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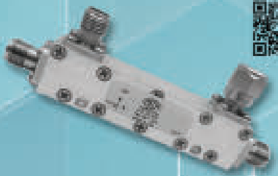

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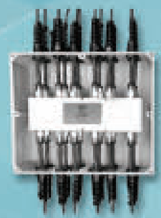

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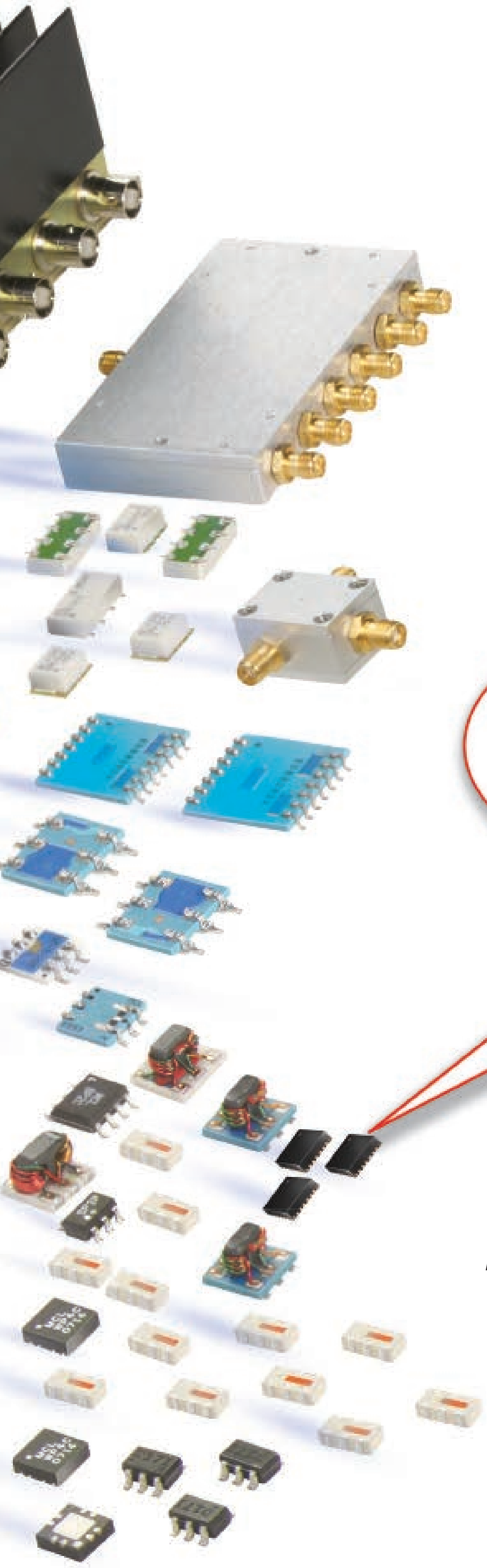

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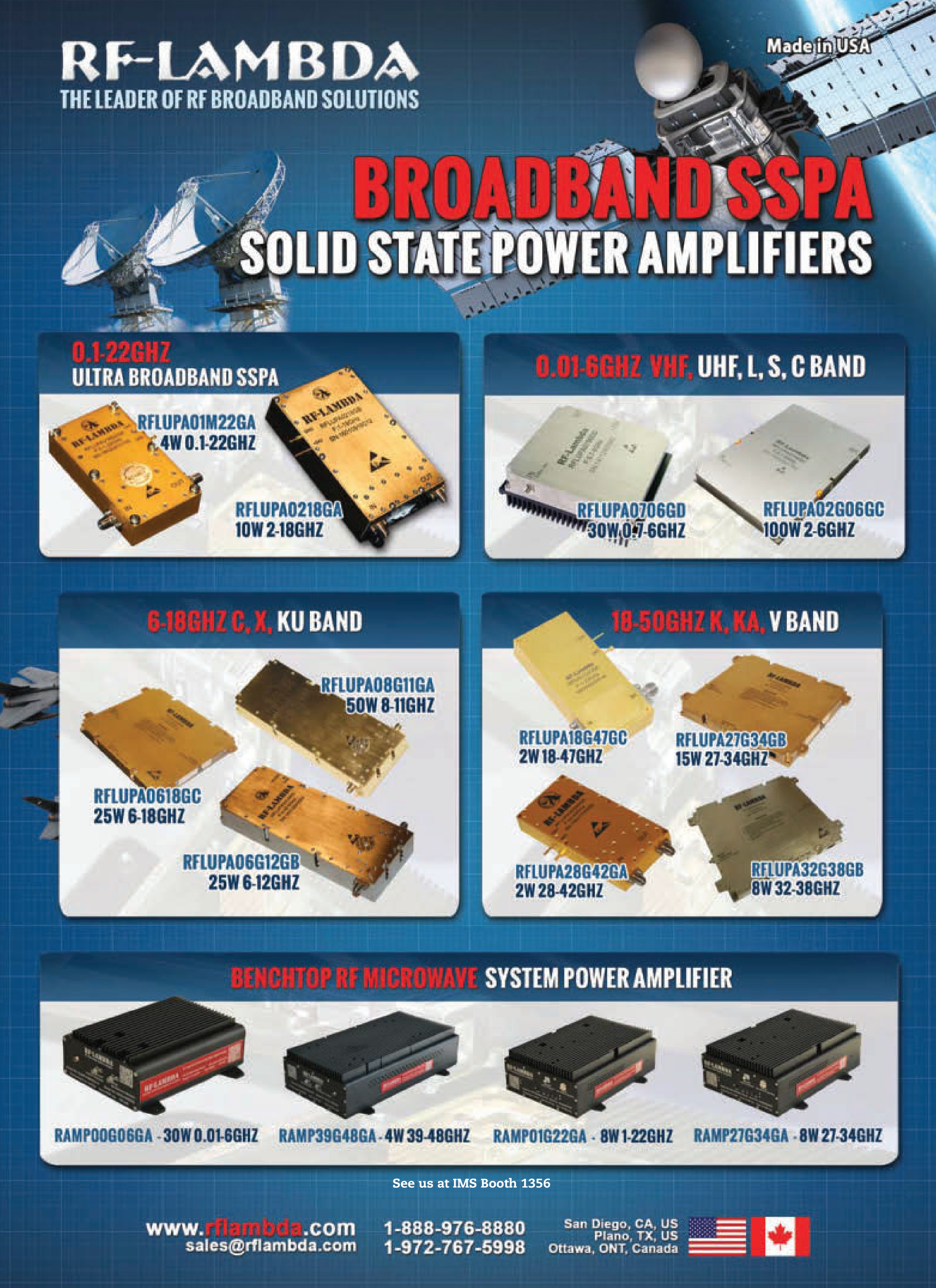
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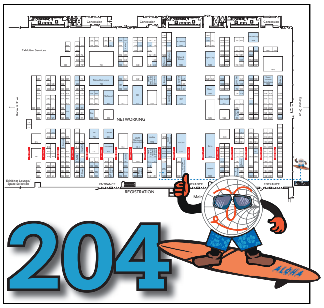

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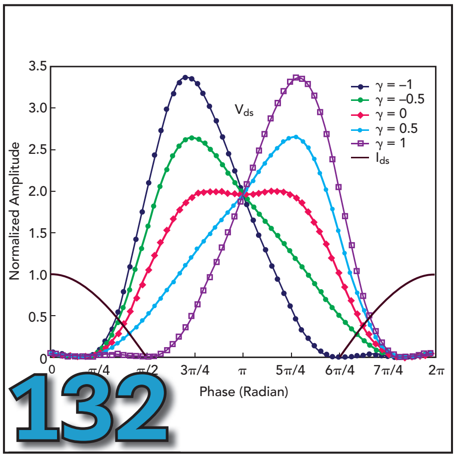

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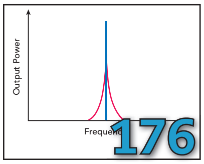

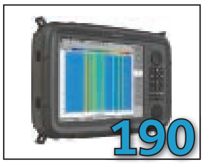

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John Richardson, president of **X-Microwave**, describes the company's modular building block system and how it merges the simulation, prototyping and production of RF/microwave subsystems to accelerate development and time-to-market.

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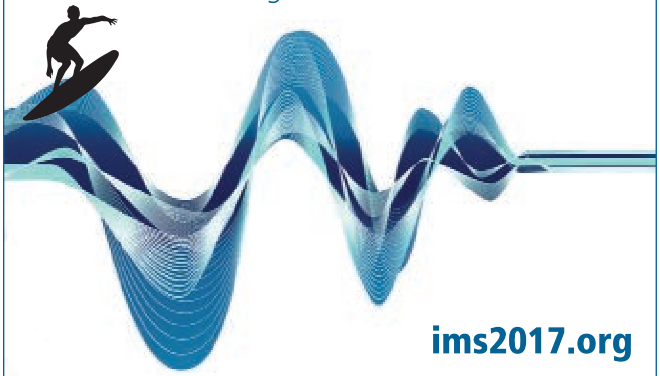

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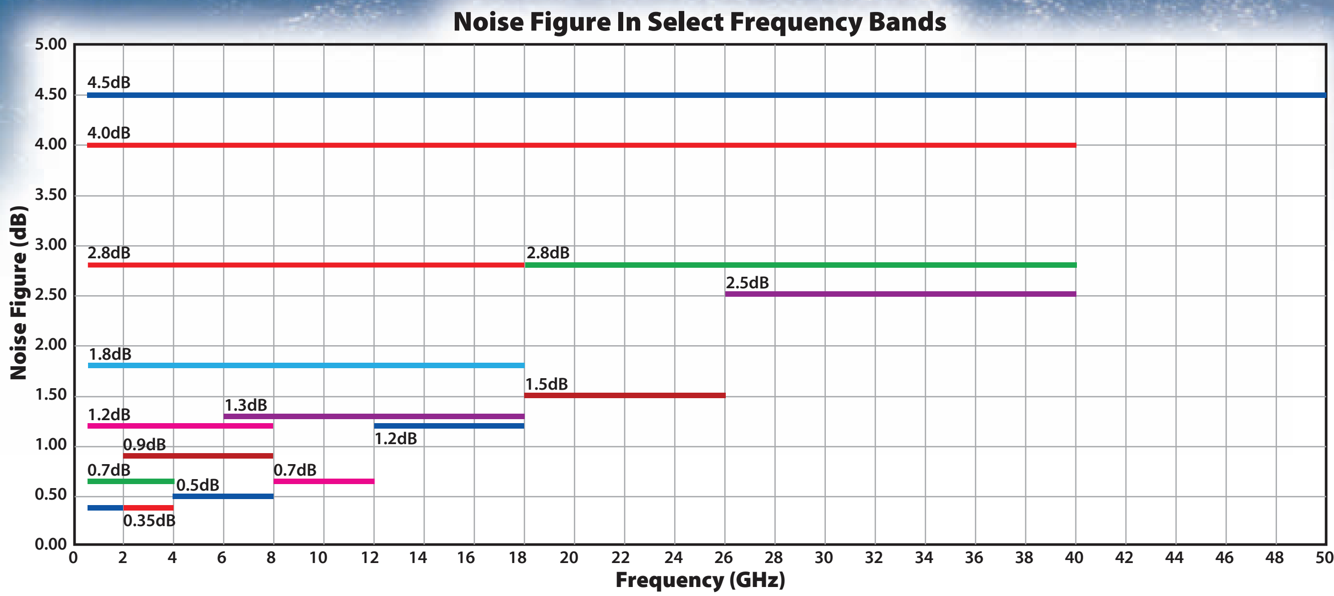


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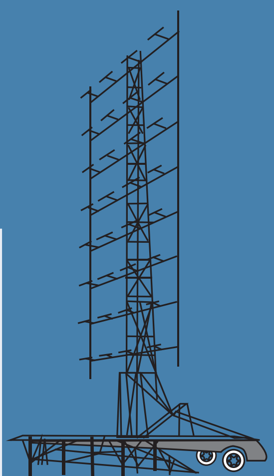

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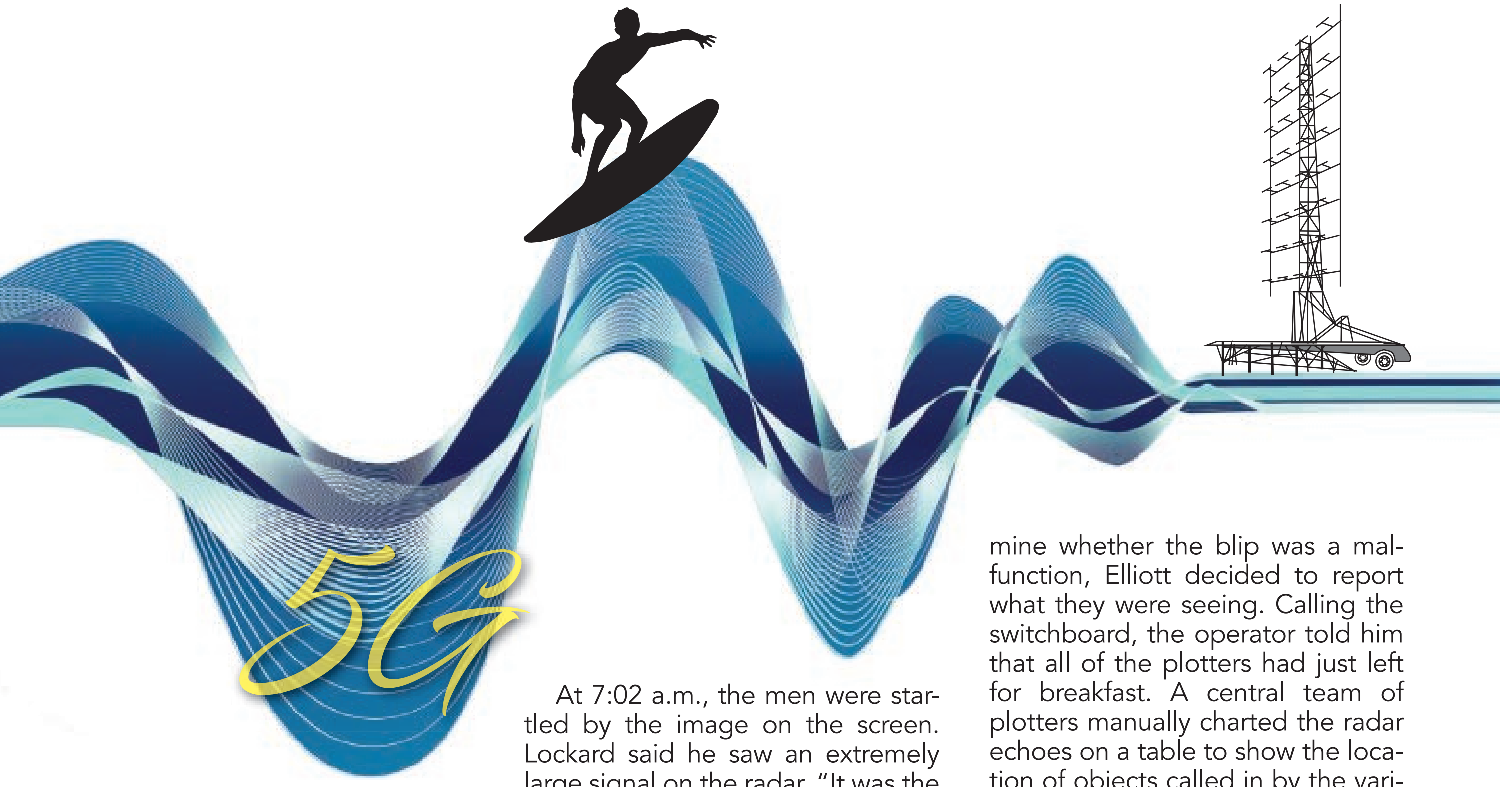
The Infamous Pearl Harbor Radar

Patrick Hindle, Richard Mumford and Gary Lerude
Microwave Journal *Editors*



On Sunday morning, December 7, 1941, U.S. Privates Joseph L. Lockard and George Elliot were ending their shift operating the new, state-of-the-art SCR-270 radar (Set Complete Radio, no. 270) at the Opana radar site on the island of Oahu in Hawaii (see ***Figure 1***). They were scheduled to shut off the radar at 7:00 a.m., but Elliott wanted to keep going. He was still learning to operate the oscilloscope and needed more practice. They had time, as the truck picking them up had not arrived. Lockard, who had more experience with the system, was training the eager Elliot.

At 7:02 a.m., the men were startled by the image on the screen. Lockard said he saw an extremely large signal on the radar. "It was the largest group I had ever seen on the oscilloscope. It looked, as I said, like a main pulse and that is why I was confused, at first, as to whether it was a flight or not. I had never seen one... it produced the largest echo on the scope that I had ever seen."[1] They had detected Japanese planes, 132 miles out from the station, on their approach to attack Pearl Harbor.

After some discussion and cross checks to determine whether the blip was a malfunction, Elliott decided to report what they were seeing. Calling the switchboard, the operator told him that all of the plotters had just left for breakfast. A central team of plotters manually charted the radar echoes on a table to show the location of objects called in by the various radar sites. Around 7:20 a.m., Lieutenant Kermit Tyler returned El-

▲ **Fig. 1 The Opana radar site was located on the northern tip of Oahu. Source: Google Maps.**

▲ **Fig. 2** **The Chain Home was the first British radar system, used during World War II to warn of approaching German aircraft. Source: Wikimedia Commons.**

liott's call and listened to his observation. Tyler knew that B-17 bombers from the west coast of the U.S. typically arrived around 8:00 a.m. He had heard the local radio station on the air before 7:00 a.m., which pilots had told him was a sure sign that the B-17s were coming, as they used the radio signal for homing.[1] He assumed that explained the blip Elliott and Lockard were observing and summarized his assessment with the infamous statement, "Well, don't worry about it."[2]

Elliott and Lockard continued to track the unidentified planes for more than 30 minutes, until the planes became lost in the ground clutter. Leaving the site and coming down the hill for breakfast, they soon learned that Pearl Harbor was under attack. Inadvertently, the blip on the oscilloscope that had confused them was the first wartime use—and validation—of radar technology by the U.S. military, a technology that played a major role during the rest of World War II.

GLOBAL DEVELOPMENT OF MILITARY RADAR

Throughout the 1930s, political unease and military uncertainty led several European countries, the United States and Japan to independently investigate the use of radio echoes for aircraft detection. This research led several countries to develop some form of operational radar equipment that was fielded by the start of the war.

Britain began radar research for aircraft detection in 1935. By September 1938, the first radar system, the Chain Home (see ***Figure 2***), was operating around the clock and remained operational throughout the war, offering vital early warning of the heavy German aerial bombardment. The Chain Home radars, which were deployed under the direction of the inventor of British radar, Sir Robert Watson-Watt, made use of "available, working technology" and operated in the shortwave region, around 30 MHz.[3] The Germans pushed the development of radar in advance of the war, installing a radar on a naval pocket battleship as early as 1936.[3] Except for some radars that operated at 375 and 560 MHz, all of the successful radar systems developed prior to the start of World War II were in the VHF band, below about 200 MHz.[3] However, VHF radar systems suffered performance issues due to broad beamwidths that limited accuracy and resolution, and they were susceptible to echoes from the ground or other clutter. In the 1930s, the Soviet Union also researched military radar, and by the time the German offensive on the country was launched in June 1941, the Soviets had developed several types of radar including a production aircraft detection system that operated at 75 MHz.[3]

These early developers were aware that higher frequency operation was desirable, particularly since narrow beamwidths could be achieved without excessively large antennas. Using microwave frequencies became feasible in 1939, when the cavity magnetron oscillator was invented by British physicists at the University of Birmingham. The concept of the magnetron was shared with the United States in 1940, which became the basis for work by the Massachusetts Institute of Technology (MIT) Radiation Laboratory in Cambridge. More than 100 different radar systems were developed by the laboratory's program during its five years of existence (1940-1945). The microwave magnetron made many radar advances possible during World War II.

U.S. RADAR DEVELOPMENT

The U.S. Signal Corps had been experimenting with radar as early as the late 1920s. In the 1930s, the U.S. made a concerted effort to develop radar technology for military use. In August 1935, pulse radar testing began at Fort Monmouth and Fort Hancock, both in New Jersey, and produced positive results using a transmitter on a rooftop at Fort Monmouth and two receivers at Fort Hancock and Monmouth Beach, New Jersey.[4] By December 1936, the U.S Signal Corps had developed a working prototype and by May 1937 had demonstrated the system detecting a bomber at night.[4] The nighttime test was particularly impressive, because the bomber was off course. Intended to fly in a specific area, so the radar could detect it, the pilot could not find the correct coordinates. The radar located the plane by searching a wider area. After the initial development and testing, the radar project was moved from Fort Monmouth to Fort Hancock, because the latter was a secure facility. From the summer of 1937 to the summer of 1938, the radar group at Fort Hancock developed and tested the SCR-268, the first radar system that utilized both infrared and radio detection. The thermal system was not developed further, after the program determined it was not needed. In parallel with the SCR-268, longer range versions of the system were developed: the SCR-270 mobile and SCR-271 fixed verions. Although the SCR-268 was deployed at the Panama Canal before the SCR-270 was fielded in Hawaii, it was not the first to be used in wartime.

The U.S. military established an Aircraft Warning Service (AWS) to defend American territory in December 1939. The AWS deployed six mobile radar early warning sites on Oahu: Kawaiola, Wainaae, Kaaawa, Koko Head, Schofield Barracks and Fort Shafter. In November 1941, the SCR-270 system at the Schofield Barracks was moved to the Opana site, 532 feet above sea level with an unobstructed view of the Pacific Ocean. The month prior, a joint exercise performed by the Army and Navy on Oahu tested the readiness of the early warning system. Carrier-based aircraft simulated an attack during the predawn hours, and three Army SCR-270 radar units were able to detect the aircraft 80 miles out.[4] The exercise was successful, showing the technology worked, but not guaranteeing that future radar returns would be interpreted correctly.

After the Japanese attack, the British Royal Air Force (RAF) sent Watson-Watt to advise the U.S. military on air defense technology. He pointed out the general lack of understanding of the capabilities of radar at all levels of command. Radar was thought of as a new gadget "producing snap observations on targets which may or may not be aircraft."[5] The SCR-270 had operated as designed, but the data it generated was not handled properly. There were several failures: The privates reporting their observations did not say that the display appeared to be a formation of more than 50 planes, which may have changed the reaction of Lieutenant Tyler, who received the report. Tyler was too quick to dismiss the information, instead of investigating further and passing the report up the chain of command. However, even if the early warning had been effectively communicated and recognized, historians doubt it would have made much difference to the outcome of the surprise attack, since the Japanese sent such an overwhelming force.

THE SCR-270 RADAR

The SCR-270 radar operated at 106 MHz, using a pulse width from 10 to 25 μs and a pulse repetition frequency of 621 Hz. With a wavelength of about nine feet, the SRC-270 was comparable to the contemporary Chain Home system being developed in England, but not as high in frequency as the microwave systems developed in Germany at the time. The 106 MHz frequency proved useful, as the wavelength was roughly the size of a plane pro-

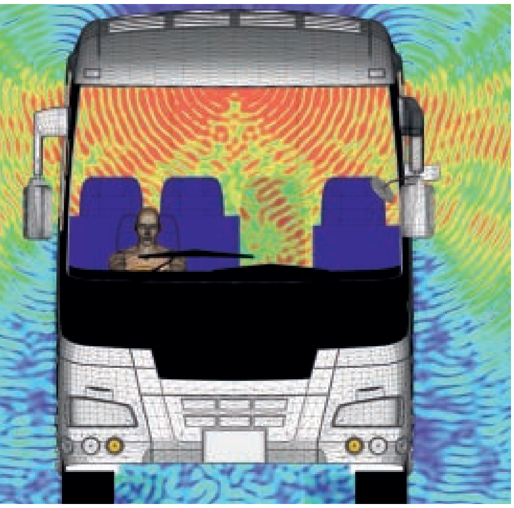


TABLE 1
SCR-270-D MAXIMUM RANGE

Aircraft Altitude	1,000 ft (300 m)	5,000 ft (1,500 m)	20,000 ft (6,100 m)	25,000 ft (7,600 m)
Radar Range	20 mi (32 km)	50 mi (80 km)	100 mi (160 km)	110 mi (180 km)

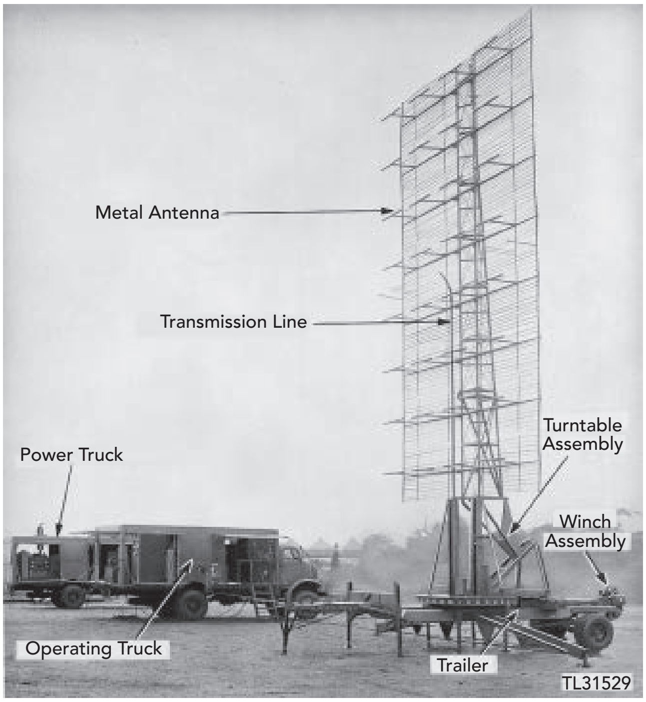


Fig. 3 SCR-270 mobile radar. Source: Wikipedia.

peller at that time, which provided strong returns (depending on the angle).[4] The radar had a maximum range of 150 miles, greater if the equipment was elevated.[7] A declassified U.S. military document, "U.S. Radar–Operational Characteristics of Available Equipment Classified by Tactical Application," gives the performance statistics for the SCR-270-D when the radar was on a flat site at sea level (see ***Table 1***).[6]

The SCR-270 was designed to be "mobile" but required four vehicles: a K-30 operations van for the radio equipment and oscilloscope, a K-31 gasoline-fueled, power-generating truck with the transmitter power supply, a K-22B flatbed trailer and a K-32 prime mover to pull the antenna mount (see ***Figure 3***).[4] A nine man field crew operated the system: a shift chief, two oscilloscope operators, two plotters, two technicians and two electricians.

