MHz)	Bandwidth (MHz)
33	1900 - 1920	20
34	2010 - 2025	15
35	1850 - 1910	60
36	1930 - 1990	60
37	1910 - 1930	20
38	2570 - 2620	50
39	1880 - 1920	40
40	2300 - 2400	100
41	2496 - 2690	194
42	3400 - 3600	200
43	3600 - 3800	200
44	703 - 803	100
45	1447 - 1467	20
46	5150 - 5925	775
47	5855 - 5925	70
48	3550 - 3700	150
49	3550 - 3700	150
50	1432 - 1517	85
51	1427 - 1432	5
52	3300 - 3400	100

W-CDMA/HSPA/HSPA+

Band	Uplink (MHz)	Downlink (MHz)	Bandwidth (MHz)	Duplex Spacing (MHz)
1	1920 - 1980	2110 - 2170	60	190
2	1850 - 1910	1930 - 1990	60	80
3	1710 - 1785	1805 - 1880	75	95
4	1710 - 1755	2110 - 2155	45	400
5	824 - 849	869 - 894	25	45
6	830 - 840	875 - 885	10	45
7	2500 - 2570	2620 - 2690	70	120
8	880 - 915	925 - 960	35	45
9	1749.9 - 1784.9	1844.9 - 1879.9	35	95
10	1710 - 1770	2110 - 2170	60	400
11	1427.9 - 1447.9	1475.9 - 1495.9	20	48
12	699 - 716	729 - 746	17	30
13	777 - 787	746 - 756	10	-31
14	788 - 798	758 - 768	10	-30
19	830 - 845	875 - 890	15	45
20	832 - 862	791 - 821	30	-41
21	1447.9 - 1462.9	1495.9 - 1510.9	15	48
22	3410 - 3490	3510 - 3590	80	100
25	1850 - 1915	1930 - 1995	65	80
26	814 - 849	859 - 894	35	45

CDMA2000 1x/1xEV-DO

Band	Uplink (MHz)	Downlink (MHz)
Band Class 0	815 - 849	860 - 894
Band Class 1	1850 - 1910	1930 - 1990
Band Class 2	872 - 915	917 - 960
Band Class 3	887 - 925	832 - 870
Band Class 4	1750 - 1780	1840 - 1870
Band Class 5	410 - 483	420 - 493
Band Class 6	1920 - 1980	2110 - 2170
Band Class 7	776 - 788	746 - 758
Band Class 8	1710 - 1785	1805 - 1880
Band Class 9	880 - 915	925 - 960
Band Class 10	806 - 901	851 - 940
Band Class 11	410 - 483	420 - 493
Band Class 12	870 - 876	915 - 921
Band Class 13	2500 - 2570	2620 - 2690
Band Class 14	1850 - 1915	1930 - 1995
Band Class 15	1710 - 1755	2110 - 2155
Band Class 16	2502 - 2568	2624 - 2690
Band Class 18	787 - 799	757 - 769
Band Class 19	698 - 716	728 - 746
Band Class 20	1626.5 - 1660.5	1525 - 1559
Band Class 21	2000 - 2020	2180 - 2200

GSM/GPRS/EDGE/EDGE Evolution

Band	Uplink (MHz)	Downlink (MHz)	Duplex Spacing (MHz)
T-GSM-380	380.2 - 389.8	390.2 - 399.8	10
T-GSM-410	410.2 - 419.8	420.2 - 429.8	10
GSM-450	450.4 - 457.6	460.4 - 467.6	10
GSM-480	478.8 - 486	488.8 - 496	10
GSM-710	698.0 - 716.0	728.0 - 746.0	30
GSM-750	777.0 - 792.0	747.0 - 762.0	-30
T-GSM-810	806.0 - 821.0	851.0 - 866.0	45
GSM-850	824.0 - 849.0	869.0 - 894.0	45
P-GSM-900	890.0 - 915.0	935.0 - 960.0	45
E-GSM-900	880.0 - 915.0	925.0 - 960.0	45
R-GSM-900	876.0 - 915.0	921.0 - 960.0	45
T-GSM-900	870.4 - 876.0	915.4 - 921.0	45
DCS-1800	1710.0 - 1785.0	1805.0 - 1880.0	95
PCS-1900	1850.0 - 1910.0	1930.0 - 1990.0	80

TD-SCDMA/TD-HSPA/TD-HSPA+

Band	Uplink and Downlink (MHz)	Bandwidth (MHz)
33	1900 - 1920	20
34	2010 - 2025	15
35	1850 - 1910	60
36	1930 - 1990	60
37	1910 - 1930	20
38	2570 - 2620	50
39	1880 - 1920	40
40	2300 - 2400	100

WIRELESS CONNECTIVITY

Name	IEEE Standard	Frequency Band	Data Rate
WLAN	IEEE 802.11a	5 GHz	54 Mbps
	IEEE 802.11b	2.4 GHz	11 Mbps
	IEEE 802.11g	2.4 GHz	54 Mbps
	IEEE 802.11n	2.4 GHz 5 GHz	600 Mbps
	IEEE 802.11ac	5 GHz	6.93 Gbps
	IEEE 802.11af	54 - 790 MHz	26.7 Mbps for 6/7-MHz channels 35.6 Mbps for 8-MHz channels
	IEEE 802.11ah	< 1 GHz	Up to 40 Mbps
	IEEE 802.11ad	60 GHz	7 Gbps
Bluetooth		2.4 GHz	1 to 3 Mbps
ZigBee		2.4 GHz (worldwide) 915 MHz (U.S.) 868 MHz (Europe)	20 to 250 kbps
LoRaWAN		915 MHz (U.S.) 868 MHz (Europe)	0.3 to 50 kbps
Z-Wave		908.42 MHz (U.S.) 868.42 MHz (Europe)	Up to 100 kbps
THREAD		2.4 GHz	250 kbps
SIGFOX		915 MHz	Very Low
NFC		13.56 MHz	424 kbps
WirelessHART		2.4 GHz	250 kbps
Weightless		< 1 GHz	Up to 10 Mbps
LTE Cat-1		Cellular bands	Up to 10 Mbps
LTE Cat-0/LTE-M		Cellular bands	Up to 1 Mbps
Narrowband IoT (NB-IoT)		Cellular bands	Tens of kbps

GNSS (GLOBAL NAVIGATION SATELLITE SYSTEM)

GPS

L1	1575.42 MHz
L2	1227.60 MHz
L3	1381.05 MHz
L4	1379.913 MHz
L5	1176.45 MHz

GALILEO

E1	1575.42 MHz
E5	1191.795 MHz
E5a	1176.45 MHz
E5b	1207.14 MHz
E6	1278.75 MHz

GLONASS

L1	1602.0 MHz
L2	1246.0 MHz
L3	1202.25 MHz

BEIDOU

B1	1561.098 MHz
B1-2	1589.742 MHz
B2	1207.14 MHz
B3	1268.52 MHz