The Westinghouse Electronics Division built the modulator, power supply, transmitter and other items and RCA supplied the receiver.[5] A production contract was awarded to Westinghouse to produce the full SCR-270 and 271 systems.

SCR-270 Antenna

The folding antenna mount, which was derived from a well drilling derrick, was mounted on the trailer so it could be moved. When deployed from its transportation position, it was 55 ft tall, mounted on an 8 ft wide base containing motors for rotating the antenna.[4] The base plate could be rotated remotely from the operating truck to steer the antenna. Numbers 3 in high were painted on plates attached to the 8 ft diameter rotating tower base, enabling the azimuth orientation to be read through a window from the operating truck, using binoculars at times—or just estimating if something obscured the numbers.[7]

The antenna consisted of a series of 36 half-wave dipoles backed with reflectors, in three bays, each with 12 dipoles arranged in a three-high, four-wide stack.[4] In use, the antenna was controlled by commands from the operations van, the angle being read from numbers painted on the antenna mount. The tuning on the

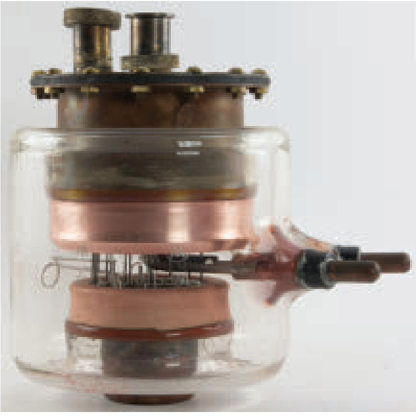


Fig. 4 Westinghouse WL-530 water-cooled triode, which was also designated by the Signal Corps number VT-122. Source: lampes-et-tubes.info.

early models was by shorting bars on parallel lines and line stretching "trombone" sections. RF to the antenna tower was carried from the operations van on a 3 in spaced copper tube parallel line to the base of the tower in a resonant line condition, terminating in a single-turn loop at the base, coupled to another single-turn loop feeding up the tower.[5]

In 1940, there was not a lot of confidence that the 106 MHz antenna could be designed and built correctly, since it had not been done. Westinghouse had a field station at Sandy Hook, New Jersey, with a distant view over the waters of New York Harbor to three large gas storage tanks in Brooklyn. To tune the antenna, the tower was aimed at the center tank. One person watched the scope in the operating truck, and one climbed the antenna tower with a 4 ft length of 1 × 2 inch wood. The person on the tower banged on the trombone sections and shorting bars to adjust them, as the scope operator 150 ft away yelled whether or not the target signal was improving. When the return from the center tank was strong and the return from the side tank small, the antenna was considered tuned. The antenna was then rotated to face the Glen L. Martin plant in Baltimore, where aircraft were almost always in the air. This also checked the performance and was a chance for final tuning. After following this process with about 25 antennas, enough data was accumulated to allow pre-positioning most adjustments. Ultimately, production used a screen reflector with pre-cut elements.[7]

SCR-270 Transmitter and Receiver

The heart of the radar was in the operating truck. Key to the system was the primary water-cooled 8 kW continuous or 100 kW pulsed transmitting vacuum tube (see ***Figure 4***). The transmitter used two water-cooled triodes with the grids held off at about −4500 V and pulsed up to 0 V to oscillate.[7] The 15 kV plate voltage required a dual-wound ceramic coil to isolate the plates from the grounded water supply, which used distilled water to minimize leakage current and ethyl alcohol as antifreeze in the winter.

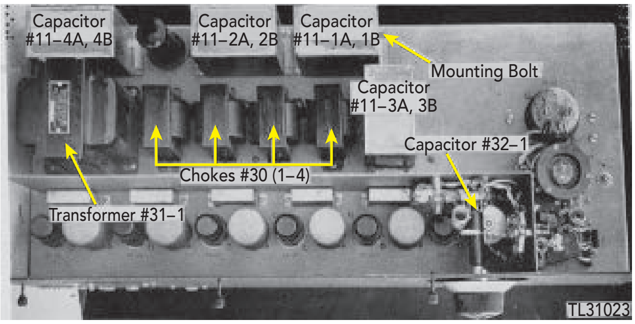
The first version of the prototype SCR-270 used a transmitter borrowed from the SCR-268, which delayed the SCR-268's development. The early SCR-270 and SCR-271 consisted of the BC-405 transmitter, built around the WL-530/VT-122 tube; its

modulator, called the BC-402 Keyer; and the RU-3 water cooler.[8]

Westinghouse delivered a pair of transmitters in January 1939, and they were incorporated into the first SCR-270 in time to be used in the Army's maneuvers that summer. These were the first tubes with enough power to enable long range detection, which the SCR-268 did not have. The development tubes were designated 3007 and WX3007, and the final version was assigned the Westinghouse catalog number WL-530 (the WL numbers were assigned in random order). Later, the Signal Corps vacuum tube number VT-122 was assigned to the WL-530.[7]

The receiver was a superheterodyne design, using a special tube (A-5588-A) and RCA experimental electron multiplier in the front-end (see *Figure 5*). RCA built the BC-403(*) 5 in oscilloscopes and the BC-404(*) receivers. The first of the BC-404s used the RCA VT-123 "Orbital Beam tube" that evolved into the 1630/VT-128.[8]

Each operating truck had a spare receiver and spare scope; however, everything was so conservatively designed that service was almost unheard of, except for the occasional modulator tube replacement.[7]



▲ **Fig. 5** **BC-404-C superheterodyne receiver used in the SCR-270. Source: TM-1-1510 service manual.**

Power Unit

The power unit truck housed a 76 horsepower gas engine driving a 31 kW three-phase, 60-cycle generator. The RA-33 15 kV, high voltage power supply, common to both the prototype SCR-268 and 270/1, was built by L.H. Terpening and later replaced by the Westinghouse RA-39 in the SCR-270-B and the similar RA-60 in later 270/1 models.[8]

The power supply—about 4 ft high, 5 ft wide and 6 ft deep—supplied 15 kV at 0.5 A from a full wave rectifier, a choke and a 0.5 mF capacitor (see *Figure 6*).[7] The power supply bottom, at the plate connection, was a cast finned structure that seated into a 3 in diameter ring mounted directly on top of the high voltage insulators on the transformer, to ensure no plate leads, caps, insulation and support problems.[7]

SUMMARY

Radar and microwave technology have made revolutionary advances since the 1930s. Consider the Sea-Based X-Band Radar (SBX-1), developed to provide early warning of ballistic missiles. Part of the Missile Defense Agency's missile defense


> Performance
> Power Density
Size <
Energy Costs <
WOLFSPEED'S NEW
KU-BAND SATCOM MMIC
• GaN MMIC for Lower Ku-Band
• 12.7-13.25 GHz Operating Frequency
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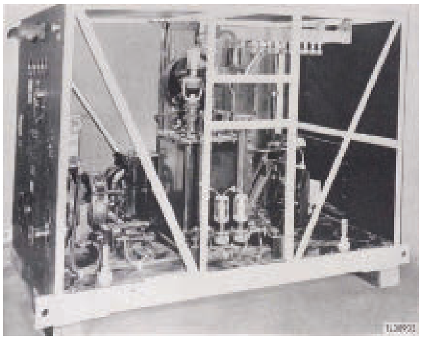

▲ **Fig. 6** **RA-60-A rectifier used in the SCR-270 power unit. Source: TM-1-1510 service manual.**

system, SBX-1 is a floating, self-propelled, AESA that uses 45,000 solid-state T/R modules (see ***Figure 7***). Deployed in the Pacific Ocean, the SBX-1 is, ironically, serviced at Pearl Harbor. Compare this to the four vehicle, mobile SCR-270, operating at 106 MHz.

Privates Lockard and Elliot stood guard over the SCR-270 radar for most of their 12 hour overnight shift, but they were able to operate the radar from 4:00 to 7:00 a.m., thought to be the most likely time the Japanese would attack. Just by chance, they kept the radar running two minutes longer and detected the Japanese planes that attacked Pearl Harbor on that infamous morning, December 7, 1941. The Opana Radar Site is now a National Historic Landmark and was designated an IEEE Historical Milestone in February 2000.[9] A plaque noting the IEEE designation was installed in a small park on the grounds of the Turtle Bay Hilton at Kuilima Point. Probably unnoticed by most tourists staying at the resort, the plaque commemorates the first operational use of radar by the United States.■

▲ **Fig. 7** **SBX-1 sea-based X-Band phased-array radar. Source: U.S. Navy Military Sealift Command.**

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Most Valuable Product

Real-Time Phase Noise Analyzer

Holzworth Instrumentation
Boulder, Colo.

Holzworth Instrumentation was founded on the sole premise of providing the industry's most accurate phase noise test systems, with a heavy emphasis on measurement speed, reliability and ease of use, while maintaining reasonable price points. Due to a lower market demand at the time, there were only a few test equipment manufacturers offering phase noise analysis products. With continuous growth occurring in both the defense and commercial high speed communications sectors, the founders of Holzworth saw an increasing demand for phase noise analysis on the production test floors of system, component and chipset manufacturers.

The HA7062C real-time phase noise analyzer is a dual-channel, cross-correlation system that was designed to address both the needs of R&D engineering as well as high volume manufacturing. The versatile design can collect data to unprecedented noise floor levels with industry-leading data acquisition speeds at the touch of a button. The reconfigurable analog front-end eliminates issues common to digital phase noise test systems, while offering numerous extended capabilities:

INTERNAL LOs

At its foundation, the analyzer utilizes two high performance HSX series RF synthesizers as the internal LO sources (see ***Figure 1***). These 10 MHz to 6 GHz synthesizers offer excellent phase noise performance (-144 dBc/Hz at 10 kHz offset with a 1 GHz: signal) and a pure spurious response of -90 dBc, typical. The use of internal LOs with these performance characteristics, as well as being optimized for low amplitude modulation (AM) noise, results in fast, clean data acquisition. For measurements using the internal LOs, the LO "jumper cables" remain in place to route each LO signal to its respective mixer (phase detector) via the LO input port.

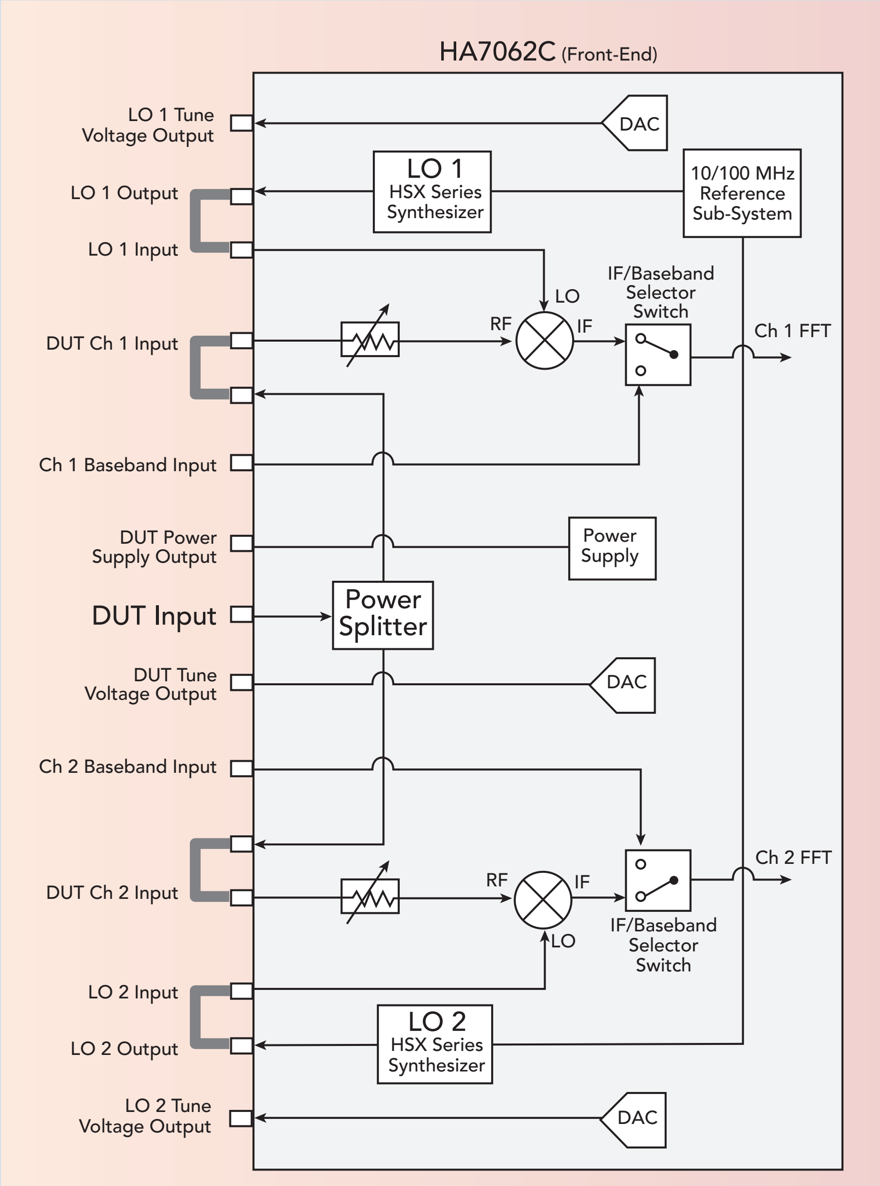
As a bonus, removing either LO jumper cable provides direct access to the independent, high performance synthesizer at the ch1 or ch2 LO output ports. Users have full graphical user interface (GUI) control of the internal synthesizers, which can be used as a high performance frequency source for additive measurements or a multitude of other test and measurement purposes.

EXTERNAL LO MODE

External LO mode is also available with the LO jumper cables removed. In 2010, Holzworth pioneered and automated the external LO mode function, primarily for high-end crystal oscillator manufacturers, with the release of the HA7402A phase noise analyzer engine (see ***Figure 2***). Utilizing two external voltage-tunable LO sources having the same frequency and similar phase noise performance as the device under test (DUT), provides immediate and accurate results to very low noise levels. This feature has been carried forward throughout Holzworth's analyzer revisions, including the current HA7062C, because profits are often measured in microseconds when it comes to high volume production. Naturally, other phase noise analyzer providers have adopted this timesaving measurement feature.

ADDITIVE PHASE NOISE

Automated additive (residual) phase noise measurements are a key feature of the HA7062C. Residual measurements have traditionally required an intensive test setup, especially when measur-



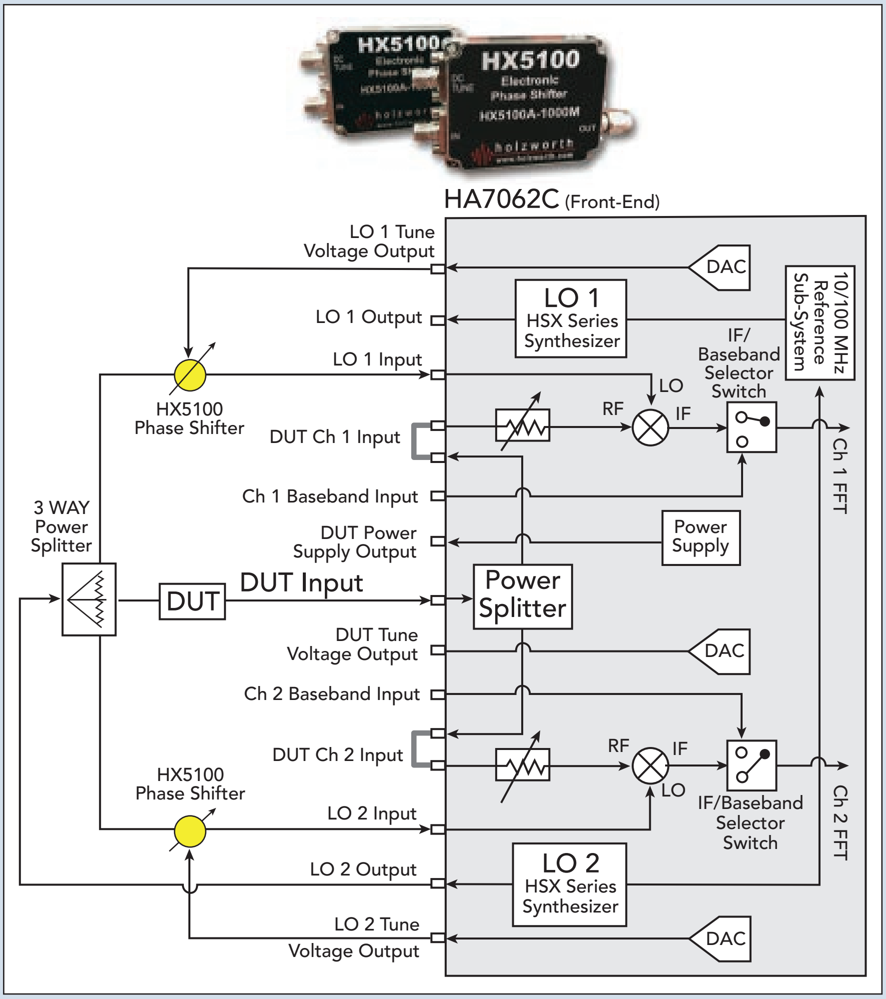
▲ Fig. 1 HA7062C front-end block diagram.

ing devices such as DDS ICs, multipliers, dividers and mixers. The HA7062C offers fully automated, cross-correlation, additive phase noise measurements by adding a pair of Holzworth exclusive HX5100 series electronic phase shifters (see ***Figure 3***). Incorporating the electronic phase shifters into an additive setup allows the analyzer to automatically set system quadrature and readily acquire data traceable to the National Institute of Standards and Technology (NIST) in Boulder, Colo. For users who prefer mechanical phase shifters, the HA7062C includes a quadrature monitor that provides visual feedback for quickly setting optimal quadrature to make valid measurements. To maintain NIST traceability, the system performs an internal calibration prior to every additive measurement, whether the HX5100 or mechanical phase shifters are used.

▲ Fig. 2 The external LO mode function was developed primarily for evaluating crystal oscillators.

MEASUREMENTS TO 26 GHz

The HA7062C base unit measures device frequencies to 6 GHz; there is no need to spend additional capital if a



▲ Fig. 3 Adding a pair of electronic phase shifters enables the HA7062C to perform fully automated, cross-correlation, additive phase noise measurements.

frequency extension is not necessary. For users pushing past 6 GHz, Holzworth offers the easily integrated HX4920 down-converter for precise, NIST traceable measurements to beyond 26 GHz. Once installed into the test setup, the user simply selects a radio button within the application GUI, and the analyzer automatically makes the appropriate system adjustments.

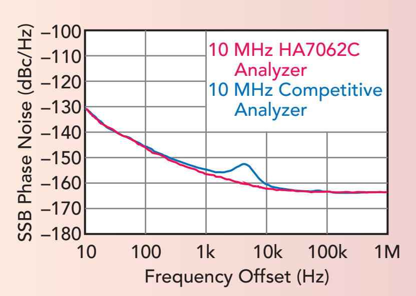
ACCURACY

Anyone familiar with phase noise measurements is aware of the constant scrutiny of the data, simply because of the incredibly low measurement levels achieved. Holzworth maintains that data accuracy is the most critical factor for any phase noise analysis system, placing it above and beyond any other parameter or feature. As modern devices push phase noise measurement requirements to lower and lower levels, accuracy becomes more difficult to maintain, especially as an instrument approaches its measurement limitations.

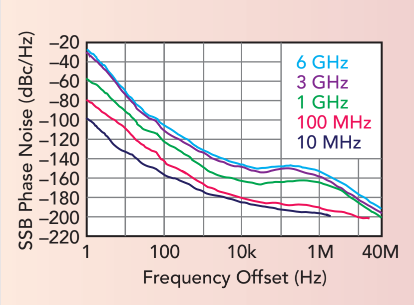
Holzworth's prior generation phase noise analyzers were designed to be calibrated to the ANSI Z540 standard, to provide NIST traceable data for specific customer requirements. The HA7062C design also incorporates the Z540 calibration standard, but it has been further extended down to a 0.1 Hz measurement offset. Each HA7062C real-time phase noise analyzer is shipped with a Z540 calibration certificate at no additional cost to the user.

AM NOISE IMMUNITY

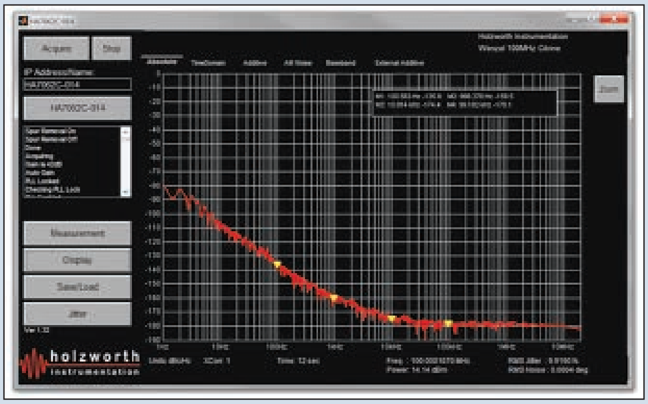
The HA7062C is capable of making precise, cross-correlated AM noise measurements while simultaneously measuring the phase modulation (PM) noise of a device. The ability to measure AM noise is not unique to the HA7062C, nor is the ability to simultaneously measure AM and PM noise. However, unlike other cross-correlating analysis solutions, the HA7062C's hardware has been specifically designed so that the AM noise does not have a direct influence on the PM noise response. As shown in ***Figure 4***, AM effects can affect the phase noise response curve in the form of an uncharacteristic bump or null.



▲ Fig. 4 AM effects can add an uncharacteristic bump or null in the phase noise response curve.



▲ Fig. 5 Measured HA7062C noise floors after 10x cross-correlations.



▲ Fig. 6 GUI screenshot showing the phase noise measurement of a 100 MHz OCXO, down to a 1 Hz offset.

The data displayed in this phase noise plot was collected using an HA7062C and a phase noise analyzer from a well known provider, both measuring the same high performance signal generator with amplitude modulation enabled, to exaggerate the potential effects of AM noise on the PM response. NIST has spent many years researching these phenomena and has published the results of their independent study. For more information, refer to "A Collapse of the Cross-Spectral Function in Phase Noise Metrology" by C.W. Nelson, A. Hati and D.A. Howe, published on February 25, 2014.

MEASURABLE NOISE FLOOR

Until the release of the HA7062C, the published noise floor limits for phase noise

TABLE 1

HA7062C PERFORMANCE SUMMARY

HA7062C Measurement Features	Absolute, Residual, AM, Baseband, Jitter, Spurious, Pulse, Time Domain
DUT Standard Frequency Range	10 MHz to 6 GHz
DUT Frequency Extension Range	6 to 26 GHz
DUT Input Power Range	-5 dBm to +20 dBm
Measurement Offset Range	0.1 Hz to 40 MHz (Z540 NIST Traceable)
Measurement Speed	INSANE
Measurement Noise Floor	<-195 dBc/Hz
Internal LO Mode	HSX Series RF Synthesizers
External LO Mode	User Supplied LOs (With Tune Voltage)
Baseband Input(s) Range	DC to 40 MHz
AM Noise Immunity	Inherent with Architecture
Data Test Standard	IEEE STD 1139-2008 (REV 2011)
Calibration Standard	ANSI Z540.1 (NIST Traceability 0.1 Hz to 40 MHz)
Power Supply	International AC Supply
Communications Interface	USB, Ethernet, GPIB, RS232
GUI Application Software	Matlab Runtime Shareware (64-bit and 32-bit)
ATE Command Line Driven	Can Be Operated Without Use of GUI
Warranty	3 Years

analyzers have been approximations, based on theoretical limits. Due to manufacturing tolerances, varying thermal noise conditions and more, not even two identical analyzers can provide the exact same test result. For these reasons, the HA7062C has been uniquely configured so that a user can actually measure the noise floor limit of their analyzer at any given frequency, based on the measurement offset value and the number of cross-correlations applied. ***Figure 5*** shows actual measured noise floors after 10x cross-correlations. Additional correlations will result in even lower measurement noise floors. The noise floor measurement configuration and additional data are available in the HA7062C product data sheet.

FAST AND EASY

Holzworth has direct experience with production test bottlenecks that are caused by phase noise measurements, because we have measured the phase noise of every single product we have ever shipped. By working closely with our customers and within our own laboratories, we have been able to greatly reduce the time to make these measurements. Immediately upon connecting a DUT, the analyzer makes all necessary system adjustments. Selecting “acquire,” the system self-calibrates and begins rapidly displaying data. As a demonstration of measurement speed, the data contained in the GUI screenshot of ***Figure 6*** is from a high-end 100 MHz oven-controlled crystal oscillator (OCXO). This is an example of a standard, yet slower acquisition when measuring down to a somewhat tedious 1 Hz offset limit. The test statistics located directly under the data plot reveal that only one correlation was required to achieve a -180 dBc/Hz DUT measurement within 12 seconds.

To further increase ease of use, Holzworth incorporated standard commands for programmable instruments (SCPI) instruction sets from historically popular phase noise analyzers, for ease of implementation into automated test equipment (ATE) systems. Updating an ATE system with an HA7062C real-time phase noise analyzer can literally be as easy as plug and play. No GUI is necessary.

FORWARD THINKING

With all Holzworth phase noise analysis solutions, the expanded capabilities keep coming. New measurement features are continuously being added to the capable platform via firmware and application updates. When new features are added, they become available to all existing and new customers. Both the firmware and GUI are easily field upgradable and are available at no additional charge.

Due to the industry’s growing demand for phase noise measurement systems, more test equipment manufacturers and rebranding companies are entering the phase noise test market. Some phase noise analyzers perform very well, and some fall short of meeting even their own published specifications. Some offer an outstanding level of features, while also having a high cost of ownership. Selecting a solid phase noise analysis solution for a specific application requires an investment in time to thoroughly evaluate the best options. The Holzworth HA7062C real-time phase noise analyzer is a highly reliable, accurate and feature rich solution that is right at home in R&D laboratories and ATE environments (see ***Table 1***).

VENDORVIEW

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Boulder, Colo.
www.holzworth.com

INVITED PAPER

Evolution of The IoT as a Service

Cees Links
Qorvo, Greensboro, N.C.

The concept of connectivity that is at the heart of the Internet of Things (IoT) is not new. The X10 communications protocol, which enabled wireless control of in-home devices, made its debut in the 1970s. We are also long accustomed to automatic garage door and car door openers and—more recently—smartphone applications that allow us to remotely manage the electronic devices in our homes.

What is different today is that advances in technology are moving us ever closer to realizing the full potential of the IoT to help manage our lives and enterprises. These innovations are enabling low power, smart sensors that can observe, learn and make decisions to create better, more efficient environments. Another new development is that we understand that consumers want more than just a collection of connected devices. They want to experience the benefits of the IoT as a service and without the challenge of having to research, locate, purchase, install and maintain a sensor network themselves.

IoT TECHNOLOGIES

To delve into the future of the IoT as a service, let's first look at the foundational technologies that support IoT content and how they are evolving to create smarter, more fully connected environments. The IoT requires connectivity at several levels: wide area networks (outdoor), local area networks (indoor) and personal area networks (wearable and mobile). The technologies that are enabling this today include LTE, Wi-Fi and Bluetooth.

LTE for Outdoor Wide Area Networks — LTE is the modern high speed wireless communications standard for mobile phones and data terminals that supports 4G services. The technology is easily deployed and optimizes network connectivity by using separate radio links for the device-to-tower uplink and tower-to-device downlink. LTE is important because it enables more efficient use of the ever-limited spectrum available to connect low power IoT devices with back-end systems.

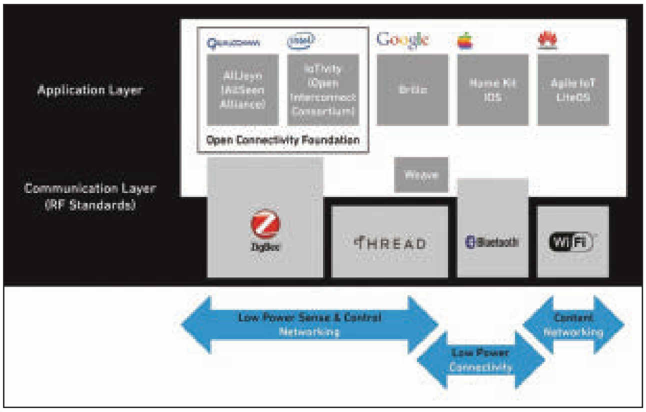
Wi-Fi for Indoor Local Area Networks — Wi-Fi, the 802.11x IEEE standard, is most commonly used for wireless networks in the home and within

businesses or organizations. Its ability to transmit data at very high rates also drains the battery and reduces operating time, which results in users having to charge their devices frequently. (Hence, the rise of technologies such as Bluetooth and ZigBee® that support small, low power IoT devices, where batteries can last for years.)

Bluetooth for Mobile or Wearable Personal Area Networks — Bluetooth is a low power, short-range communications technology primarily designed for point-to-point communications between wireless devices. While it has been used most often for applications in keyboards, mice, smartphones and headsets, Bluetooth is becoming more network capable, in the form of Bluetooth Low Energy (BLE), which supports lower power consumption and can directly access the internet.

At the heart of the IoT's future are small, "smart," lower power sensors and devices. Foundational connectivity technology is evolving to address the networking requirements for low power, just as chip technology is advancing to support multiple communications protocols within the same device. These newer options include:

Long Term Evolution for Machines (LTE-M) — LTE category M1 (LTE-M) is a low power version of LTE that enables IoT devices to connect to a 4G network directly. It supports significantly extended battery life—longer than 10 years—through a power savings mode where devices awaken only to transmit or receive data. LTE-M eliminates the need for full-featured LTE devices while still providing cellular-quality coverage.



▲ **Fig. 1** **Ensuring interoperability among competing standards is essential to the successful adoption of the IoT.**

ZigBee® — This low cost, low power, wireless, mesh network protocol is based on the IEEE 802.15.4 standard and is the most common protocol in the low power networking market, with a large installed base in both industrial environments and home devices. ZigBee 3.0 is the foundation for the IoT and "smart home" solutions, with redundant, low cost, ultra-low power devices and nodes. It is already anchored in the consumer electronics world with ZigBee RF4CE and ZigBee Green Power features. ZigBee Green Power minimizes power demand with self-powered energy harvesting. ZigBee RF4CE defines a low power, low latency, RF remote control network for two-way, device-to-device control applications that do not require a full-featured wireless mesh network.

Thread — A ZigBee 3.0 challenger, Thread entered the market as both a mesh networking protocol and working group founded by Google subsidiary Nest.

BLE — BLE devices consume significantly less power than traditional Bluetooth devices and can access the Internet directly through IPv6 over low power wireless personal area networks (6LoWPAN) connectivity. These features make it well suited for IoT devices that operate on small batteries or for energy-harvesting devices.

THE MOVE TO SMART DEVICES

In addition to competing standards at the communications layer, there is industry competition at the application layer (see ***Figure 1***). Both pose significant challenges for anyone who is developing, selling or purchasing products for the home. Consumers who wish to have a smart home are faced with having to decide between Wi-Fi, Bluetooth, ZigBee and other technologies. Companies that develop and market components for the home risk millions of dollars in development and customer support costs if they make the wrong choice.

Many IoT device discussions use the terms "smart" and "connected" interchangeably. Many devices called "smart" today are only slightly more capable than those launched decades ago. They are mostly standalone units that require human action to be turned on and off. For example, while a home security sensor may be "connected" and detects that no one is in the home, it does not interact with the lighting sensor to turn off the lights or with the heating system to turn down the thermostat.

A smart device and application can analyze incoming data and make a decision to control or activate a device without human intervention. In the case of the smart home environment, a network of devices can sense who is in the home, where they are in the home and learn what "normal" activity is at a particular day and time. Using this intelligence about the residents, the network makes decisions about whether to lock doors and windows; turn on or off the heater, air conditioner, lights or entertainment system; or activate the security system. To be considered "smart," a device must have three capabilities:

- Connect to and exchange data with other smart or connected devices in the home
- Recognize what goes on in the home and learn what is normal, beyond being programmed for a certain function at a certain time
- Use a single integrated application on a smart phone or other web-connected device to manage all the functions.

THE SMART HOME AS A SERVICE

While the IoT ultimately will affect every aspect of how our world operates, the home environment provides an excellent example of what is emerging as the future of the IoT as a service. Consumers are making it clear that they want more than a collection of sensors in their homes. They are not really seeking to own smart technology, rather they are looking for smart services and the ability of those services to help manage their lives.

The Smart Home as a Service (SHaaS) is the next phase of the home IoT evolution. SHaaS is a collection of services where devices, sensors and applications work to-

gether without human interaction. This network makes intelligent decisions that render homes more comfortable, safe and energy efficient. SHaaS solutions can reduce the number of sensors required in the home, and a single sensor can be used for a variety of applications. For example, a motion sensor can be used for the security system, light control, managing the temperature and controlling entertainment and senior lifestyle systems. There are four components of a SHaaS:

- A network of sensors in the home provides a general indication of when and where movement occurs, the environmental conditions and whether the home is secure or there are issues, such as a leak
- The information derived from these sensors is wirelessly collected by a local hub (e.g., gateway or set-top box) and securely transmitted to an intelligent cloud service that collects and analyzes the data and sends alerts to family members when it detects changes
- A central management app enables the consumer to manage the network using a single user interface on a smartphone or any web-connected device
- The service provider is easily able to handle customer support, billing, subscriber management, software and service upgrades and changes.

A SHaaS eliminates the need for the consumer to be technology-savvy. Rather than having to research, select and purchase equipment and try to guess which wireless technology standard to use, the consumer simply relies on the providers of the services they already use, such as internet access, security and entertainment. Their routers, modems and set-top boxes are already in the home, and customers are accustomed to paying a monthly bill for these services. Consumers can select the services they want and control them through a single smartphone app.

Retail organizations that provide some home services, such as Wal-Mart, Home Depot, Costco and others, could easily enter this market. Large security firms and integrators could market an entire suite of services as a unified package.

Applications and Benefits

The benefits of the SHaaS are limited only by the imagination. Here are a few examples:

Comfort, Cost Savings and Sustainability — If a family were watching a movie on a cold winter night, a smart home system would turn off the lights and turn down the heat in the empty parts of the home. Power-consuming devices that are on but not in use would also be turned off. The system would lower the temperature for sleeping during the night and begin to raise it again before the family awakens and begins the day. If the home network recognizes that the family is away on vacation, it would disconnect devices that consume standby power.

Connecting the water heater to a smart sensor would allow leaks to be detected early. The smart sensor would alert the homeowner and also control the power and water systems connected to it. With smart sensors, homeowners can remotely run their dishwashers and appliances. Problems would automatically be detected and relayed to a repair service. Home energy use and repair costs would be

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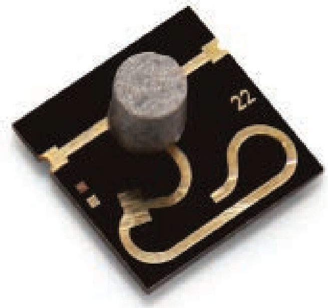

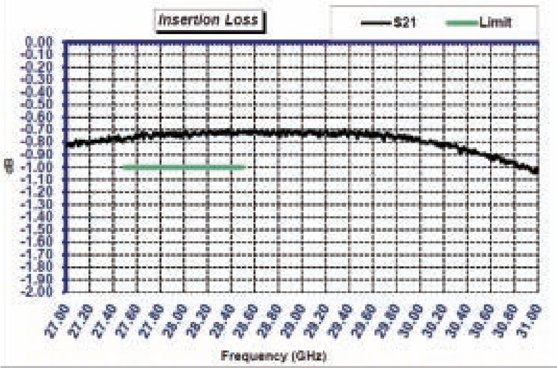

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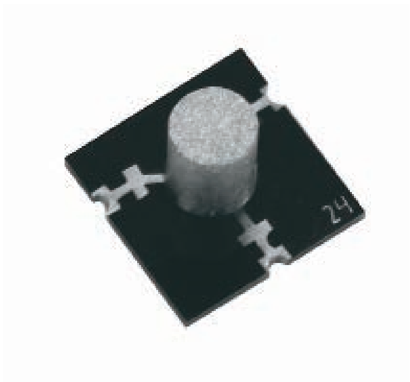

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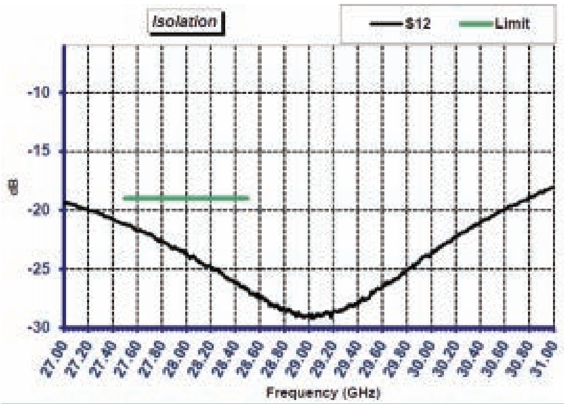

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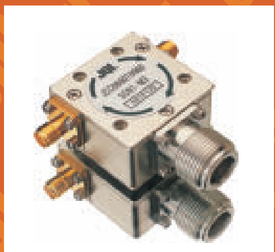

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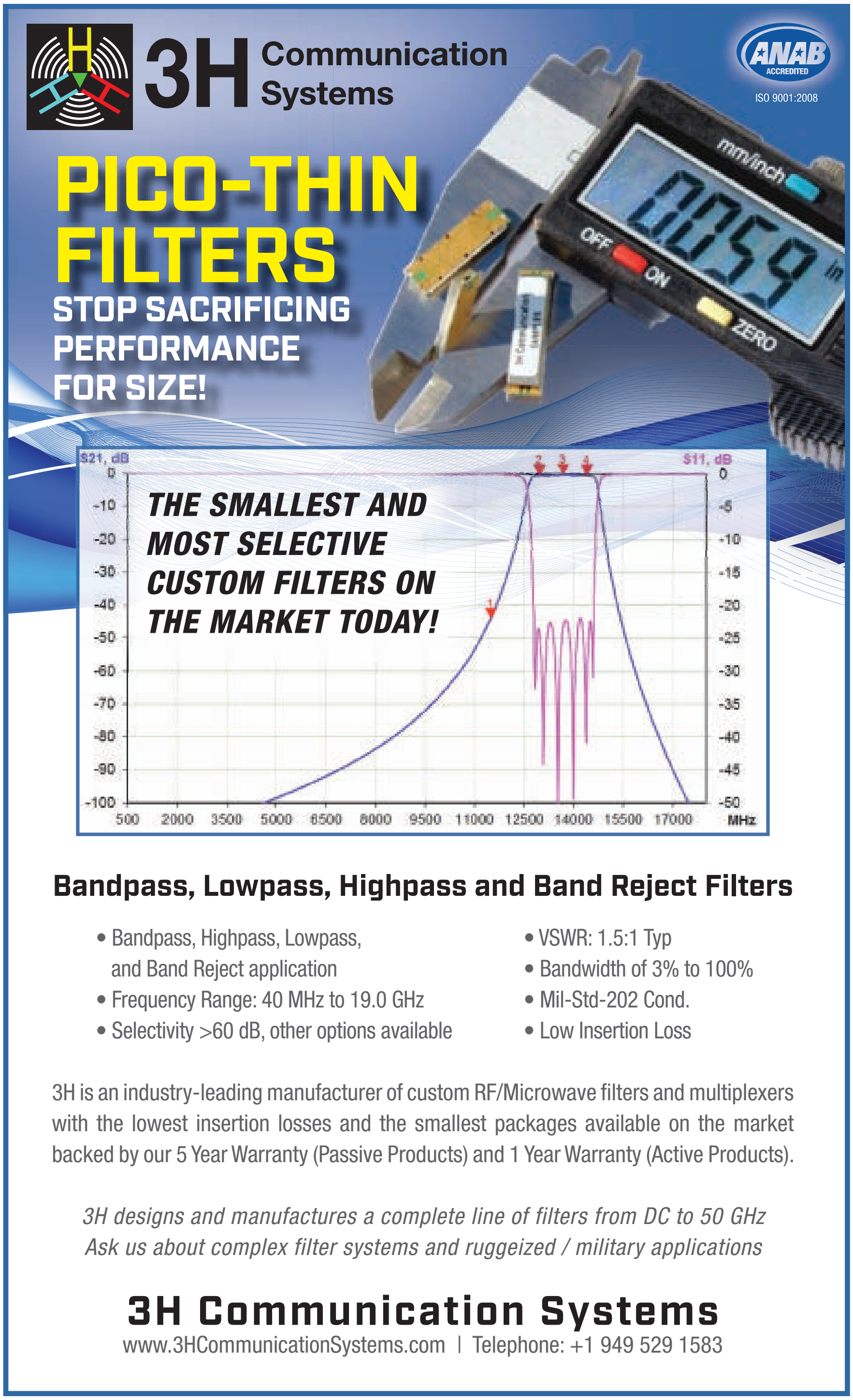
reduced and natural resources conserved. Insurance companies already are noting smart home applications that provide early warning of water leaks, heating system defects and fire, which can reduce repair, renovation and replacement costs.

Senior Lifestyle — Many of us are living longer and want to remain independent. The SHaaS for seniors can help keep us safe and comfortable in our own homes without feeling that we are being watched by cameras. To do so, a limited number of small, battery-powered sensors for motion detection and door opening and closing, strategically placed throughout the residence, would "observe" activities and collect data. When something out of the ordinary occurs, the system would automatically notify family members, a friend or emergency personnel.

Fitness and Healthcare — Wearable lifestyle and fitness technology would integrate many more data points, including from sensors in the home, and help ensure proper nutrition and rest based on our health goals and medical histories.



INDUSTRIAL IoT

The IoT is destined to have a profound impact, well beyond the home environment. It will transform virtually all industries, from hospitality and retail to automotive, agriculture and healthcare, altering the way that municipalities and public services operate. For example, smart cities of the future will likely leverage the IoT for city lighting management, traffic flow monitoring and control, emergency services deployment and natural resource management.

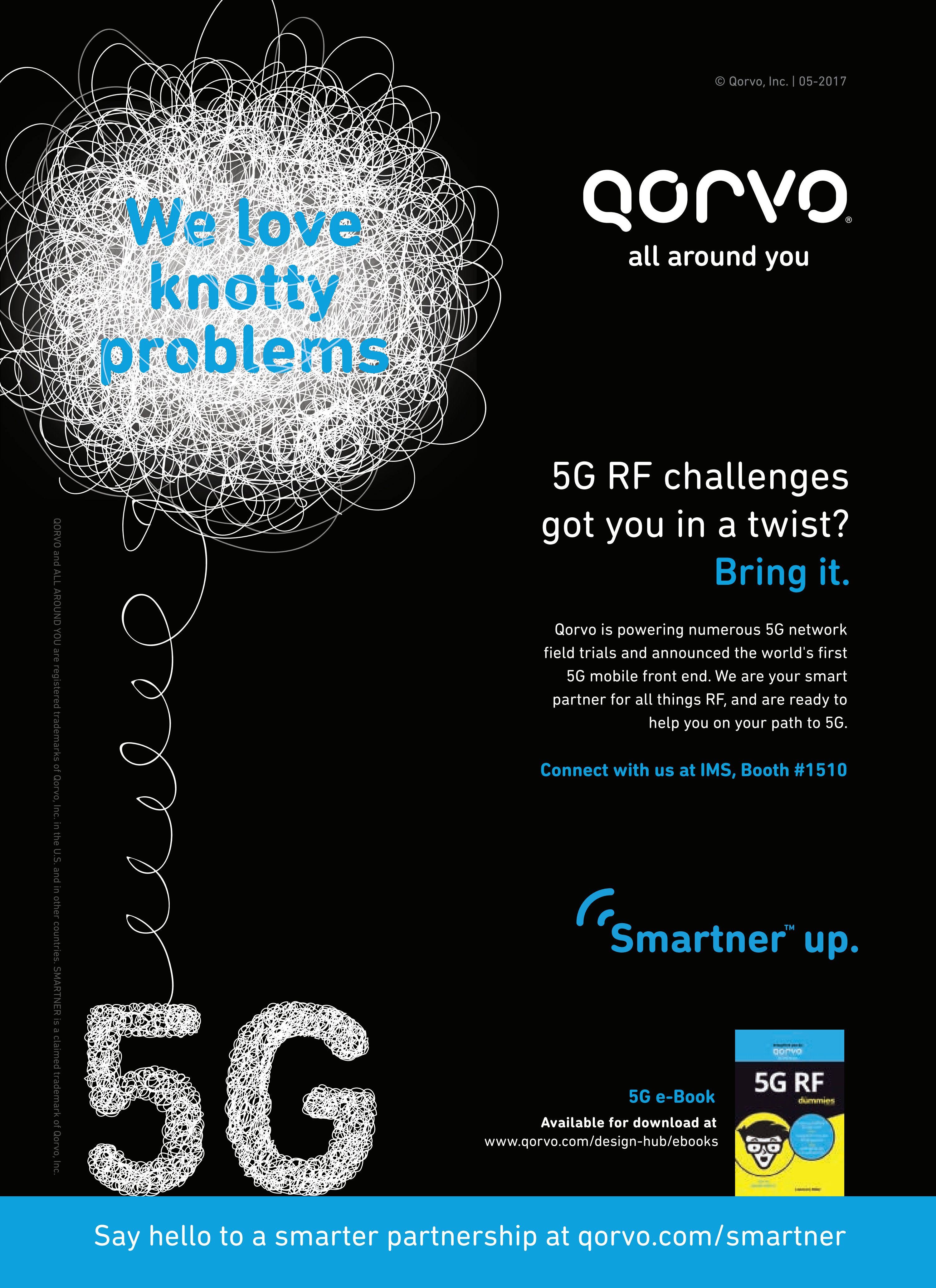
In manufacturing, the increasing complexity of just-in-time supply chain processes will benefit from IoT applications that enable more precise forecasting, inventory tracking and delivery of needed parts, as well as better collaboration between suppliers and customers. Biosensors in the healthcare environment will speed testing and accurate diagnosis of a wide variety of conditions. They will also monitor the ecosystems related to wellness, such as water quality, drug and food safety.

IT'S ALL ABOUT SERVICES

While advancing technology is essential to the future of the IoT, the goal of a more connected world is really about services. These services will enable informed decisions faster than ever, allowing us to better manage our lives as individuals and families and operate more efficiently as organizations.

A unified, smart IoT network, such as a SHaaS, delivers the benefits of connectivity, without the need for users to be technical experts. Device and system technologists can help realize the full potential of the IoT as a service by working together to develop the hardware, software and web intelligence that will make this possible.■

Cees Links *is general manager of the wireless connectivity business at Qorvo. He was the founder and CEO of GreenPeak Technologies, acquired by Qorvo in April 2016. Links pioneered the development of the first wireless LANs and has been recognized as a Wi-Fi pioneer with the Golden Mousetrap Lifetime Achievement award. He was instrumental in establishing the IEEE 802.15 standardization committee, the basis for ZigBee® sense and control networking.*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Catch the 5G Wave at IMS2017

Patrick Hindle
Microwave Journal *Editor*

The IEEE MTT International Microwave Symposium (IMS) returns to Honolulu, Hawaii this year taking place June 4-9 at the Hawaii Convention Center. It last visited the city in 2007 and celebrates its 60th year in 2017. It is the largest annual gathering of the RF and microwave industry consisting of a full week of events, including technical paper presentations, workshops, tutorials and commercial exhibition as well as numerous social events and networking opportunities. IMS is part of the larger Microwave Week, which includes the Radio Frequency Integrated Circuit Symposium (RFIC) and the Automatic Radio Frequency Techniques Group Conference (ARFTG) and new this year, the IEEE 5G Summit. *Microwave Journal* has gathered a complete preview of the week's events from conference overviews to special events to products featured in the exhibition from many of the major exhibitors.

Honolulu is Hawaii's largest city and is similar to any major metropolitan area but add to that nearby rainforests, canyons, waterfalls, mountains and beautiful beaches; then you have a unique city. Waikiki is an urban beach with over 170 high-rise hotels, hundreds of bars and restaurants, crowded streets and constant action. Ala Moana is known for its famous shopping mall and beach. The mall has over 290 stores, 70 dining options and attracts over 42 million visitors a year. Manoa Valley was one of the first areas inhabited by non-native settlers. It contains vintage houses, botanical gardens, Manoa Falls and the University of Hawaii at Manoa where more than 18,000 students attend the main campus. Of course, there is Pearl Harbor with its famous memorial and visitor's center.

IMS2017 PREVIEW

Dr. Wayne Shiroma, IMS2017 General Chair

Aloha! IMS2017 has six consecutive days of the latest developments in RF/microwave technology and applications in the form of workshops, short courses, plenary session, technical sessions, interactive forums, panel sessions and other formats. Plus it has various receptions, awards ceremonies and company-sponsored events where attendees can interact and network outside of the exhibition or technical program. The exhibition will feature more than 400 companies covering a wide variety of products from devices to components to software and test equipment.

The IMS2017 Steering Committee has added several new initiatives to enhance the experience during Microwave Week:

- A joint MTT-S/ComSoc-sponsored IEEE 5G Summit featuring two half-day programs beginning on Monday, followed by a 5G Executive Forum on Tuesday.
- Dedicated Exhibit Hours on Wednesday to ensure that even the most die-hard technical attendees have an opportunity to visit the show floor.
- Exhibitor Workshops that offer exhibitors an opportunity to provide hands-on, practical training in areas.
- The first-ever IMS Hackathon–a fast-paced competition where participants use basic microwave theory and design techniques to build a simple device on


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the fly, without using any CAD software or tools other than a calculator and internet references.

- The inaugural Three Minute Thesis Competition (3MT®), in which student and young professional finalists who have had a paper accepted to IMS give a non-specialist, three-minute presentation aided only by a single static slide.

In addition to these new initiatives, there is an array of activities highlighting several focus groups.

Young Professionals in Microwaves aims to encourage and engage the next generation of microwave professionals in the IEEE. This year they are hosting an interactive panel and networking event. Enjoy drinks, food and lively conversation between attendees and panelists who will be sharing some of their personal experiences and tips for being a microwave professional.

Women in Microwaves (WIM) is coordinating three events this year: a panel session, a special technical session and a networking event. The WIM panel session will be open for the first time to our STEM participants, to encourage young women interested in engineering. A social and networking event will occur after the panel session and offers a chance to meet with the panelists as well as other WIM. IMS2017 also debuts a special technical session called "Women in Defense," showcasing the work of leading women microwave engineers in the defense field.

The **STEM** program introduces a diverse and highly motivated group of middle and high school students and teachers to the world of professional microwave engineering. Students participate in a structured agenda of STEM experiences with members of the microwave community designed to further encourage interest and engagement in STEM subjects and careers.

The **Project Connect** program provides outreach to underrepresented minority groups in the microwave field. Approximately 30 undergraduate and graduate student applicants attend IMS2017 through a travel grant and participate in a three-day agenda designed to expose them to the microwave engineering community and current research and industry.

For newcomers, try the **RF Boot Camp**, a one day course ideal for beginners in the microwave world and the workshop, "**From Bits to Waves: Building a Modern Digital Radio in 1 Day**," a fun and interactive short course where participants learn the basic theory of modern digital radios as well as the RF circuits and systems used to build them.

Whether you are an IMS veteran or a first-time attendee, IMS2017 invites you to Catch the Wave and experience what's new at IMS2017!

2017 RFIC SYMPOSIUM

Kevin W. Kobayashi, General Chair; Walid Ali-Ahmad and Stefano Pellerano, Technical Program Co-Chairs

The 2017 IEEE Radio Frequency Integrated Circuits Symposium (RFIC 2017) is the premier integrated circuit (IC) design conference focused exclusively on the latest advances in RF, microwave and millimeter-wave IC technologies and designs, as well as innovations in high-frequency analog/mixed-signal ICs and will be held on June 4-6. Attendees will have the opportunity to interact with world experts, expand their network and leave invigorated with new ideas and a drive to innovate.

RFIC 2017 will continue to offer a number of initiatives: The 2-page industry brief format, allowing the latest state-of-the-art RF IC design results to be presented without requiring die photos and detailed schematics, will continue in 2017. The popular Industry Showcase Session, featuring poster presentations (and optional demos) of the most innovative and highly-rated industrial papers (both 2- and 4-page), will be the highlight during the RFIC Reception on the evening of Sunday, June 4, 2017. The Interactive Forum (IF) Session will continue

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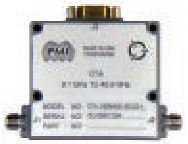

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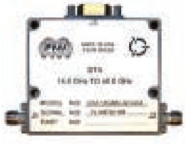

Package Size: 2.0" x 1.8' x 0.5"
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Connectors: 2.92mm (F) & 15 Pin Micro-D-Female
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Frequency	0.1 to 40.0 GHz	14.0 to 40.0 GHz
Attenuation Range	30 dB	32 dB
Insertion Loss	5.0 dB Typ. (to 20 GHz) - Measured 4.9 dB 8.0 dB Typ. (to 40 GHz) - Measured 7.1 dB	9.0 dB Typ. - Measured 8.62 dB
VSWR	2.5:1 Max. - Measured 2.49:1	2.0:1 Typ. - Measured 1.75:1
Attenuation Flatness	±1.5 dB Typ. Measured: @ 10 dB: ±0.95 dB @ 20 dB: ±1.47 dB @ 30 dB: ±2.13 dB	±1.5 dB Typ. Measured: @ 8 dB: ±0.61 dB @ 16 dB: ±1.01 dB @ 32 dB: ±1.77 dB
Attenuation Accuracy	±2.5 dB Typ. Measured: 0 to 10 dB: ±0.59 dB 10 to 20 dB: ±0.09 dB 20 to 30 dB: ±0.20 dB	±2.0 dB Typ. Measured: 0 to 8 dB: ±0.28 dB 8 to 16 dB: ±0.05 dB 16 to 32 dB: ±0.15 dB
Operating Temperature	-50 ºC to +85 ºC	-40 ºC to +85 ºC

Model: DTA-18G40G-30-CD-1 & DTA-18G40G-50-CD-1

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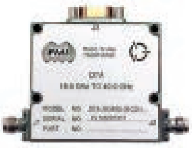

Package Size: 2.0" x 1.8' x 0.5"
DC Voltage: +15 VDC @ 38 mA
Connectors: 2.92mm (F) & 15 Pin Micro-D-Female
Switching Speed: Measured 0.30 µs

Package Size: 2.0" x 1.8' x 0.5"
DC Voltage: +15 VDC @ 38 mA
Connectors: 2.92mm (F) & 15 Pin Micro-D-Female
Switching Speed: Measured 0.12 µs

Specfications	DTA-18G40G-30-CD-1	DTA-18G40G-50-CD-1
Frequency	18.0 to 40.0 GHz	18.0 to 40.0 GHz
Attenuation Range	30 dB	50 dB
Insertion Loss	6.0 dB Typ. - Measured 6.1 dB	8.5 dB Typ - Measured 10.4 dB
VSWR	2.5:1 Max. - Measured 2.11:1	2.5:1 Typ. - Measured 2.27:1
Attenuation Flatness	±1.5 dB Typ Measured: @ 10 dB: ±0.98 dB @ 20 dB: ±1.27 dB @ 30 dB: ±1.93 dB	±1.5 dB Typ Measured: @ 16 dB: ±2.10 dB @ 32 dB: ±2.10 dB @ 50 dB: ±3.88 dB
Attenuation Accuracy	±2.0 dB Typ. Measured: 0 to 10 dB: ±0.39 dB 10 to 20 dB: ±0.54 dB 20 to 30 dB: ±0.76 dB	±2.0 dB Typ. Measured: 0 to 16 dB: ±0.14 dB 16 to 32 dB: ±0.18 dB 32 to 50 dB: ±0.48 dB
Operating Temperature	-40 ºC to +85 ºC	-40 ºC to +85 ºC

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to be held jointly with the Industry Showcase during the RFIC Reception, and will offer the attendees an enhanced interactive technical experience in a relaxed environment. Short 1-minute video highlights of each industry showcase and interactive forum poster presentation will be featured on IEEE.tv and posted on the RFIC website after the conference, providing authors and their affiliations publicity for their work.

The 2017 RFIC Symposium will begin on Sunday with 16 RFIC focused workshops (10 full-day and six half-day) held at the Convention Center. In addition, there will be several joint RFIC/IMS workshops on Sunday and Monday. These workshops cover a wide range of advanced topics in RFIC technology and IC design, including 5G systems and beyond.

The Plenary Session will be held on Sunday evening at the Hilton Hawaiian Village Hotel, the IMS headquarters, after a full day of workshops that take place at the Hawaii Convention Center. Shuttle buses will be ready to promptly take RFIC workshop participants from the Convention Center to the RFIC Plenary session at the Hilton Hawaiian Village Hotel. The Plenary Session will begin with conference highlights, followed by presentation of the Best Student Paper Awards sponsored by TSMC and the Industry Best Paper Award.

The Plenary Session will conclude with two outstanding keynote talks focused on 5G, beginning with Dr. Seizo Onoe, CTO and EVP of NTT Docomo who will enlighten us on the "Deployment Realities of 5G." In this talk, Dr. Seizo Onoe will discuss 5G technologies, the timelines, lessons learned from past generations and experimental trials and their latest results.

The second plenary talk will be given by the Wireless Communications Industry Chair Professor at UCSD and National Academy of Engineering member, Prof. Gabriel Rebeiz, who will share his vision on "RFIC/Silicon-based Phased Arrays and Transceivers for 5G." Prof. Rebeiz will present the progression of phased-array systems from defense-oriented applications to becoming the cornerstone of commercial 5G systems, and the role of silicon RFICs and advanced packaging in the deployment of these 5G systems.

Immediately following the plenary session will be the RFIC "Interactive" Reception that will highlight the Industry Showcase and Interactive Forum papers in an engaging social and technical evening event supported by this year's RFIC Symposium corporate sponsors (SMIC, MaxLinear, Qorvo, TSMC, ADI, GLOBALFOUNDRIES, Intel, Qualcomm, TowerJazz, Cadence, Skyworks).

On Monday and Tuesday, RFIC will have multiple tracks of oral technical paper sessions. Keeping with the 5G plenary theme, Monday morning will feature 5G focused technical sessions. Two entertaining panels will be featured during lunchtime on both days. The Monday panel session, moderated by

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Brian Floyd and Oren Eliezer, is titled "5th Generation Wireless–Where is that going and what's in it for me?" The Tuesday panel session will be a gameshow-quiz titled "Who Wants to be a Millimeterwavionaire?" Two teams of contestants, including preselected and randomly selected contestants from the audience, will compete in answering questions on RF and microwave theory and history, including IMS/RFIC conference trivia. Be ready to answer questions like "Who really invented the Smith Chart?" and "What is WIM?" Prizes will be awarded to the contestants, as well as to others in the audience who may be called upon for answers.

On behalf of the RFIC Steering and Executive Committees, we welcome you to join us at the 2017 RFIC Symposium in Honolulu, Hawaii!

2017 ARFTG CONFERENCE

Peter H. Aaen, ARFTG Chair

The theme for this year's conference is "Advanced Technologies for Communications" and the ARFTG conference will highlight the following key topics:

- 5G communications and beyond
- Internet of Things (IoT)
- Nanomaterials for communications

as well as contributions in other areas of RF, microwave and millimeter wave measurement techniques and technologies, such as wide bandwidth measurements, nonlinear systems and power amplifier measurements and modeling, calibration techniques, de-embedding and more.

The environment at the conference is informal and friendly. There are technical sessions and invited speakers, an exhibition of instrument and equipment vendors, a poster session and an awards luncheon. The oral technical sessions at ARFTG conferences are conducted in a single-track style, with papers on topical subjects that are both theoretical and practical, address both end-user and manufacturer and cover both modeling and measurement. Authors may present their work as poster papers in the open forum that jointly runs with the vendor exhibition.

One of the most stimulating parts of the ARFTG experience is the opportunity to directly interact on a one-to-one basis with colleagues, experts and vendors in the RF/microwave test and measurement community. Networking is a key feature of ARFTG's conference, with ample breaks to allow attendees to view the posters, meet the vendors and discuss their new products and measurement solutions, as well as meet up with old friends and new colleagues. Attendees will always come away with something—maybe some new ideas to help with current projects, some new technical

contacts to use in the future or some answers to your tough questions.

WHAT IS ARFTG?

ARFTG is the "Automated RF Techniques Group." It is a technical organization interested in all aspects of RF and microwave test and measurement. ARFTG was originally set up in 1972 to help end-users get the most from the latest generation of test and measurement equipment; at the time, this was predominantly the vector network analyzer or VNA: a completely new instrument class. As the high frequency measurement industry has continued to evolve, so has ARFTG, and it now covers the measurement space from kHz to THz, nonlinear or large signal network analyzers, signal analyzers, mixed-signal domains, signal integrity and much more. ARFTG now has more than 900 members worldwide.

ARFTG's core mission is education, and it achieves this by hosting conferences, workshops and training courses covering a wide range of topics in RF, microwave and millimeter wave measurement, and by awarding research fellowships for graduate students and sponsorships to enable students to attend.

5G SUMMIT

The IEEE Microwave Theory and Techniques Society (MTT-S) in partnership with the IEEE Communications Society (ComSoc) have joined forces to offer a special 5G Summit this year on June 5-6 at IMS2017. The summit will feature industry experts representing both the hardware/systems and networking/services aspects for the upcoming 5G standard.

The 5G Summit will feature a keynote presentation from Flavio Bonomi, founder and CEO of Nebbiolo Technologies, and Professor (Emeritus) Arogyaswami Paulraj of Stanford University. Bonomi will provide an overview of 5G and show the relationship between fog computing and networking as a key enabler of the technology, whereas Prof. Arogyaswami will focus on the latest research in massive MIMO.

For an insider's view of 5G, the Summit includes the 5G Executive Forum, a two-hour session with executive leaders in the field that will be open to all conference attendees—concluding with a networking reception. Speakers include:

- Dr. Sanyogita Shamsunder, Exec Director 5G Strategy/EcoSystem, Verizon
- Dr. Vida Ilderem, Vice President of Intel Labs and Director of Wireless Communication Research
- Dr. Bami Bastani, Senior Vice President for the RF Business Unit at GLOBALFOUNDRIES
- Dr. Michael Stewart, CEO and a Co-Founder of Escape Communications Inc.
- Dr. Khurram P. Sheikh, CEO of Kwikbit

- Dr. Mark Pierpoint, Vice President and General Manager of the Internet Infrastructure Solutions Group at Keysight Technologies Inc.

IMS2017 MICROAPPS

The Microwave Applications Seminars (MicroApps) will take center stage at the 2017 International Microwave Symposium (IMS) Exhibition on Tuesday, June 6 through Thursday, June 9 during the IMS Exhibition. MicroApps seminars are 20 minute technical presentations presented by IMS exhibitors, addressing commercial microwave technologies that are of interest to the microwave community.

The program will include more than 42 presentations from categories that include components, materials, CAD/simulation, design and test and measurement. In addition, MicroApps will feature three keynote talks and a panel discussion session, by microwave industry leaders. One of the feature panel sessions is organized by *Microwave Journal* on "The Future of RF Semiconductor Test," taking place on Wednesday, 12:00-1:00 p.m. This panel will be made up of test and measurement and semiconductor experts covering topics like on-wafer mmWave testing, low power/low cost approaches for IoT testing, RFFE module testing challenges and OTA testing; and how they will play in the future of semiconductor testing. The panelists include:

- Steve Reyes, VNA Product Manager, Anritsu
- Jason White, Director of Marketing, RF & Wireless Test, National Instruments
- Chris Scholz, North American Product Manager for VNAs, R&S
- Greg Peters, VP and GM, Aerospace/Defense/Government Solutions, Keysight
- Brad Nelson, Director of Engineering RF Components and Sources, Qorvo
- Rene Rodriguez, Senior Antenna Engineer, Skyworks

The complete, up-to-date MicroApps schedule is available in the IMS Program Book or online. In addition, posters placed near the MicroApps Theater will display the complete schedule during the Exhibition. MicroApps give IMS Exhibition attendees an ideal opportunity to see the latest products, services and technologies at the world's largest microwave exhibition. The MicroApps Theater will be in a prominent and very easy to find location at booth 1946 in the Exhibition Hall.

We invite you to visit the MicroApps Theater during IMS2017 to see the latest in microwave products and technology, in a dynamic live setting, right on the exhibition floor and "Catch the 5G Wave at IMS2017."■

IMS 2017 SHOW COVERAGE

Catch our exclusive conference information, news, social networking, photos, videos and more at mwjournal.com/IMS2017


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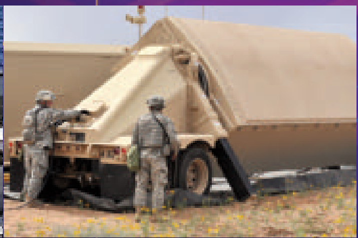

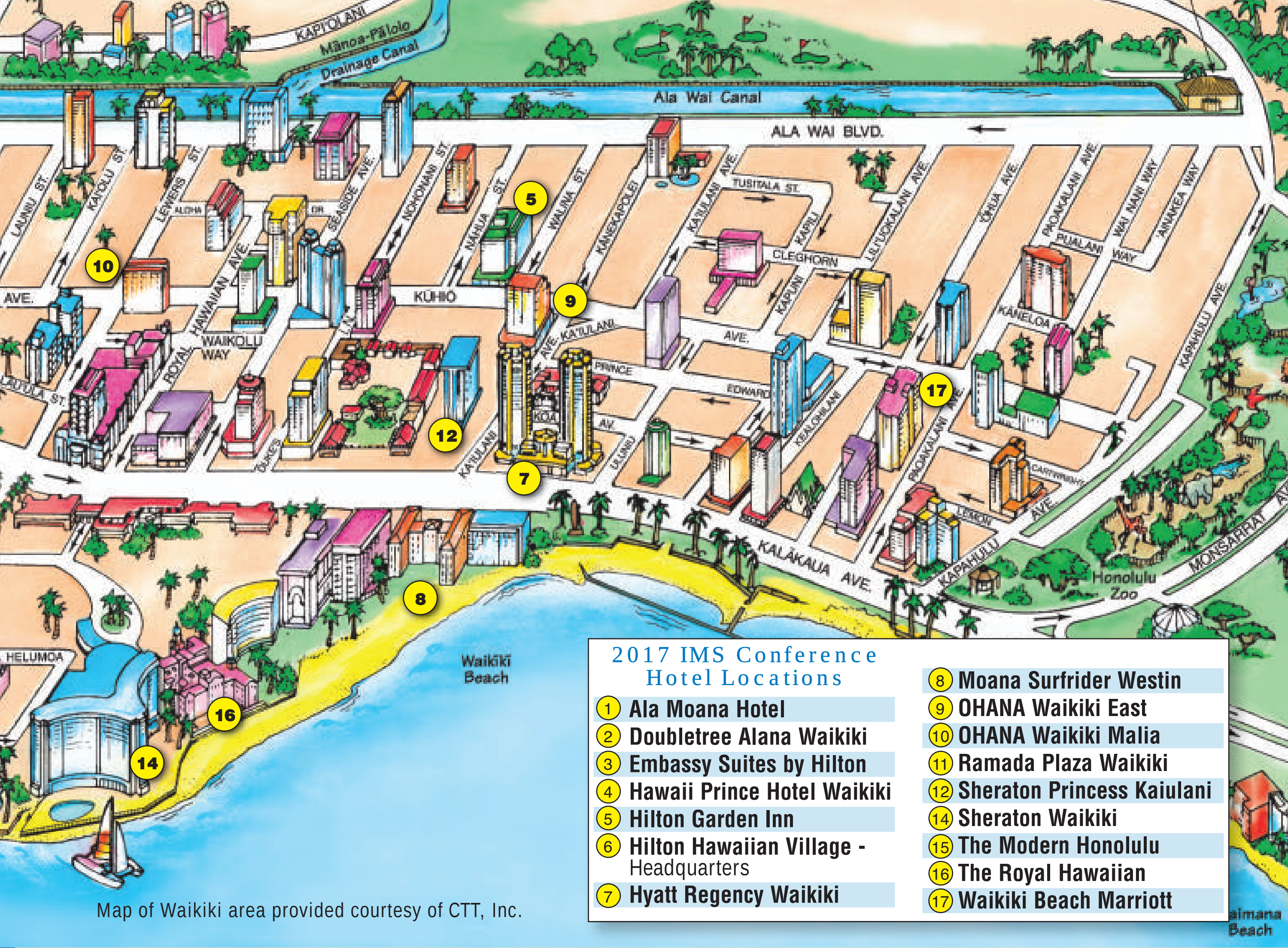

2017 IMS Conference Hotel Locations

1. Ala Moana Hotel
2. Doubletree Alana Waikiki
3. Embassy Suites by Hilton
4. Hawaii Prince Hotel Waikiki
5. Hilton Garden Inn
6. Hilton Hawaiian Village - Headquarters
7. Hyatt Regency Waikiki
8. Moana Surfrider Westin
9. OHANA Waikiki East
10. OHANA Waikiki Malia
11. Ramada Plaza Waikiki
12. Sheraton Princess Kaiulani
14. Sheraton Waikiki
15. The Modern Honolulu
16. The Royal Hawaiian
17. Waikiki Beach Marriott

Map of Waikiki area provided courtesy of CTT, Inc.

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- UAVs

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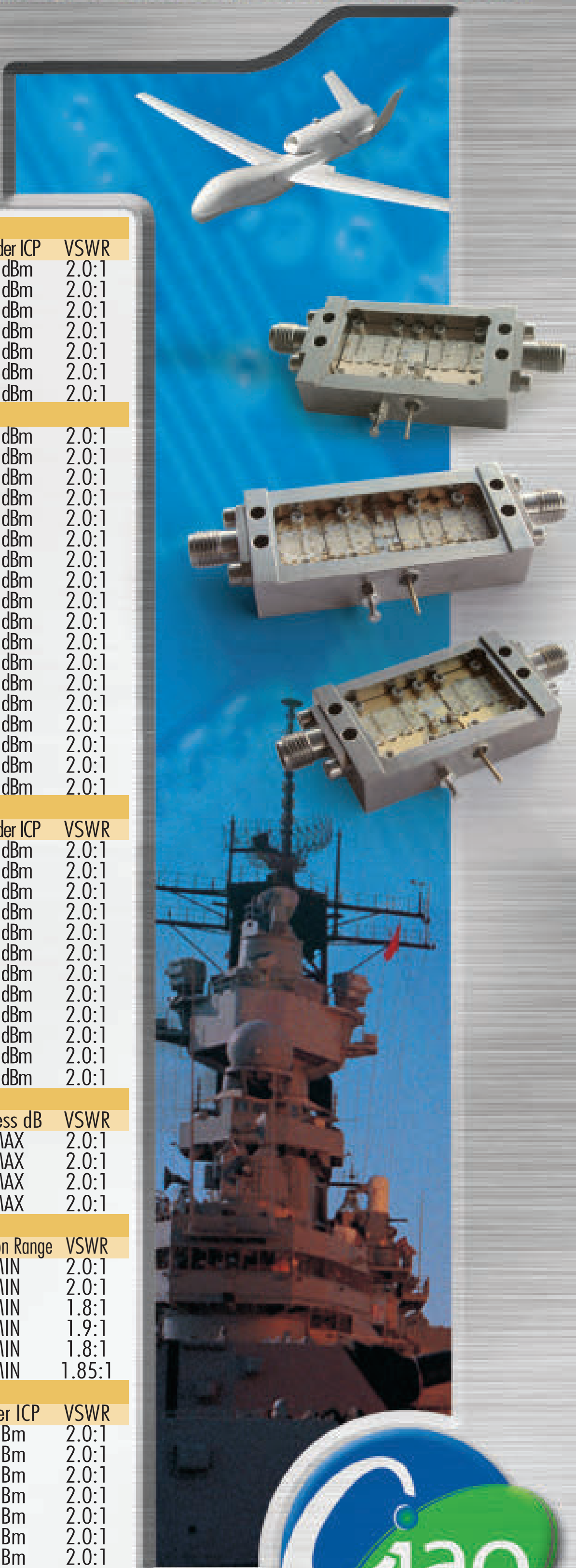

OCTAVE BAND LOW NOISE AMPLIFIERS

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

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

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

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

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

LIMITING AMPLIFIERS

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

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

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

LOW FREQUENCY AMPLIFIERS

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

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Raytheon's AMDR Successfully Executes 1st Ballistic Missile Test

Raytheon Company's AN/SPY-6(V) Air and Missile Defense Radar searched for, acquired and tracked a ballistic missile test target during the radar's first dedicated Ballistic Missile Defense exercise at the U.S. Navy's Pacific Missile Range Facility (PMRF) in Kauai, Hawaii. This result followed a series of successes for AN/SPY-6, including the tracking of integrated air and missile defense targets of opportunity, satellites and aircraft.

"We remain on track to deliver an unprecedented capability to the Fleet. The live testing we've been doing here at PMRF continues to demonstrate the maturity of the hardware and software and the performance of the overall system. The radar performed exactly as we expected it to during this mission–all systems were green," said Raytheon's Tad Dickenson, director of the Air and Missile Defense Radar program.

"This marked a historic moment for the Navy. It's the first time a ballistic missile target was tracked by a wideband digital beamforming radar," said U.S. Navy Captain Seiko Okano, Major Program Manager for Above Water Sensors, Program Executive Office Integrated Warfare Systems, "AN/SPY-6 is on track for delivery to DDG 51 Flight III."

Since installation at PMRF in May 2016, AMDR has tracked targets of increasing complexity. In October 2016, AN/SPY-6 first tracked multiple satellites, hundreds of miles above Earth, from search and acquisition through their orbits. In the following month, the radar executed its first integrated air and missile defense track by simultaneously tracking aircraft and satellites. Most recently, in conjunction with a Standard Missile 3 Block IIA SFTM-01 flight test, AN/SPY-6 executed an engineering exercise where it searched for, acquired and tracked a medium range ballistic missile target, from launch through flight.

These are the most recent milestones as the Navy's new radar advances on schedule through Engineering and Manufacturing Development. Soon to transition to Low-Rate Initial Production, AN/SPY-6(V) remains on track for delivery for the first DDG 51 Flight III destroyer.

Arleigh Burke Class Destroyer (U.S. Navy photo)

AN/SPY-6(V) provides greater capability—in range, sensitivity and discrimination accuracy—than currently deployed radars, increasing battlespace, situational awareness and reaction time to effectively counter current and future threats. It is the first scalable radar, built with Radar Modular Assemblies—radar building blocks. Each RMA, roughly 2 in x 2 in x 2 in in size, is a stand-alone radar that can be grouped to build any size radar aperture, from a single RMA to configurations larger than currently fielded radars. The U.S. Navy's new Enterprise Air Surveillance Radar leverages the highly-scalable design and mature technologies of AN/SPY-6 in a scaled nine-RMA configuration to meet the mission requirements of carriers and amphibious ships. The commonality—in both hardware and software—with AN/SPY-6 offers a host of advantages, including maintenance; training; logistics and lifecycle support.

DARPA's Battle of the ModRecs Lays Groundwork for Improved Spectrum Management

If human ears could hear the electromagnetic spectrum, the noise levels these days would be overwhelming. The skyrocketing use of wireless devices in military and civilian domains has created a complicated and cacophonous environment, filled with signals of widely varying frequency and amplitude and a menagerie of modulations. For warfighters trying to maintain critical communications links, interpret ambiguous radar returns or defend against electronic warfare tactics, the ability to sort through that thicket of waveforms is essential—to identify where key signals are coming from, what kind of signals they are and how best to send and receive information via the least contested spectral bands.

Toward that end, DARPA earlier this month hosted the Battle of the ModRecs—a low-key competitive opportunity for engineers with a penchant for antennas and algorithms to test their skills in modulation recognition.

"We're looking to push modulation recognition out of its comfort zone," said DARPA program manager Tom Rondeau. "We want scientists and engineers to rethink conventional approaches and advance the technology to new heights, so it will function dynamically and with precision—not just under laboratory conditions but in real-world scenarios."

Held for a few days in conjunction with the IEEE DySPAN conference in Baltimore, where Rondeau and staffers created a sort of pop-up spectrum testbed, the battle put hand-coded, expert systems against newer, experimental systems designed to take advantage of recent advances in machine learning. "In this realistic scenario with complex waveforms, the hand-coded sys-

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

tems performed better than the machine-learning systems," Rondeau said. "But it was close, and we don't think that lead is going to last for long. We now have a better understanding of the state of the art and which directions to explore as we pursue our goal of more effectively managing the spectrum."

The Baltimore event was one of several related exercises planned for this year. A February hackfest hosted in Brussels, for example, focused on radio interference, and an upcoming event in the San Francisco Bay Area will focus on unmanned aerial vehicles. Through these efforts and a variety of ongoing DARPA programs, including the Spectrum Collaboration Challenge that program manager Paul Tilghman is overseeing, DARPA aims to build an improved technological capacity for spectrum-related situational awareness and help U.S. forces make better use of this powerful but limited electromagnetic resource.

LM LRASM Conducts Successful Jettison Flight Test from US Navy F/A-18E/F

Lockheed Martin's Long Range Anti-Ship Missile (LRASM) was successfully released from a U.S. Navy F/A-18E/F Super Hornet at NAS Patuxent River, Md.

The jettison release of the first LRASM from the Super Hornet is used to validate the aerodynamic separation models of the missile. This successful test event paves the way for flight clearance to conduct captive carry integration testing scheduled for mid-year at the Navy Air Weapons Station (NAWS) China Lake, Calif.

Precision-guided long-range anti-ship standoff missile...

"The first time event of releasing LRASM from the F/A-18E/F is a major milestone towards meeting early operational capability in 2019," said Mike Fleming, Lockheed Martin LRASM program director. "The program is executing the integration and test contract, maturing subsystems and proving flight worthiness."

LRASM is designed to detect and destroy specific targets within groups of ships by employing advanced technologies that reduce dependence on intelligence, surveillance and reconnaissance platforms, network links and GPS navigation.

Once operational, LRASM will play a significant role in ensuring military access to operate in open ocean/blue waters, owing to its enhanced ability to discriminate and conduct tactical engagements from extended ranges.

Switched Filter Banks

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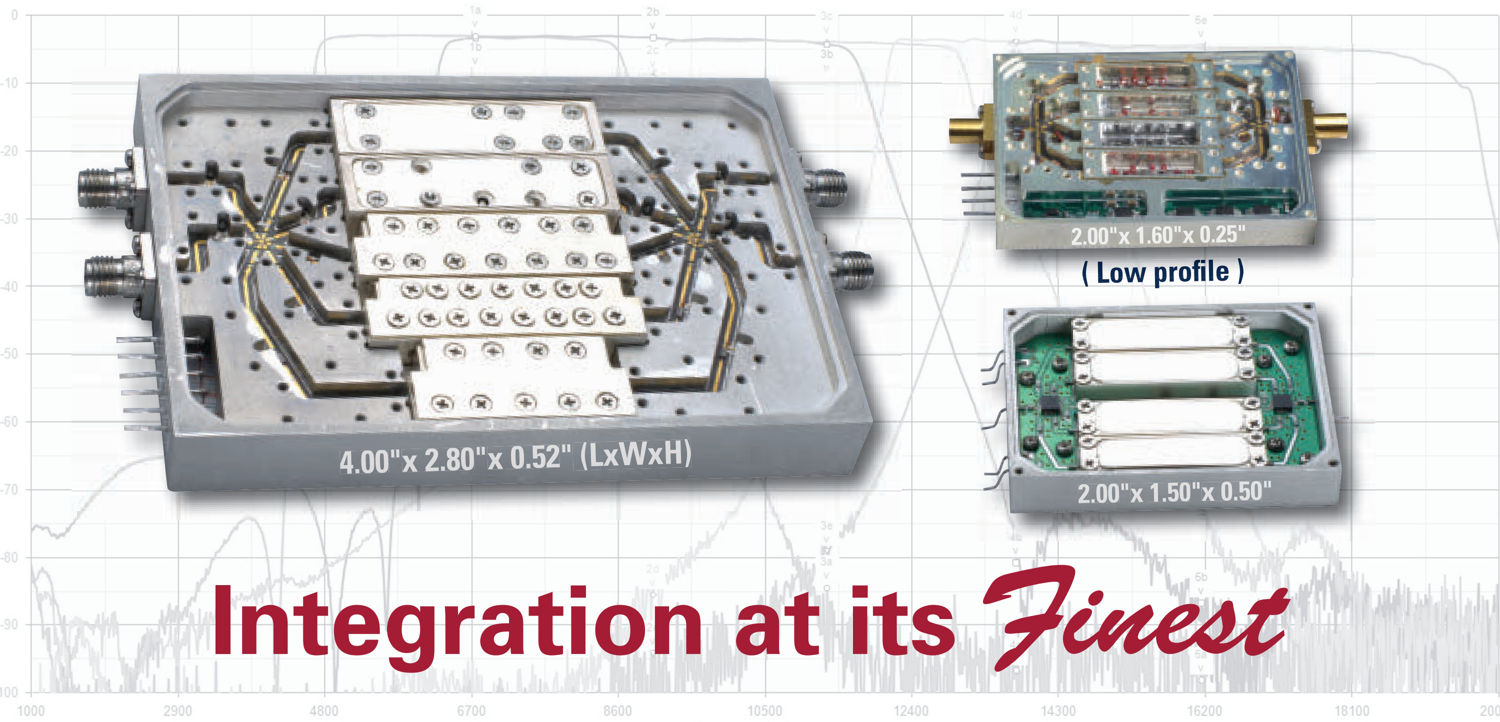

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Research Fab Microelectronics Germany is Founded

To reinforce the position of Europe's semiconductor and electronics industry within global competition, 11 institutes within the Fraunhofer Group for Microelectronics have, together with two institutes within the Leibniz Association, developed a concept for a cross-location research factory for microelectronics and nanoelectronics. The Federal Ministry of Education and Research (BMBF) is providing support with investment.

In order to be able to offer smaller companies top technology under optimum conditions, 11 Fraunhofer Group institutes, as well as the Leibniz Institute for Innovative Microelectronics (IHP) in Frankfurt/Oder and the Ferdinand-Braun-Institute, Leibniz Institute for Maximum-frequency Technology (FBH) in Berlin, will combine their technology research into a joint, cross-location technology pool to be known as the Research Fab Microelectronics Germany, and develop it.

> "...a cross-location research factory..."

The focus of the cross-institute work will lie in four future-relevant areas of technology–silicon-based technologies, compound semiconductors and special substrates, heterointegration and design, testing and reliability.

The institutes' existing locations will be retained, while expansion and operation will be coordinated and organized in a shared business office. The aim is to be able to offer customers from large industry, small and medium enterprises and universities the entire value chain for microelectronics and nanoelectronics in an uncomplicated manner and from a single supplier.

New jobs will also be created: The Microelectronic Fab for Research Germany will represent a reorganization of more than 2000 scientists and the necessary equipment for technological research and development under a single, virtual roof. In the medium term, the measure is expected to create an additional 500 jobs for highly qualified candidates.

EPoSS SRA 2017 Progresses Smart Systems Integration

European Technology Platform for Smart Systems Integration (EPoSS) has published the 2017 update of its Strategic Research Agenda (SRA) defining research and innovation priorities for the next 15 years. To develop the report, EPoSS members considered objectives, strategy and impact of Smart Systems Integration (SSI) for seven major application fields, and derived related system integration needs and pointed to research priorities in four transversal fields of enabling technologies.

The contributing experts developed roadmaps, set milestones and defined actions to be taken for each of these fields. This document therefore aims to provide the basis for joint activities in the area of SSI, and thus has the potential to shape the future landscape of smart systems research.

Smart systems combine cognitive functions with sensing, actuation, data communication and energy management in an integrated way. The enabling principles of these functions include nanoelectronics, micro-electromechanics, magnetism, photonics, chemistry and radiation.

Source: Strategic Research Agenda (EPoSS)

"In providing a range of novel functionalities, smart systems have become a driving force behind almost all product innovations, and smart-enabled solutions can be found in almost every application field: transportation, health, manufacturing, IoT, energy, natural resources and security," said Dr. Carmelo PAPA, CEO and Director General of STMicroelectronics Italy & Chairman of EPoSS.

UK Government to Establish CAV Cluster

Business Secretary Greg Clark launched the first competition to access funding from the UK government's £100 million investment programme supporting the creation of test facilities for Connected and Autonomous Vehicles (CAV). The programme is being match funded by industry, to take the total spend up to £200 million over four years.

Speaking to an international audience of over 400 industry leaders at the Society of Motor Manufacturers and Traders Connected Conference in London on 30 March 2017, Clark outlined plans to create a cluster of excellence in connected and autonomous vehicle testing along the M40 corridor between Birmingham and London.

By creating a coherent national cluster, government and industry will be able to rapidly accelerate the development of CAV technology in the UK, grow intellectual capital in this field, attract overseas investment and create a national ecosystem that covers all testing

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requirements for CAV technology from computer program design to on road testing.

CEO, Society of Motor Manufacturers and Traders (SMMT) Mike Hawes stated: "The UK is a hotbed of innovation and one of the fastest moving areas is in connected and autonomous vehicles. We want the UK to be the destination of choice for the development and testing of this new generation of vehicles. Government support and investment will help this technology flourish allowing the UK to reap the economic and societal benefits."

ETSI Releases Specifications for LSA

The European Telecommunications Standards Institute (ETSI) Technical Committee for Reconfigurable Radio Systems (TC RRS) has announced the completion of the specification for the support of Licensed Shared Access (LSA). This provides a means to enable spectrum sharing coordination between LSA licensees and existing spectrum licensees, thereby ensuring Quality of Service (QoS).

The recently completed specification, ETSI TS 103 379 addresses information elements and protocols for the operation of LSA in the 2300 to 2400 MHz band. The document defines the application protocol, also known as LSA1 protocol, on the interface between the LSA Controller and the LSA Repository and the content of the information conveyed by this protocol.

"...regulation and standards challenges..."

With this new specification, ETSI TC RRS completes a set of specifications that opens the way for interoperable implementation of LSA Repositories and LSA Controllers to support LSA deployments in the initial target band. Extensions to other bands are not precluded, in response to future regulatory requirements.

"ETSI's LSA activities are a perfect example of the efficient interaction between the European Commission, CEPT and ETSI. Within the EC mandate M/512 framework, the regulation and standards challenges were efficiently addressed, leading to a ready-to-use package for LSA technology in Europe. Furthermore, ETSI's specifications have substantially influenced related activities in other regions, such as the Federal Communications Commission's (FCC) Report and Order on the Citizens Broadband Radio Service in the 3550 to 3700 MHz band," said Markus Mueck, chairman of ETSI TC RRS. "LSA based spectrum sharing is expected to be a key element in the tool box of regulatory administrations in order to address future 5G spectrum needs."

Cliff Drubin, Associate Technical Editor

The Future of Retail: Electronic Shelf Labels

As retailers increasingly struggle to effectively match online pricing, digitize their physical stores, meet new order fulfillment models and streamline the shopping experience, electronic shelf labels (ESL) are gaining market momentum. ESLs will hit the mass market and accrue more than $4 billion in global revenues by 2022, finds ABI Research, with several big box retail deployments to trigger a domino effect in market growth over the next two years.

ESLs provide retailers with a significant ROI by streamlining paper/staff costs, reducing the risk of human error, cutting back on waste and improving price perception. All the benefits can collectively affect retailers' bottom lines by as much as five percent.

With multi-color graphic display prices falling, in-aisle promotion barriers are disappearing, with many major grocery chains in the U.S. and UK expected to roll out ESLs over the next three years. Germany continues to see a lot of activity with trials suggesting a strong pipeline of opportunity across the continent. Asia also represents a huge opportunity, with the global industry watching to see if market incumbents can expand into these two markets despite increasing competition from local players.

> Market will increase 10-fold in next five years...

While Amazon Go and its global effect on the retail technology market landscape is clear, the role that dynamic pricing plays in Amazon's model remains less apparent. ABI Research anticipates that online pricing will become omnichannel pricing, which means in-store dynamic pricing will soon become a reality with ESLs playing a predominant role. In collaboration with BLE and NFC technologies, ESLs can track purchases as customers shop, allowing retailers to build apps that eliminate the need for queues and checkout processes entirely.

New Smart Cities Funding and Deployment Strategies to Boost GovTech Sector

Local governments face the twin challenges of funding and deploying smart city technologies to guarantee the continuous provision of mobility, communication, energy, water, accommodation, healthcare, education and security services while ensuring livable, affordable and sustainable environments for citizens in the wake of fast global urbanization. New paradigms like citizen participation, data capitalization through mobile sensors in smartphones and vehicles for informational services, holistic approaches that leverage vertical adjacencies and acceptance of the overall sharing economy will allow governments to adopt smart city technologies at minimum costs.

Unlocking underutilized private resources through car sharing, micro-grid home energy networks, charging stations, private parking and accommodation sharing will allow governments to meet surging demands for services in a cost-effective way while avoiding expensive physical infrastructure extension projects. Such smart funding and deployment approaches will equal fast return on investment, critical for obtaining additional private and/or public funding for more structural smart city platform approaches in the long term.

"This is creating a reversal of fortune for suppliers so far frustrated with dealing with city governments' complex procurement processes, opaque sales cycles, long decision and implementation trajectories and the overall lack of smart city technology business development opportunities," says Dominique Bonte, Managing Director and Vice President at ABI Research. "We see the GovTech industry starting to gain momentum, especially in the U.S. The city tech start-up scene is also developing clout, and venture capital is finding its way into public sectors."

> New paradigms will allow governments to adopt smart city technologies at minimum costs.

ABI Research finds that Urbantech, Civictech and GovTech are quickly becoming established terms for designating the overall smart city ecosystem, technology and investment environment. Key smart city venture capital players include Fontinalis Partners, General Catalyst Partners, Goldman Sachs, GovTech Fund, Lightspeed Venture Partners, Motorola Solutions Venture Capital, New York Angels and Vista Equity Partners. The groups invest in technology vendors like law enforcement information management software vendor Mark43 and smart communication solutions provider Avaya. GovTech merger and acquisition activity is also ramping up, as evident through OpenGov's acquisition of Open Data and Ontodia.

IoT Marketplace Offerings Rise as Suppliers Attempt to Defragment a Diverse IoT Landscape

As companies seek to transform themselves with IoT technologies, they are confronted by an incredibly complex and diverse supplier market from which to build IoT solutions. To address this challenge, suppliers are leveraging ecosystem part-

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nerships to provide end-users with a one-stop-shop portfolio of hardware, software and services. These emerging IoT Marketplaces not only simplify IoT solution creation and adoption, but also facilitate supplier and buyer interactions, ultimately creating open networks that encourage innovation.

"The IoT supplier landscape is scattered right now with a diverse array of companies offering a myriad of complex components and solutions," says Ryan Harbison, Research Analyst at ABI Research. "IoT Marketplaces are a response to this complexity designed to reduce the friction buyers face when adopting and implementing IoT solutions."

To reduce the friction, IoT Marketplaces need to effectively address all components of the IoT value chain. While some IoT Marketplaces currently offer all solution components, many are not comprehensive. Suppliers are currently working to formalize and expand marketplace offerings and in some cases, integrate them with resources and programs already in place to fully leverage existing relationships.

"IoT Marketplaces allow suppliers to build an IoT solution centered around their core offerings," continues Harbison. "These marketplaces are particularly effective when they are built around a single connection point, such as a platform or gateway, because that simplifies the work enterprise developers need to do on both the front and back end."

ThingWorx successfully leverages its platform alongside its partners' expertise to offer a comprehensive supplier exchange. Aeris' Neo Marketplace provides enterprises not only end-to-end IoT solutions, but also access to support services, APIs and network services tools. Dell, likewise, works with its partner program to center its end-to-end marketplace offerings on its IoT edge gateways. Companies like Libelium, Sierra Wireless and Telus offer solutions in the form of vertical-specific application development and solution kits aimed at enterprise developers. Other companies like Amazon Web Services and Microsoft currently limit their IoT Marketplace offerings to software solutions, but both are looking to integrate their existing program into a cohesive end-to-end IoT solution.

"Today's IoT supplier base is vast, and finding a singular entity to navigate the technology and supplier choices is a challenge for both enterprises and end-users," concludes Dan Shey, Vice President and Managing Director at ABI Research. "These marketplaces are relatively new, with only a select few offering a full set of products and services to build fully integrated, end-to-end IoT solutions. But this channel will only continue to grow as suppliers seek to 'take the complexity out of the possible.'"


Amplifiers
Packaged
Transistors
& MMICs
DIE
Diodes
Oscillators
Filters
GaN
Devices
Detectors
Counterfeit Parts
Frequency Dividers
Attenuators
POWER DIVIDERS
Mixers
Custom Packaged Devices
STANDARD & CUSTOM SCREENING FLOWS
MILITARY SPACE & INDUSTRIAL
MICROCIRCUIT & SEMICONDUCTOR DIE EVALUATION
DIE VISUAL, SORTING, PACKAGING
ON-SITE ENVIRONMENTAL TEST LAB
DIE BANK & STORAGE
BUILD TO PRINT ASSEMBLY

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Analog Devices Inc. announced the completion of its acquisition of **Linear Technology Corp**. The combination creates the premier analog technology company with the industry's most comprehensive suite of high-performance analog offerings and integrated engineering, manufacturing, sales and support operations that will accelerate innovation and revenue growth opportunities. ADI also announced that Robert H. Swanson, former Executive Chairman of Linear Technology, has been elected to the ADI Board of Directors, effective immediately after the closing of the acquisition.

RFHIC Corp. of Anyang, South Korea has signed a deal with **Element Six (E6)**, a member of the De Beers Group of Companies, to acquire its GaN-on-Diamond technology. RFHIC has been investing in GaN technology since 2004. In 2008, the firm expanded its core competency from GaN-on-silicon (Si) to GaN-on-silicon carbide (SiC). Applications of the technology include 4G LTE, next generation radar and communication systems. The rate of adaptation has exploded as the cost of GaN-based solutions has become competitive compared to LDMOS and other legacy technologies, while the performance advantages are becoming clearer for industry demands.

Teledyne Technologies Inc. and **e2v technologies plc** jointly announced the successful completion of the previously announced acquisition by Teledyne of e2v by means of a Scheme of Arrangement. For the machine vision market, e2v provides high performance image sensors and custom camera solutions and application specific standard products. In addition, e2v provides high performance space qualified imaging sensors and arrays for space science and astronomy. e2v also produces components and subsystems that deliver high reliability radio frequency power generation for healthcare, industrial and defense applications. Finally, the company provides high reliability semiconductors and board-level solutions for use in aerospace, space and communications applications.

Gowanda Components Group (GCG) announced that its electronic component products and technologies are expanding in connection with the acquisition of **Dyco Electronics** in Hornell, N.Y. Terms of the deal were not disclosed but GCG has stated that Dyco Electronics' operations will remain in Hornell, N.Y. In addition to Hornell, GCG has three other production facilities located within the U.S. This is the sixth acquisition for GCG within the last five years.

With the recent closing of its acquisition of electronic design automation (EDA) software leader, **Mentor Graphics Corp.**, **Siemens** sets out to underscore the significant customer value it envisions for both Electronic Systems and Integrated Circuit design tools. Mentor is now part of Siemens' product lifecycle management (PLM) software business, making the combined organization a leading supplier of industrial software used for product design, simulation, verification, testing and manufacturing.

Sierra Wireless announced that it has completed the acquisition of the embedded GNSS module business from **GlobalTop Technology** for approximately $3.2 million. GlobalTop's GNSS embedded module portfolio will become part of the Sierra Wireless OEM Solutions product line, and the GNSS staff from GlobalTop will join Sierra Wireless. GlobalTop's GNSS products generated approximately $5 million U.S. in revenue during the last 12 months, and the business is approximately breakeven. With a wide array of modules and established sales channels, as well as a proven engineering team, the GlobalTop GNSS business is an important addition to Sierra Wireless.

Mercury Systems has announced that it has acquired **Delta Microwave LLC**. Delta is a designer and manufacturer of high-value RF, microwave and millimeter wave subassemblies and components for military and space markets. Under the terms of the purchase agreement, Mercury acquired Delta for $40.5 million in cash, subject to net working capital and net debt adjustments, and is expected to be treated as an asset sale for tax purposes. The transaction presents opportunities for significant cost synergies in addition to the tax benefits associated with the transaction structure.

MaxLinear Inc. and **Exar Corp.** announced that they have entered into a definitive agreement under which MaxLinear has agreed to acquire Exar for $13.00 per share in cash. This price for each share of Exar represents a 22 percent premium over the company's closing price of $10.62 on March 28. The total value is approximately $700 million, or $472 million net of Exar's cash acquired. MaxLinear intends to fund the transaction with cash from the combined balance sheets and a $425 million term loan. The transaction will be conducted by means of a tender offer and is expected to close in the second quarter of 2017, subject to customary closing conditions and U.S. regulatory approvals.

COLLABORATIONS

Microsemi Corp., a provider of semiconductor solutions differentiated by power, security, reliability and performance, and **The Athena Group Inc.**, a provider of security, cryptography, anti-tamper and signal processing intellectual property (IP) cores, announced Athena's TeraFire® cryptographic microprocessor is included in Microsemi's new PolarFire™ field programmable gate array (FPGA) "S class" family members. The TeraFire hard core provides Microsemi customers access to advanced security capabilities with high performance and low power consumption. The need for increased cyber-

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Around the **Circuit**

security has been recognized industrywide, particularly throughout the communications, defense and industrial markets.

NEW STARTS

Highlighting its ongoing mission to help customers navigate an ever-changing technology landscape, **Avnet** introduced "Reach Further," its new global branding campaign. Reach Further reflects Avnet's corporate transformation as well as the collaborative relationship with the company's customers in navigating the complex process of bringing new technology to the marketplace. The campaign launches with a cohesive marketing, digital and media strategy to introduce a new brand and visual identity which underscores Avnet's approach and commitment to helping customers reach further every day.

ACHIEVEMENTS

Lockheed Martin's innovation in manufacturing technology led to four awards from the Manufacturing Leadership Council. Now in its 13th year, the Manufacturing Leadership Awards honor manufacturing companies and individual manufacturing leaders that are shaping the future of global manufacturing. Rick Luepke, a Lockheed Martin engineering Fellow, was awarded the Visionary Leadership Award, and Lockheed Martin won three awards in the Engineering and Production Technology Leadership category for its ultrasonic hole cutting tool, forced mechanical oscillation drilling technology and mold-in-place inlet coatings project.

Anaren IoT Group announced that Intel has selected Atmosphere 2.0, the company's leading IoT platform for rapid prototyping and design. The Intel Curie module is now available as a design element within Atmosphere, both at the module level and within devices like the Arduino 101 development board and the element14 tinyTILE from Premier Farnell.

Hi-rel connector and SMT board hardware manufacturer **Harwin** announced it has been awarded EN 9100/AS9100C accreditation, recognizing the company's commitment to quality and supply chain excellence. The internationally-recognised 9100 Series Quality Management System standard (referred to as AS9100 in the U.S. and JISQ 9100 in Japan) is specific to the aerospace industry and is adhered to and supported by all major aeronautics manufacturers worldwide.

CONTRACTS

BAE Systems has received a contract worth up to $112 million from the **U.S. Army** to perform technical support and sustainment of M88 recovery vehicles. The contract, awarded by the Army's TACOM Life Cycle Management Command, is for ongoing service and improvements to BAE Systems-built M88A1 and M88A2 recovery vehicles over the next four years. The M88 vehicle provides recovery support to troops in the field,

and is the only vehicle able to recover the M1 Abrams tank and all of the vehicles required to maneuver with the Armored Brigade Combat Team during battle.

Orbital ATK, a global leader in aerospace and defense technologies, announced that it has received a $21 million contract for first article test and production of the MK419 Mod 1 Multi-Function Fuze (MFF). The MK419 MFF-equipped round gives a 1980s-era, single-dimension Naval Surface Fire Support munition more modern, multi-dimension capability. This includes support against multiple threats. The contract was awarded by the **U.S. Army Contracting Command** on behalf of the U.S. Navy and is the first full-rate production contract for the MK419 Mod 1. The MFF is designed for use on the MK187 projectile used on U.S. Navy guns. The awarded contract value is $20.8 million.

Comtech Telecommunications Corp. announced that its Command & Control Technologies group, which is part of its Government Solutions segment, received a $3.4 million order from a prime contractor to the Department of Defense (DoD) to renew managed network services. Comtech Telecommunications Corp. designs, develops, produces and markets innovative products, systems and services for advanced communications solutions.

PEOPLE

Telewave Inc., a manufacturer of RF and microwave products for public safety, land mobile radio and other radio communications services, announced that **Robert Bagheri** has joined the company as chairman and chief executive officer. Bagheri has more than 35 years of experience in executive, management and engineering positions within the electronics industry. Before joining Telewave, Bagheri was founder, investor and chairman of a stealth start-up serving the wearables and mobile markets.


▲ *Robert Bagheri*

Integrated Device Technology Inc. announced the appointment of **Chris Allexandre** as its new senior vice president of global sales and marketing. A sales veteran with more than 20 years in the semiconductor industry, Allexandre's experience covers analog mixed signal products in the mobile, industrial, telecom, cloud, consumer and automotive markets. Prior to joining IDT, Allexandre worked for NXP as senior vice president Worldwide Sales for Mass Market and Global Distribution. Before that, he was senior vice president of Worldwide Sales, Marketing and Supply Chain at Fairchild Semiconductors. Prior to Fairchild, he held various positions at Texas Instruments, up to vice president of EMEA Regional Sales & Applications and Distribution.


▲ *Chris Allexandre*

Around the Circuit

▲ Jim Cable

▲ Stefan Wolff

▲ Dylan Kelly

The CEO of **Peregrine Semiconductor, Jim Cable**, announced significant changes to Peregrine's executive team. In a bold move to increase the company's semiconductor capability, Cable announced the appointment of **Stefan Wolff** as Peregrine's new chief executive officer. Cable will be stepping into the role of Peregrine Chairman and CTO and will serve as the Global R&D director for Peregrine's parent company, Murata. In addition to these significant changes, Cable has appointed **Dylan Kelly** as the company's new chief operating officer. Kelly has held the position of VP and general manager of Peregrine's mobile wireless solutions business unit since 2010.

REP APPOINTMENTS

Premier Farnell announced a new global distribution agreement with **EAM**, a manufacturer of precision RF and microwave interconnect products. Under their ConductRF Brand, the company offers, innovative and reliable performance interconnect products operating from DC to 110 GHz. ConductRF's products are recognized for their excellent performance and cost effectiveness by engineers and technicians in numerous demanding industries including: defense, aerospace, industrial, medical infrastructure, instrumentation and test and telecommunications.

Southwest Microwave announced that **Melcom Electronics Ltd.** is their new exclusive distribution rep for the United Kingdom and Ireland. Established for over 20 years and operating within the defence, space, aerospace and avionics, test and measurement and other markets, Melcom Electronics is an independent, privately-owned supplier of analog, RF and microwave components, sub-systems and solutions. To discuss project needs in the UK and Ireland, please contact John Melas at +44 (0) 7969 666913 or email him at john@melcom.co.uk.

International Manufacturing Services is pleased to announce the appointment of **Electron Marketing** as the exclusive sales representative for Illinois and eastern Wisconsin. Electron Marketing will be instrumental in helping IMS strengthen and extend its presence in this region. Electron Marketing Corp. has been representing manufacturers of passive, power and electromechanical components since 1978.

INVITED PAPER

Wideband Millimeter Wave Test Bed for 60 GHz Power Amplifier Digital Predistortion

Stephen J. Kovacic, Foad Arfaei Malekzadeh, Hassan Sarbishaei
Skyworks Solutions, Woburn, Mass.

Mike Millhaem, Michel Gagne, Greg Jue, Jin-Biao Xu, Jean-Marc Moreau
Keysight Technologies, Santa Rosa, Calif.

Even as fourth-generation (4G) cellular systems—LTE and LTE-Advanced—are being deployed, research and active development has begun on fifth-generation (5G) systems. 5G mobile networks offer a vision of *everything, everywhere and always connected*. In a 5G system, key attributes may include a dense, highly flexible network comprised of small cells supporting data rates on the order of 10 Gbps, with roundtrip latency of 1 ms or less. Most studies assume multiple air interfaces operating at microwave or millimeter frequencies—the new radio (NR). 5G NR has three basic use cases: enhanced mobile broadband (eMBB), massive machine-type communications (MMTC), ultra-reliable and low latency communications (URLLC). Achieving this vision will require a combination of evolution and revolution in technology, business models and policy.

As a policy example, the U.S. Federal Communications Commission (FCC) recently announced new rules to enable rapid development and deployment of next-generation 5G technologies and services.[1] These rules create a new flexible use service in the 28, 37 and 39 GHz frequency bands, as well as a new unlicensed band from 64 to 71 GHz. This new band, combined with the existing unlicensed band from 57 to 64 GHz, opens up a 14 GHz span of unlicensed spectrum from 57 to 71 GHz, some of which lies well outside the high absorption peak associated with oxygen.

The movement to the new frequency bands at 28 GHz and above will bring new challenges in the development of power amplifiers (PA), both for base stations and mobile devices. At 28 GHz, 100 MHz wide carriers are expected, with carrier aggregation providing signals as wide at 800 MHz. At 60 GHz and above, carriers are already 2 GHz wide with 802.11ad. Proposals for 802.11ay add aggregation or bonding of two or more of these channels. It is expected that 5G will use similar bandwidths in these frequency bands. Using these frequency bands and signal bandwidths requires a new wave of signal generation and analysis equipment.

With 3G and 4G cellular communication, digital predistortion (DPD) was used to allow PAs to operate with higher efficiency without sacrificing modulation quality. This became important as the peak-to-average ratios (PAPR) of the signals increased, so did the demand to reduce the power consumption of the amplifiers. With 5G, the proposed waveforms may demand even higher PAPR. DPD compensates for the AM/AM and AM/

PM distortion in the amplifier. In the simplest form, the inverse of the AM/AM and AM/PM curves can be applied to the input signal, producing the ideal signal at the output. In practice, it is also important to consider memory effects in the amplifier, which are exacerbated with very wide signal bandwidths. Circuit models that are typically used for the design and simulation of PAs cannot predict the memory effect, and the only practical way to deal with it is to test the PA and capture the time domain modulated signal after it passes through the amplifier. Established techniques typically require that the input signal be generated and measured at 3 to 5× the bandwidth of the signal.

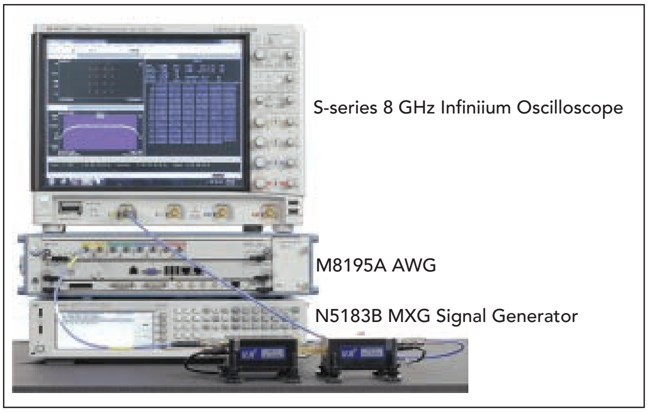
The test equipment available for testing 4G PAs could easily handle these sample rates, even for the widest 20 MHz LTE signals. For 5G and 802.11ad signals with bandwidths as wide as 2 GHz, the techniques used for 4G are beyond the capabilities of most vector signal generators (VSG) and vector signal analyzers (VSA) currently available.

A DIFFERENT APPROACH

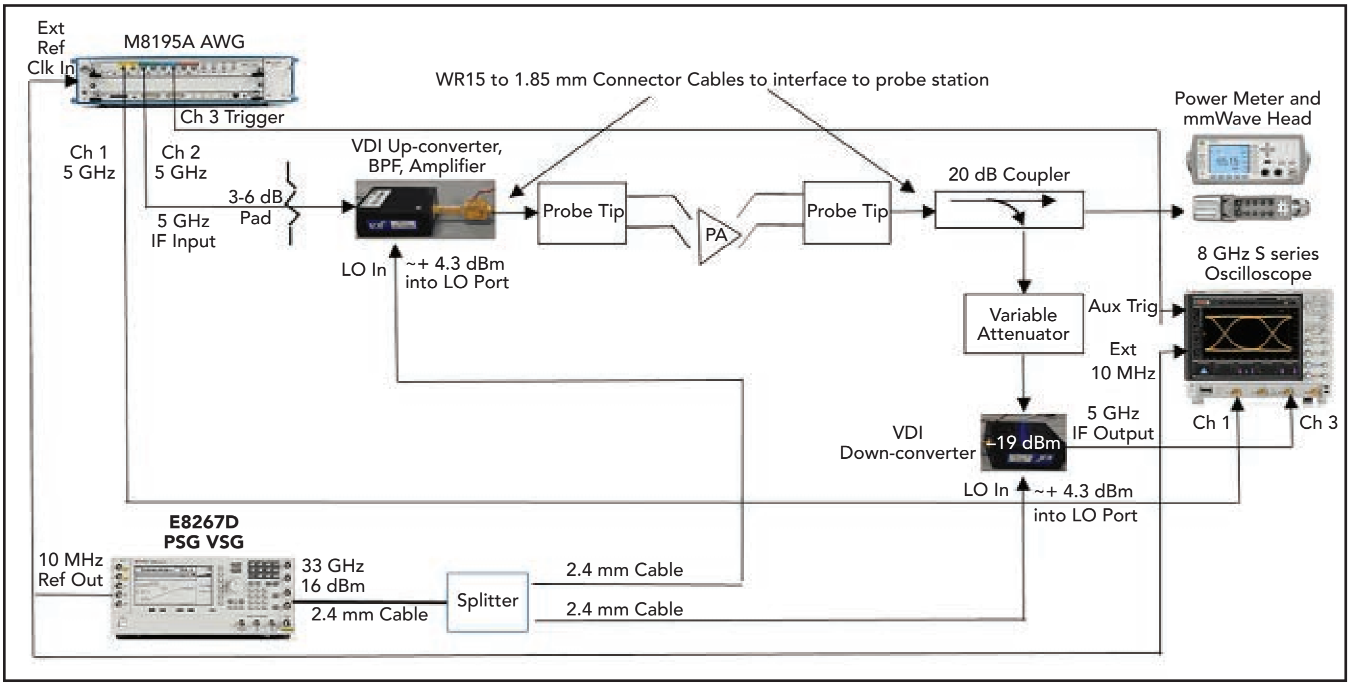
To address the DPD bandwidths of 5G and 802.11ad, wide bandwidth arbitrary waveform generators (AWG) and oscilloscopes can be used to generate and analyze intermediate frequency (IF) signals, with up- and down-converters to convert the IF signals to the required carrier frequencies.

To perform DPD measurements on a Skyworks 60 GHz PA designed for 802.11ad, the Keysight M8195A 8-bit, 65 GSPS AWG and S-Series 10-bit, 20 GSPS oscilloscope were used with compact up- and down-converters from Virginia Diodes Corporation (VDI). Using second harmonic mixers, the up- and down-converters require a local oscillator (LO) signal that is one half the final LO frequency. A Keysight 40 GHz continuous wave (CW) signal generator was used to generate the LO. ***Figure 1*** shows the equipment used and ***Figure 2*** shows the block diagram of the test setup. One channel of the AWG was used to generate an IF signal at approximately 4 GHz. Since the same LO signal was used for both up- and down-conversion, the IF input to the scope was also centered at 4 GHz. Using this approach, almost the entire 8 GHz bandwidth of the scope could be used to capture the signal. For the DPD analysis, QPSK and 64-QAM signals were generated with a 1.5 GHz symbol rate and an occupied bandwidth of approximately 2 GHz. The signal was generated and analyzed at a 7.5 GHz sample rate, 5× the symbol rate. For the AWG, the 7.5 GSPS I/Q signal was modulated to the IF frequency in software and up-sampled to the AWG sample rate in the range of 56 to 65 GHz. The DPD measurements were performed on wafer. One advantage of the VDI up- and down-converters is their small size, allowing them to be placed very close to the probes to minimize the cable loss.

Keysight SystemVue and 89600 VSA software were central to the measurements and analysis. SystemVue generated the test waveforms and performed DPD model



▲ **Fig. 1 Test equipment used for 60 GHz DPD measurements.**



▲ **Fig. 2 Block diagram of the 60 GHz test system. The M8195 AWG, E8267D VSG and oscilloscope were connected via LAN.**

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GaN

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Application	Function	Part Number	Frequency
Basestation	Power Transistor	MAGB-101822-360A0P MAGB-100710-550S0S	1.8 – 2.2 GHz 0.7 – 1 GHz
RF Energy Cooking & Lighting	Power Transistor Power Transistor	MAGe-102425-300 MAGe-100809-500	2.45 GHz 915 MHz
Avionics	Power Transistor	MAGX-100914-250	1.2 – 1.4 GHz

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MACOM delivers the leading design and applications expertise with proven technical support to enable the most demanding wideband applications.

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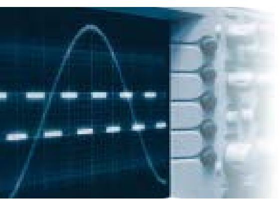
Application	Function	Part Number	Frequency
Test & Measurement	Wideband Power Amplifier	MAAP-011249	DC - 22 GHz
	Voltage Variable Attenuator	MAAV-011013	5 - 45 GHz
	Wideband Mixer	MAMX-011036	8 - 43 GHz
	Wideband Low Noise Amplifier	MAAL-011141	DC - 26.5 GHz
Aerospace & Defense	Octave Voltage Controlled Oscillator	MAOC-415000	10 - 20 GHz

Diodes

The Trusted Name in High Performance RF Diodes



MACOM is committed to offering unrivaled diode development and design expertise to tackle any RF challenge. We'll partner with you to create a specific diode solution for your most critical RF applications, strengthening signals in markets from A&D and ISM to wired broadband.

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- Hi-Rel Screening capabilities – Space & JAN, JANTX, JANTXV, and JANS qualified RF & DC devices
- Applications support – Industry leading world class experienced team available to support your critical requirements

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- PINs, Schottkies, Varactors, Zeners, Rectifiers, Current Regulators
- Chip Capacitors, Attenuator Pads, Thin Film Resistors, Spiral Inductors
- RF / Mw /mMW and DC General purpose solutions
  - Integrated Diode Products
  - Switch Modules
  - Limiter Modules
  - Comb Generators
  - Driver Modules

Patented Technologies

- AlGaAs – Industry leading high frequency switch portfolio (Products up to 94 GHz)
- HMIC – Industry leading high power diode & switch portfolio (0.1-20 GHz , 6.5W CW Incident Power)

Featured MACOM Diodes

Application	Function	Product Family	Description	Part Examples
Medical - MRI	RF Switching	MELF PIN Diodes	Non-Magnetic SMT PIN Diodes	MA4P7464F-1072T MA4P7446F-1091T
Test & Measurement	RF Switching	AlGaAs Switches	AlGaAs PIN Switch IC's (to 50GHz)	MA4AGSW2 MA4AGSW4
		Beamlead PIN Diodes	Fast Switching Mesa & Planar Beamlead Diodes	MA4PBL027 MPND4005-B15
Aerospace & Defense	Double Balanced Mixers	Silicon Schottky Quads	Low, Medium & High Drive Quads (Beamleads & Packaged)	MSS30 / MSS40 / MSS50
	Passive Limiter Circuits	Limiter Diodes	Silicon Limiter Diodes	MA4L021 MADL-011023-14150T

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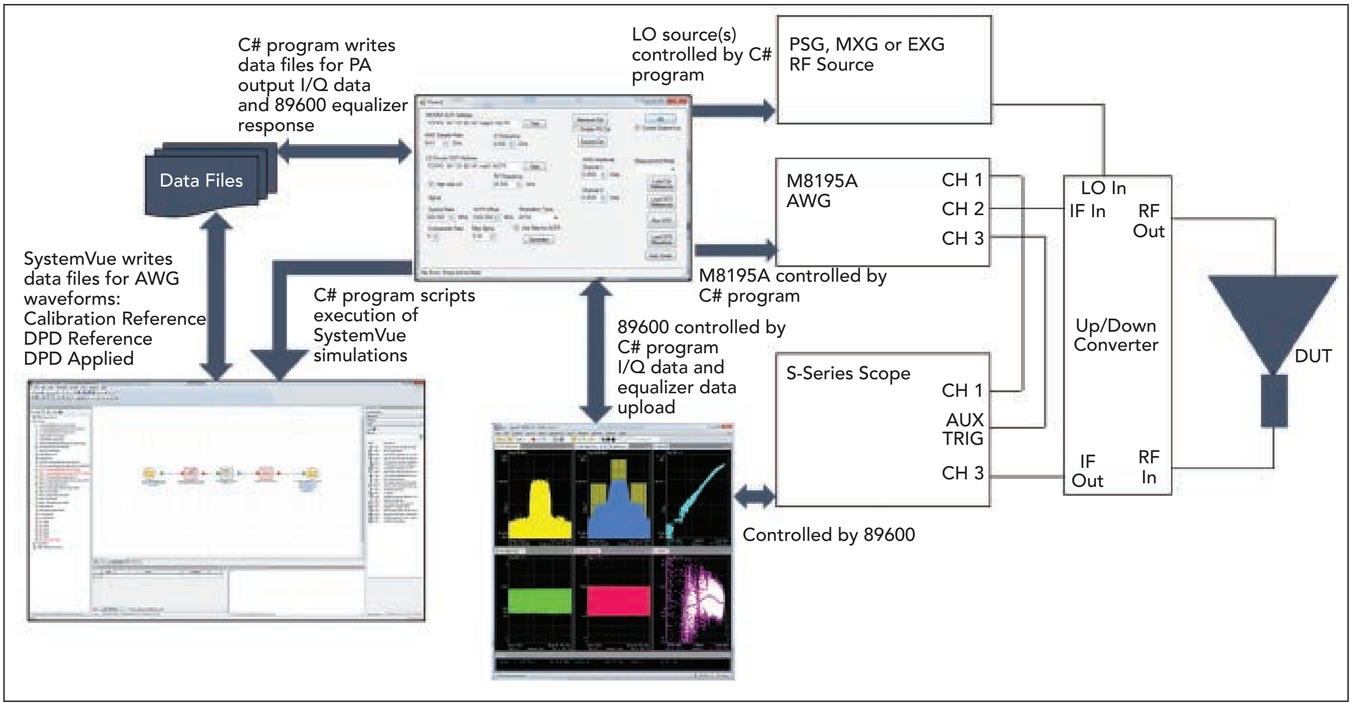


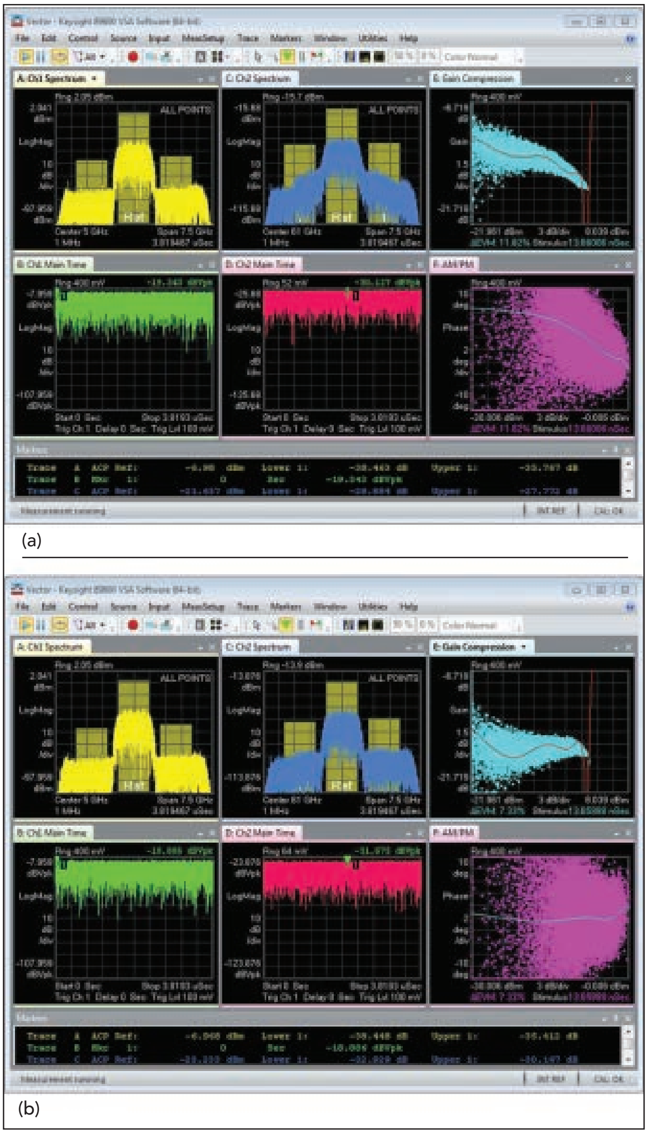
▲ **Fig. 3** Test system software structure.

extraction, then applied the DPD model to generate predistorted waveforms. The VSA software measured the error vector magnitude (EVM) and adjacent channel power (ACP) visualized the AM/AM and AM/PM conversion and extracted the I/Q data for the DPD model. A C# program coordinated the software applications and controlled the M8195A and LO signal generators. ***Figure 3*** shows a block diagram of the software structure.

MEASUREMENT RESULTS

Two different devices under test (DUT) were measured. One was a single-stage PA fabricated on a 45 nm SOI CMOS technology with approximately 7.5 dB gain and a CW 1 dB compression point (P_{1dB}) of approximately 11 dBm and saturated output power (P_{sat}) of around 15 dBm. The other DUT, fabricated on the same semiconductor platform, was a three-stage PA with 14 dB gain and a CW P_{1dB} of approximately 15 dBm. In designing the PA, the goal was to render an amplifier with minimum AM/AM and AM/PM distortion and little or no memory effect. Variation of AM/PM across the design frequency band is a measure of the amplifier's memory effect; sudden variations in AM/PM versus frequency are symptoms of linearization problems.[2]

The DPD measurements were performed at several RF input power levels for the single-stage PA and over a range of input power for the three-stage PA. In general, DPD



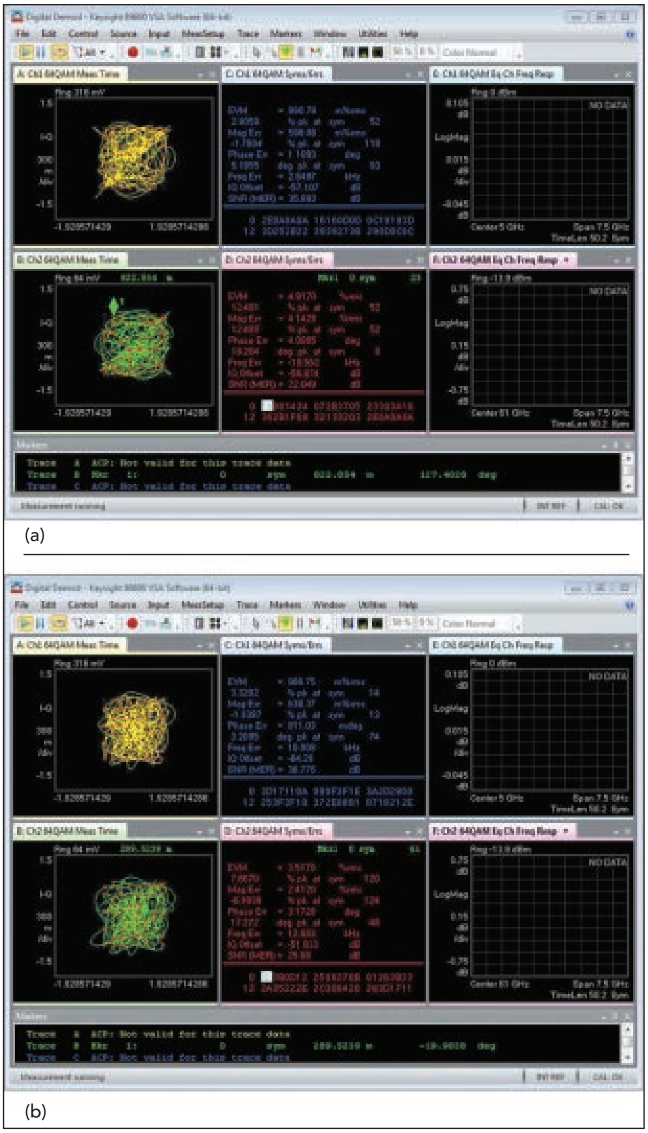
▲ **Fig. 4 ACPR performance without DPD (a) and with DPD (b).**

provided 2 to 4 dB of improvement in ACP and a 1 to 2 point improvement in EVM, compared to results without DPD. ***Figures 4*** and ***5*** show the ACP and EVM results for a single test case of the three-stage PA. Figure 4a shows the lower and upper ACP levels without DPD are -28.8 dB and -27.7 dB, respectively. With DPD (see Figure 4b), the lower and upper adjacent power levels are -32.9 dB and -30.2 dB respectively. DPD improves the lower and upper levels by 4.1 dB and 2.5 dB, respectively. EVM performance improves 1.4 points, from 4.9 percent without DPD (see Figure 5a) to 3.5 percent with DPD (see Figure 5b).

Several approaches were used to properly model the PA; a third-order memory polynomial with one memory span most accurately represented PA behavior. This eliminated the need to use more complicated Volterra models, even at high compression values.

CONCLUSION

This new, flexible millimeter wave test system is capable of very wideband signal generation and analysis



▲ **Fig. 5** EVM performance without DPD (a) and with DPD (b).

to research amplifier DPD at 60 GHz. Key components of the test bed include the M8195A AWG, VDI WR15 compact up- and down-converters, wideband DSO S-Series oscilloscope, 89601B VSA software and SystemVue. Digitally-modulated single-carrier waveforms were generated and measurements performed in the 60 GHz band with a sample rate of 7.5 GHz. These wide bandwidth measurements enabled DPD model extraction with SystemVue, and the model successfully demonstrated improved amplifier linear performance, both ACPR and EVM. Using other available converters, the system can be expanded to research other millimeter bands such as 64 to 71, 71 to 76 and 81 to 86 GHz.■

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INVITED PAPER

Design of a State-of-the-Art Modularized Radar Test System

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Saab Aerodefense, Stockholm, Sweden

Modern radar systems require advanced test and verification techniques to ensure that these systems can operate under complex and cluttered communication environments, and that their performance specifications are fully met and further characterized. When engineers configure an automated test setup for radar systems, some of the most important instruments used to evaluate the system are an RF/microwave signal generator and a spectrum analyzer. A signal generator can be used as a test stimulus to simulate the operational environment precisely, and a basic function generator can be used to drive the pulse, AM and FM circuitry of an analog signal generator. In the receiver, the weak signals received by the antenna can be detected and amplified by a spectrum analyzer with high dynamic range and low phase noise.

With the recent advancements in radar technology, such as active electronically scanned arrays (AESA) and multifunction systems, radar test requirements are becoming increasingly challenging. This article will describe these challenges and the test requirements of a modern automated test equipment (ATE) system that is capable of next-generation radar test.

TESTING MODERN RADAR SYSTEMS

Modern radar systems must be able to resolve targets in complex signal environments, requiring a lower distortion receiver than what was historically used. To meet the most stringent receiver specifications, testing requires a source that can generate a signal with low phase noise and excellent spurious and harmonic performance. Because of the difficulties involved in the direct conversion from the digital domain to microwave frequencies, or vice versa, it is common to use more than one local oscillator (LO) for multi-stage conversion. When using multiple LOs, they must all be synchronized and phase locked with each other, as tightly and quickly as possible. The faster they can be phase locked and synchronized at the desired frequency, the faster the overall test and measurement time. Synchronization is of particular concern in an AESA radar, as it involves thousands of receivers connected to the antennas, and each of the receivers needs to be synchronized.

As mentioned, testing radar receivers can use signal generators for a variety of test signals, ranging from pulsed CW to chirps using frequency modulation and sweep. Commonly, radars use pulsed RF/microwave signals for testing, and the characteristics of the pulse

largely determine the performance and capabilities of the system. For instance, pulse power determines the range of the target and the pulse width ascertains the spatial resolution of the target. In radar test and verification, a signal generator can be used as a source for LO substitution, where the low phase noise and high spectral purity of the signal generator allow for a higher dynamic range and improved sensitivity of the measurement receiver.

The advent of AESA multifunction radar systems has led to an unprecedented enhancement in radar performance, reliability and scanning speed. A typical AESA architecture involves thousands of transmit/receive (T/R) modules, each with an antenna. Adding to the complexity of the design, the precise phase and amplitude alignment of each T/R module challenges radar testing and verification.

GIRAFFE 4A AESA RADAR

AESA radars have significantly evolved over the past three decades, with continuous advancements in signal processing and RF/microwave technologies such as GaN power amplifiers, monolithic microwave integrated circuits (MMIC), millimeter wave integrated circuits—all leading to reduced cost of the T/R modules. Unlike conventional mechanically steered array (MSA) or passive electronically steered array (PESA) radars, AESA radars allow digital and independent control of the module transmit/receive gain and phase. This capability provides a significant advantage in beamforming and the beam steering agility of the radar. AESA radars are much more reliable than the traditional radar, mostly because the thousands of independent T/R modules—instead of a single channel—allow the radar to sustain some level of failure without disabling the entire system. The modular approach of the AESA provides a seamless ability to replace the T/R modules with more advanced elements as they become available, leading to notable improvements in performance.

Fig. 1 Giraffe 4A AESA radar.

One example of an AESA multifunction radar is Saab's Giraffe 4A radar (see ***Figure 1***). The Giraffe 4A is a software-defined radar with multifunction operational flexibility; the operator can adaptively switch between different modes of operations by dynamically modifying signal processing tasks and waveforms. The Giraffe 4A is a great case study to highlight the requirements for the modularized radar ATE system needed to address the radar test requirements. The Giraffe 4A radar is composed of three functional elements: the exciter, receiver and antenna. The major requirements of testing and characterizing each of these elements are defined below:

Exciter: The primary role of an exciter is to generate the internal LOs for the receivers and a carrier signal for the transmitters. The generated signals must be stable, low in phase noise and spurious content and fast when switching frequencies. Low spurious content and harmonics make a clean transmitted signal. With a clean LO signal fed to the receiver, it is much easier for the receiver to detect the signal of interest in a cluttered environment.

Receiver: The function of a receiver is to extract the weak reflected signals from the antenna, amplify them without adding noise or distortion and pass them to the processor for pulse decompres-

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sion/signal processing. The receiver must have a low noise factor and high resistance to interfering signals. Receiver noise (precisely, the sensitivity) limits the range of the radar. Low phase noise is critical to detect and track small changes in the targets. The receiver must also have a high dynamic range to prevent large clutter signals from saturating the system.

Antenna: The antenna receives energy from an electromagnetic (EM) field and radiates EM waves produced by the exciter. The AESA antenna consists of radiating elements and an antenna structure, T/R modules and associated control circuitry, RF beamformers, DC power distribution and a beam steering controller. The antenna must have

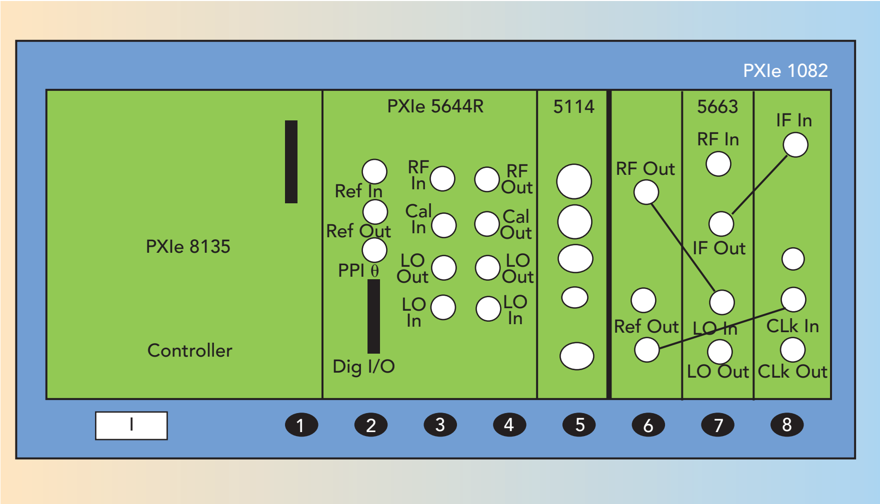


Fig. 2 Battlefield simulator consisting of an NI PXIe-5663 VSA for performing RF measurements, a PXIe-5114 digitizer acting as an oscilloscope and a PXIe-5664R vector signal transceiver for real-time scenario simulation using an onboard user-programmable FPGA.

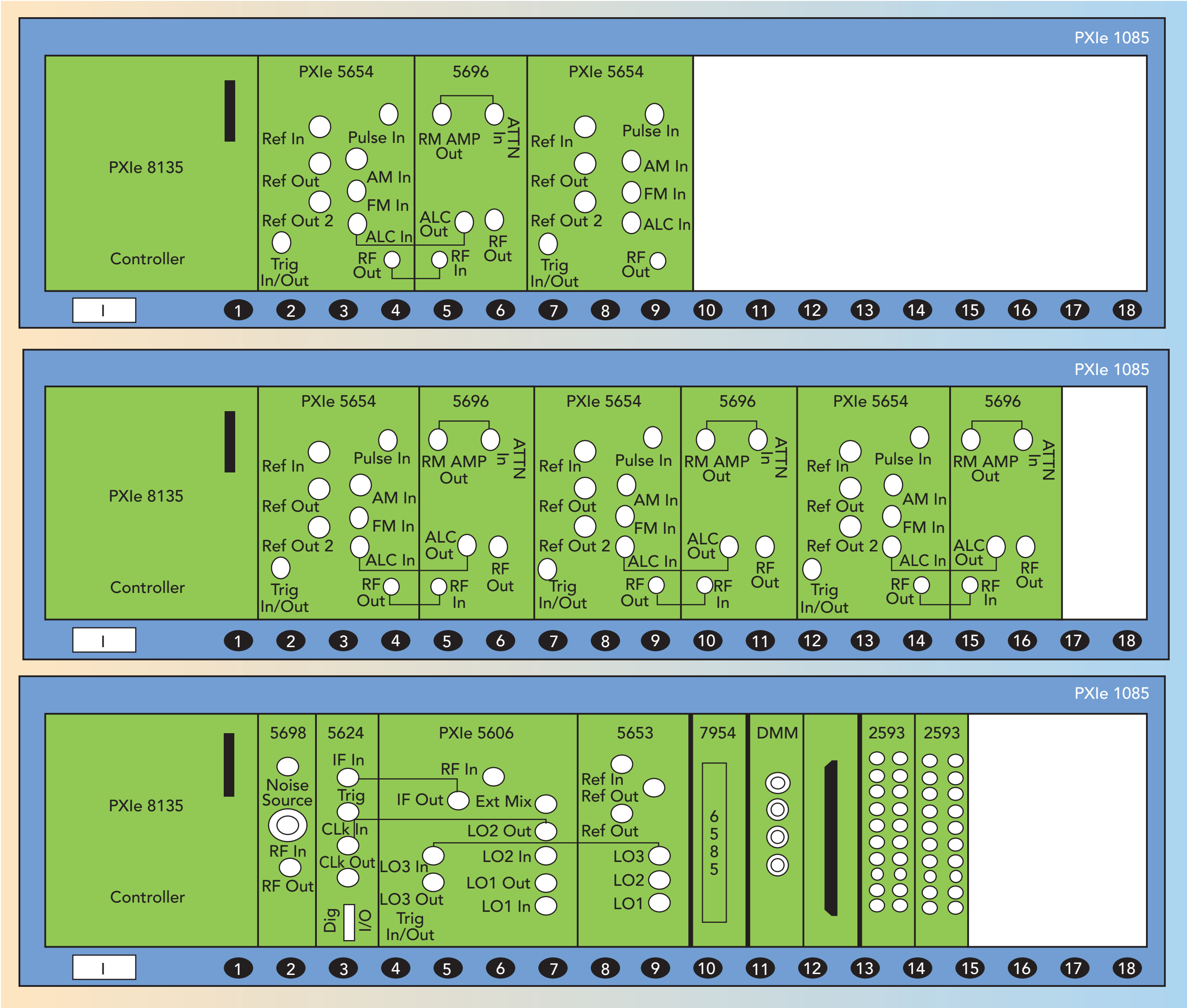
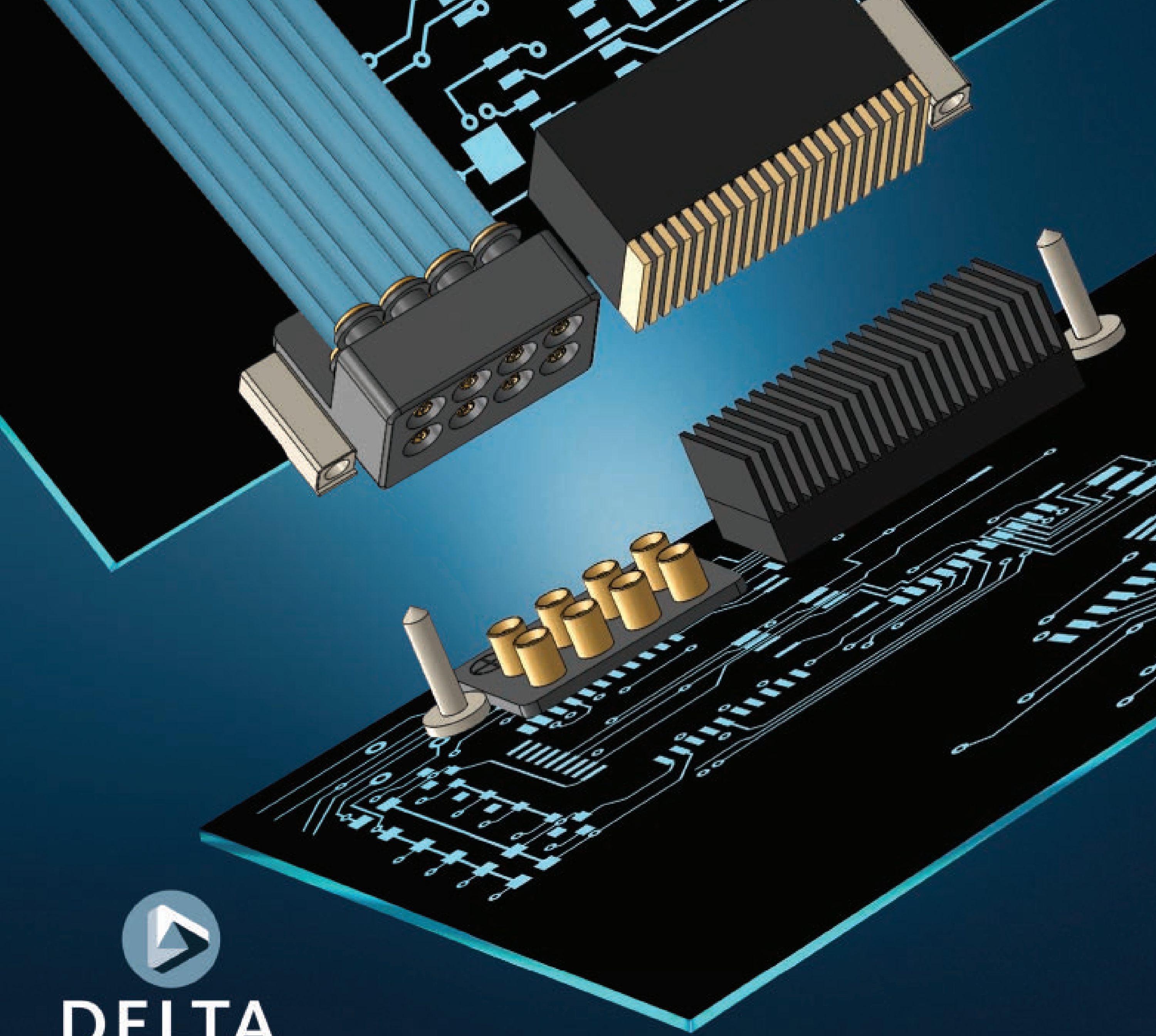
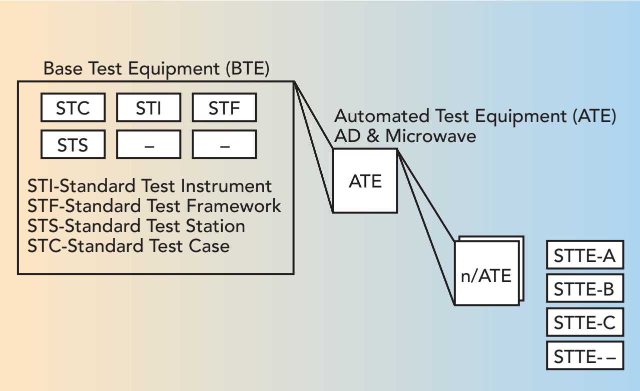


Fig. 3 The three PXIe chassis configuration for the Giraffe 4A radar.





▲ **Fig. 4** **BTE building blocks provide the resources for the UUT tests.**

TABLE 1

BUILDING BLOCKS OF BASE TEST EQUIPMENT

Building Block	*Function*
Standard Test Instruments (STI)	A list of instruments that are certified to be used in an ATE, along with certified instrument drivers
Standard Test Framework (STF)	The software standard that builds up the base of an ATE
Standard Test Station (STS)	All the other materials that can be used for building parts of an ATE
Standard Test Case (STC)	Current released version of the test stand sequences for test management

a precise main lobe (the region around the direction of maximum radiation), low side lobes to minimize radiation in undesired directions and rapid steering of the main lobe for beamforming.

MODULARIZED RADAR ATE SYSTEM

To test and characterize the performance of the sub-modules of the Giraffe 4A radar, engineers at Saab decided to use the National Instruments (NI) PXIe-5668, a multi-stage, superheterodyne, 26.5 GHz vector signal analyzer (VSA). Along with low spurious and harmonic content, NI's VSA offered the desired dynamic range with a reasonable sweep time across the entire instantaneous bandwidth of 765 MHz. The modular form factor of the PXIe-5668R was well-suited to the standard of the Saab radar test bench. To meet cost and size constraints, Saab's test engineers designed an in-house phase noise measurement system using NI PXIe modular instruments. The phase noise measurement splits the acquired signal into two channels, down-converts each into baseband analog waveforms using LO signals and feeds these analog waveforms to the digitizers for cross-correlation. This system also uses other PXIe instruments, such as digital I/O, driver and switch modules to control the down-converters, multipliers, dividers and switching circuits. The entire phase noise measurement system is controlled using LabVIEW. For antenna testing, the test engineers built an indoor test range and simulated the battlefield scenario using an NI PXIe-based scenario simulator, with remote access through a LabVIEW-based application (see ***Figure 2***).

The modular nature of the test setups, using LabVIEW, allowed for integration of many instruments into one state-of-the-art radar ATE system. This ATE system contains three PXIe chassis (see ***Figure 3***) equipped with five PXIe-5654 RF signal generators, four PXIe-5696 amplitude extension modules and a PXIe-5668R VSA with a low noise microwave front end. It also contains an NI FPGA board with a low voltage differential signaling (LVDS) module, used mainly as a controller for sending and receiving commands to the units under test (UUT). Included in the system is an NI relay driver module to control the switching in the ATE fixture, a microwave PXI switch module to route signals in the ATE, an NI PXI digital multimeter (DMM) and PXI multiplexer modules to route low frequency signals. In addition to the three PXI chassis, the ATE system has two 19-in racks that hold a computer, power distribution circuit, power supplies and Virginia Panel Corporation (VPC)

interface, with room to add more instrument signal paths, depending on UUT requirements.

Figure 4 shows the general building blocks of the base test equipment (BTE) in an ATE, and their functions are listed in ***Table 1***. The VPC interface is used as a mass interconnect between the test instruments and the UUTs, allowing the user to connect different fixtures, such as special type test equipment (STTE) designed and built according to customer specifications (see ***Figure 5***).

BENEFITS OF PLATFORM-BASED RADAR ATE

Architecting a modularized radar ATE system involves addressing several key requirements determined by the UUT, as seen in the Giraffe 4A AESA radar example. Building a PXI-based modular ATE system offers advantages over conventional approaches for radar testing, including cost, time and standardization.

Time and Cost Savings

With the continuous evolution of and rising demand for new test requirements for modern radars, the BTE libraries are adding more functionality and support for verified drivers and documentation of the instruments in the ATEs. Traditional ATE systems require expensive retooling on the test floor, as generations of systems become obsolete or are unable to meet new test requirements. The nature of the open

Fig. 5 VPC interface used to select resources from the BTE.

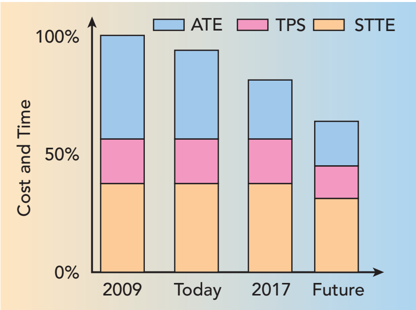
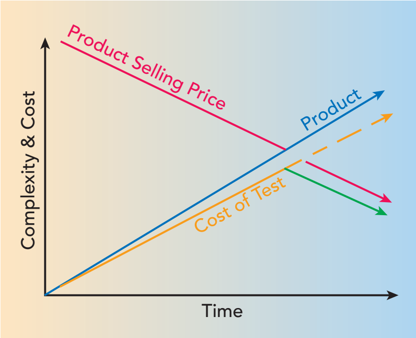
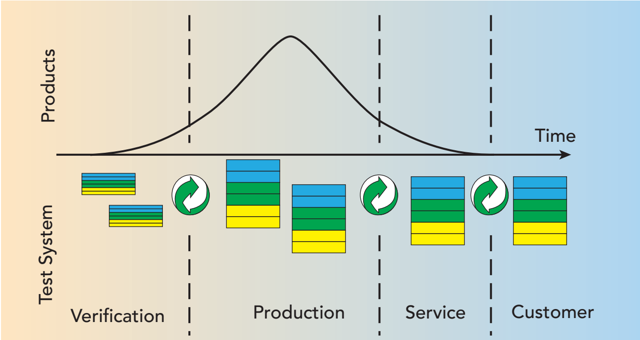


Fig. 6 Reduction in ATE cost and time for testing new radar systems.



▲ **Fig. 7** **Complexity and cost vs. time for high-tech products.**



▲ **Fig. 8** **Correlation between test strategy and product life cycles.**

PXI architecture helps ensure an efficient use of resources and optimal reuse of products and engineering. ***Figure 6*** shows the reduction in engineering effort, reflected in cost and time, to meet the demands of new radar test requirements.

As illustrated in ***Figure 7***, products are becoming more complex, and the cost of development and testing is increasing with the complexity. However, the average selling price is declining, driving the demand to lower test cost. For the system to remain profitable, the cost of test must be reduced at or faster than the reduction in manufacturing price. By adopting a PXIe platform-based approach, Saab reduced test cost and achieved improved performance, scalability and test speed with reduced footprint and power consumption.

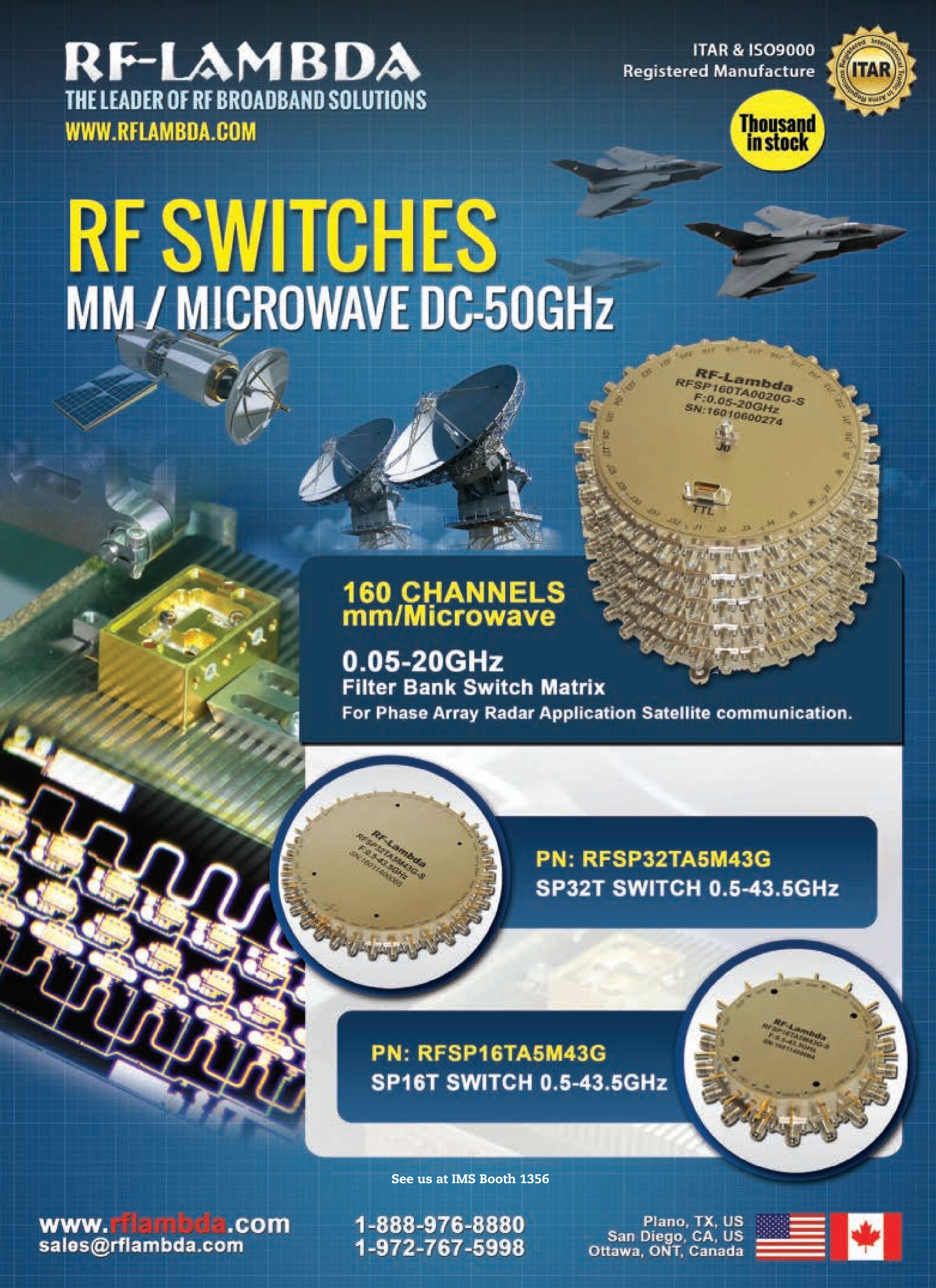
ATE Standardization

The process of standardizing a radar ATE system using a platform-based approach has the advantage of interchangeability. As new technology becomes available, it can seamlessly upgrade older test systems, delaying or eliminating obsolescence. The PXI platform-based radar ATE has interoperable components that work in combination through a common programming and operating environment, such as LabVIEW. Over time, the personnel required for utilizing, operating and maintaining these systems do not need specialized training, which leads to cost saving.

Figure 8 illustrates the correlation between test strategy and product life cycles. The "Products" curve in the figure indicates the number of products that will pass the test during a production lifetime and "Test Systems" reflects the total number of ATEs. Blue indicates test software, green indicates test hardware and yellow indicates instruments from the list of BTE described in Table 1. The plot shows that the capacity of the production line can be more than doubled with an additional ATE fixture. Standardizing on a PXIe platform-based approach for ATE establishes a long-lasting test strategy that correlates with the product's life cycle.

SUMMARY

The radar design and test engineer must carefully assess the specifications of test instruments when building a radar test system and make choices to maximize the return on the investment. With recent advancements in multifunction radars, such as AESAs, test systems are becoming more complex and expensive, driving the need for a state-of-the-art, modularized radar test system that meets the testing requirements while reducing the cost of test. By standardizing the radar ATE framework on the NI PXI platform-based approach, Saab was able to significantly reduce the engineering resources, in cost and time, required to meet the increasingly complex test requirements of advanced AESA radars.■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Controlling Single Microwave Photons: A New Frontier in Microwave Engineering

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VTT, Finland

In microwave engineering we are accustomed to thinking of the electromagnetic energy in our circuits as transmitted by waves. Now, new technologies are being developed that deal with signals at the level of single photons where this is no longer valid. Here we describe some of the challenges and opportunities in this rapidly developing field.

While Maxwell's equations are valid at all frequencies, in practice, we still think of the electromagnetic spectrum as being "segmented" because of the vastly different tools used to manipulate, for example, laser light versus microwaves. In this review we consider microwave "single photons," which are single energy quanta of radiation, with four to five orders of magnitude lower energy than their optical counterparts. A 1 GHz photon has an energy of 0.66 yoctojoule (0.66 $*10^{-24}$ J); 1/200,000th the energy of an optical photon at 1.55 μm or, equivalently, about 1/6000th the thermal energy at room temperature. This explains why, until recently, single photon sources were available only for optical frequencies. As discussed below, manipulating the particle nature of microwave signals is extremely challenging but offers exciting scientific and technological prospects.

Over the past couple of decades, enormous progress has been made in the research field now known as solid-state quantum engineering. The origin of this field can be traced back to the mid-eighties, when the scientific community started to wonder if it would be possible to observe exotic quantum effects such as entanglement and superposition in man-made electronic circuits.[1] The invention of quantum computing algorithms, promising to solve hard computational problems, led to an explosion of experimental activity in the field. However, it was not until the late nineties, with the cre-

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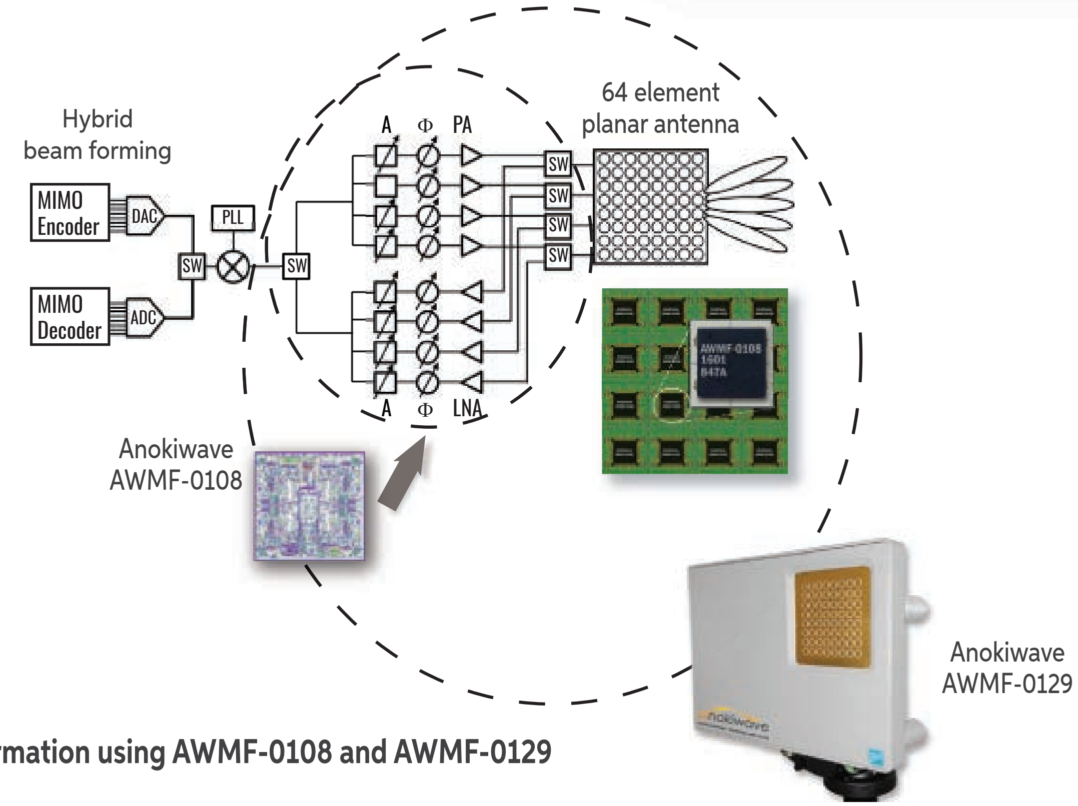

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ation of the first solid-state quantum bits (qubits) that the field really took off.[2] The past few years have seen the complexity of these quantum circuits go up enormously; some circuits now contain hundreds of elements[3] all operating at microwave frequencies, typically in the range 1 to 12 GHz.

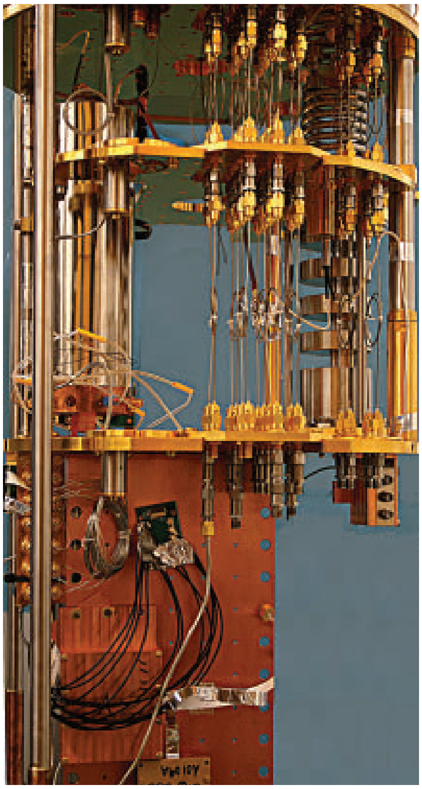
The headline-grabbing long-term goal of all of this effort is to build a quantum computer; a type of a computing device that uses quantum algorithms to solve certain problems, most notably factoring large integers for code breaking, much faster than a classical computer. However, in the pursuit of this goal researchers have also developed a toolbox containing novel microwave components and devices that may turn out to be useful in a much wider range of applications.

This is a very active research field and there are many ongoing projects around the world. The authors are involved in one such international project called MICROPHOTON which is funded by Euromet.[4] In this brief review, we will describe some of the latest developments in this rapidly advancing area.

QUANTUM CIRCUITRY

One remarkable aspect of Maxwell's equations is that they are valid even in the "quantum" regime where we are dealing with single photons. This means that single microwave photon systems can, from an engineer's point of view, be treated as any other microwave circuits and we can use many of the same familiar tools. The systems need detectors, sources and ways to manipulate and guide the photons.

It would be difficult to distinguish a chip with a quantum circuit from one with a conventional electronic circuit. A typical chip made using, for example, superconducting device technology (one of the leading contenders in this field) contains 50 Ω transmission lines (usually coplanar waveguides), planar inductors (spirals or meanderlines) and capacitors (interdigital, planar or parallel-plate types) fabricated on a low loss substrate (usually sapphire or silicon). Other common elements include resonators, either lumped



▲ **Fig. 1 The sample stages of a dilution refrigerator equipped with microwave lines, where the different levels get progressively colder. The device under test is mounted at the bottom, where T ≈ 10 mK.**

or transmission line λ/2 and λ/4 sections.

The key elements of quantum circuits are qubits that are used as "artificial atoms." For superconducting circuitry these are typically based on so-called Josephson junctions; although they are also fabricated using standard microfabrication techniques and are therefore, from a design point of view, just another type of circuit element. As the complexity of these circuits continues to grow, so does the importance of precision microwave engineering.

A COOL TECHNOLOGY

The energy of a single microwave photon is very small compared to the thermal background at room temperature. This dictates that any device using single microwave photons must be cooled to cryogenic temperatures. In practice, most of the single photon devices that are currently being developed must be operated at temperatures below 0.1 K.[5-8] Not long ago this would have meant using cryostats that used liq-

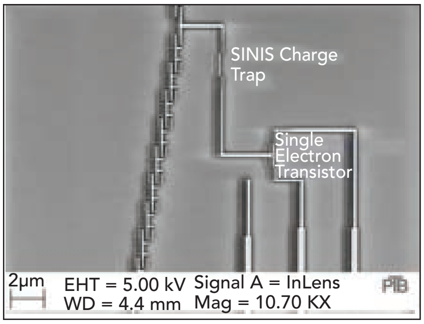
uid helium for cooling, which is generally unsuitable for use outside of research labs; however, rapid progress in the field of cryogenics has already seen the development of much more user-friendly dry (cryogen free) mechanical systems (see ***Figure 1***) that require only a source of electricity to run.[9] Currently available systems are still too bulky and expensive for widespread use, but smaller and cheaper systems are in development.

At these low operating temperatures, superconductors are typically used for transmission lines even when normal metals such as copper would, in principle, work. The benefit is very low loss; the equivalent resistance can be lower than 10^{-4} Ω/square at GHz frequencies. Hence, it makes sense to fabricate most circuit elements out of superconducting aluminum or niobium, for example, rather than copper even though this is not, strictly speaking, necessary from a functional point of view. This also means that circuit elements can usually be modeled as lossless metals.

DETECTING SINGLE MICROWAVE PHOTONS

Detecting a single microwave photon is extremely challenging. Several companies now produce low noise amplifiers (LNA) with noise temperatures as low as 2.1 K for C-Band (4 to 8 GHz);[10] however, even this impressively low figure is still too high to detect a single microwave photon. Moreover, there are intrinsic issues, such as amplifier self-heating, based on conventional III-V semiconductors making it unlikely that they will ever be useful as practical single photon detectors. In order to overcome this problem, new types of advanced instrumentation, parametric amplifiers (paramps) and bifurcation amplifiers, have been developed over the past few years.

Parametric amplification is not a new idea, but paramps based on superconducting circuits have literally pushed the technology to its physical limits. Several research groups have demonstrated designs that are truly quantum limited; i.e., noise is limited only by quantum fluctuations.[11] Typical gain of these amplifiers is 20 to 30 dB, which brings the signal up to a level where conventional LNAs can be used for further amplification.



▲ **Fig. 2 Scanning electron microscopy of a photon detector based on conversion of a single photon into charge. The device is fabricated by MICROPHOTON partner PTB (Germany).[6]**

For single photon detection, it would be desirable to develop a circuit that sends out, for example, a voltage pulse (a click) whenever a single photon is absorbed. These click detectors are widely available for frequencies in the optical range, where typical photon energies are 1,000,000 times higher, but has proven very difficult to develop for microwave frequencies. However, recent results from several research groups, suggest that such detectors might soon become available.[8]

An approach, which has already demonstrated single photon sensitivity in special circumstances, utilizes phenomena that directly exploit the quantum-particle nature of photons. Photons are trapped in a resonator (the microwave equivalent of photons bouncing between two mirrors) and their presence detected indirectly using a qubit.[5] This method is extremely sensitive, but in the absence of additional circuitry, is inherently slow and inefficient.

Figure 2 shows an example of a threshold detector that sends out an electrical signal when a single photon with high enough energy is absorbed. The implementation in Figure 2 is a nanofabricated circuit which detects absorbed photons by sensing when electrons are knocked out of a charge trap using a single electron transistor (essentially a very sensitive electrometer). Absorption events of single microwave photons can be detected clearly, but the

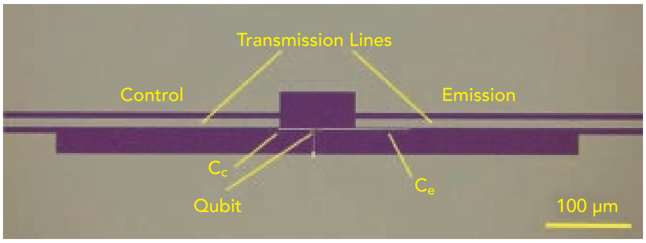


Fig. 3 **Single photon source based on a superconducting qubit (an "artificial atom"). The qubit is asymmetrically coupled to two 50 Ω coplanar waveguides via coupling capacitances C_c = 0.5 fF and C_e = 5 fF.**

quantum efficiency of such a detector is very low; only a tiny fraction of incoming photons are actually absorbed in the detector.

A very sensitive thermal power sensor can also, at least in principle, be used for sensing microwave photons. This would detect a single photon bolometrically or calorimetrically by measuring the increase in temperature as the photon hits a 50 Ω absorber terminating a waveguide. A recently demonstrated state-of-the-art result for this approach is a detector capable of sensing pulses containing about 200 photons at 8.4 GHz.[12] Other approaches include using so-called bifurcation amplifiers (essentially bistable threshold amplifiers) that can already be made sensitive enough to detect pulses containing a few photons.[13] Unfortunately, both thermal and bifurcation amplifier detectors realized to date must integrate the signal for a long time to achieve anywhere near single photon sensitivity, meaning this is an area with a lot of potential for improvement.

An efficient single microwave photon detector would be useful not only as a fundamental physics experiment or for quantum information processing. In principle, it would also enable counting the number of incoming photons per second, thus providing a measure of absolute microwave power without any need for calibration.

GENERATING MICROWAVE PHOTONS

Creating an electric circuit that functions as an on-demand source of microwave photons has only become possible in the past decade. The seemingly obvious way to do this would be to take an ordinary microwave generator and attenuate its output; however, this approach does not work. While it can create a source that over some timespan, on average, emits energy equivalent to one photon (or even less) it cannot be used to make a true single photon source, since the photons are uncorrelated. In a true single photon source, the spacing between photons is very regular, which is what gives the radiation its non-classical nature.

So how do you generate a single photon? The solution is once again to use quantum technology originally developed for quantum computing. The quantum bit, or qubit, is the quantum mechanical version of the digital bit, albeit with some very special properties. This can be exploited to make a single photon source since a qubit switching from its "1" state to "0" emits a single photon. It is similar to how an atom emits light when an electron moves from an excited state to a lower energy state. The engineering challenge is to create circuits that can reliably prepare a qubit in its "1" state and also guide the resulting photon. Doing this at optical frequencies is extremely difficult due to the low collection efficiency of emitted photons in three dimensional space. In the microwave regime, however, where transmission lines are one dimensional and circuit elements are "point-like" with respect to a wavelength of radiation, quantum output efficiencies are already above 50 percent in the first candidate devices. Work on devices for single photon generation in the microwave regime was pioneered by research groups at Yale University in the U.S. and ETH in Switzerland.[7,14]

An implementation of a microwave single photon source is shown in ***Figure 3***. This circuit is based on a qubit embedded in a 50 Ω coplanar waveguide. The trick here is that the qubit is much more strongly coupled to the "out" port than the "in" port.

A large amplitude trigger pulse generated by a conventional microwave pulse generator in the "in" port excites the qubit, which then (a few tens of nanoseconds later) decays into the "out" port, emitting a photon. The coupling capacitances are chosen in such a way that stray coupling between ports is minimized. Hence, this circuit functions a bit like the quantum equivalent of a monostable multivibrator (a familiar circuit from conventional electronics) in that it is an on-demand source. MICROPHOTON partners RHUL and NPL (U.K.) have with Japanese collaborators recently demonstrated on-demand generation of single microwave photons with such a source.[15]

There has been remarkable progress in this area over the past few years, but making large-scale quantum circuits still presents numerous challenges.[16] Fortunately, where hundreds or thousands of qubits are needed to build a practical quantum computer, only one is required to make a source. Hence, practical single microwave photon sources are likely to become available for real-world applications much sooner than quantum computers.

CONTROLLING PHOTONS

Emitting and detecting single microwave photons remains challenging and is much more difficult than in the optical regime. However, microwave photons have one very important advantage over optical photons: they are much easier to control. A signal consisting of a stream of individual microwave photons will behave just like any other microwave signal, and normal passive microwave components can therefore be used.

Researchers in the field have developed specialized circuits (often using Josephson junctions or qubits as building blocks), but these are typically, from an engineering point of view, little more than high performing versions of commonly used elements such as filters, couplers, transformers and switches. The main difference between these and off-the-shelf microwave components is usually only that they have very low losses and can be operated at low temperatures.

There are some philosophical differences, however, in how one chooses to interpret what is happening. An example is the common hybrid coupler which is functionally identical to the half-silvered mirror commonly used in optics. The magnitude of a classical signal will be split equally between the two output ports; but, if the signal consists of a single photon, it can only exit through one of the ports. This is the one example of a phenomenon one would never encounter in a classical circuit.

APPLICATIONS

The technology discussed in this article was developed primarily for fundamental research and designed to meet the needs of researchers working in the field of solid-state quantum engineering. While widespread usage of quantum computers is still decades away, an obvious question is whether there are any current real-world applications of single microwave photon technology. As with any new technology, it is difficult to predict the impact. The first users will likely be scientists working in radio astronomy and other areas where the extra overhead in terms of cost and equipment can be tolerated if it leads to significantly higher performance. The paramp, essentially just a very good microwave amplifier, is likely to find applications in demanding areas such as space communications.

Another area that will benefit from this technology is precision metrology. The quantum nature of this technology is an advantage since it gives direct connection to the primary standards of the international system of units; this would be especially true if sources and detectors become available with efficiencies high enough to allow for direct microwave photon detection.

CONCLUSION

Microwave photonics is a new field and contains elements that one would not normally encounter in microwave engineering. However, most of the fundamentals are still the same as for any other microwave circuit design; and, as the complexity of quantum circuitry continues

to grow, so does the importance of sound microwave engineering.■

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Broadband High Efficiency Power Amplifier Design Using Continuous Class F Mode

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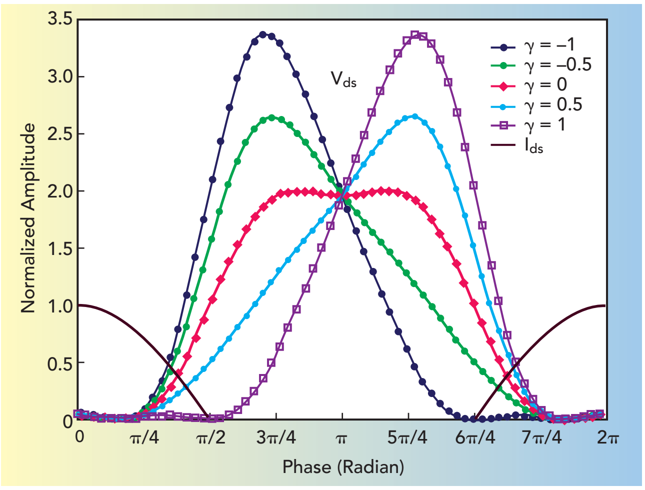
A novel approach for the design of broadband high efficiency power amplifiers (BHPA) simplifies the process of synthesizing a wideband output matching network by realizing harmonic tuning and fundamental matching separately. First, the second and third harmonic load impedances are calculated based on the theory of the continuous class F mode. Then, a novel wideband harmonic suppression network is obtained by using microstrip radial stubs (MRS) that is unaffected by the adjacent fundamental matching circuit. A power amplifier (PA) designed with a 10 W Wolfspeed GaN HEMT device achieves a fractional bandwidth of 30.4 percent from 1.95 to 2.65 GHz, with 60.9 to 81.6 percent drain efficiency (DE), 60 to 79.9 percent power-added efficiency (PAE) and 39.7 to 41.7 dBm output power across the operating band. As shown through the design process, simulation and measured results, this approach makes the design of the harmonic load network easier and more accurate compared to existing methods, for which it is difficult to simultaneously control the fundamental and harmonic impedances, especially at higher frequencies. This method can be widely applied to BHPA design for modern wireless communication systems.

Besides linearity, a major concern in PAs today is the improvement of output power and efficiency across a wide bandwidth, to meet the demands of expanding communication networks and increasing data rates in various wireless standards such as GSM, WCDMA, WIMAX and LTE. For the PA modes so far considered, the switch-mode PA (SWPA) has attracted considerable research attention due to its high performance with respect to output power and conversion efficiency. Class F mode in the SWPA achieves high efficiency with nonoverlapping square wave voltage and half-sinusoidal current drain waveforms at the output of the active device. In this simple way, the class F mode PA has become one of the most cited.[1-3]

For practical reasons, finite harmonics (typically the second and third) are controlled by λ/4 transmission line resonators to approximate the proper harmonic load impedances. This method, however, inevitably results in an output matching network with a high Q factor. Consequently, the inherent narrowband performance (typically less than 10 percent) of a class F amplifier is difficult to overcome and limits its potential for wideband applications. Some pioneering work[4-6] provides several good approaches for expanding the bandwidth of the class F mode PA, but its limitations can only be moderately overcome.

An extended PA mode, derived from class J PAs and known as the continuous class F[7], demonstrates a great advantage in terms of high efficiency across a broad band. In the continuous class F case, amplifiers can achieve high output power and efficiency delivered by class F through various combinations of voltage and current. Only the current waveform needs to be constant, and the voltage wave-



▲ **Fig. 1** Continuous class F voltage and current waveforms.

form is no longer just a square wave, but a collection of waveforms.

The output matching impedance is generally controlled up to the third harmonic. The third harmonic remains in the open state and the second harmonic on the impedance Smith chart runs along the R = 0 circle, while the fundamental wave impedance is on a resistance circle moving in the opposite direction. Taking parasitic elements such as drain capacitance and bonding wire inductance into consideration, the situation compared with the ideal will change at different frequency points. Actually, the continuous class F mode provides a series of solutions for optimal fundamental and harmonic matching impedance across a wide frequency band.

The design described here employs a new architecture addressing the difficult harmonic control problem (up to the third harmonic). In the output network, MRSs are used to obtain precise harmonic impedances, while fundamental impedances are achieved with stepped impedance transformers.

THEORY

In a class F mode PA, the drain voltage and current are shaped into nonoverlapping square and half sinusoid waves, respectively, by shorting the even harmonics and presenting an open to the odd harmonics. Typically, only second and third harmonic control is taken into account in a practical design because of small improvements in efficiency with greater circuit complexity when higher harmonics are considered. The normalized, optimum drain voltage waveform with a corresponding efficiency of 90.7 percent[8] is expressed as:

$$V_{ds} = 1 - \frac{2}{\sqrt{3}}\cos\theta + \frac{1}{3\sqrt{3}}\cos 3\theta \quad (1)$$

The above equation represents a voltage waveform that must be tuned precisely at the current generator plane of the device; therefore, a class F PA is usually implemented for maximum power and efficiency at a single frequency. Efficiency degrades quickly for frequencies outside the operating band.

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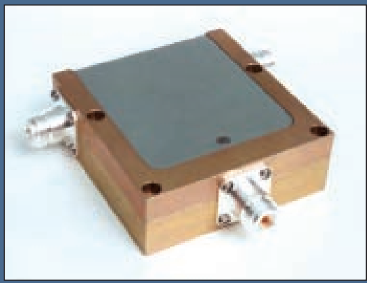

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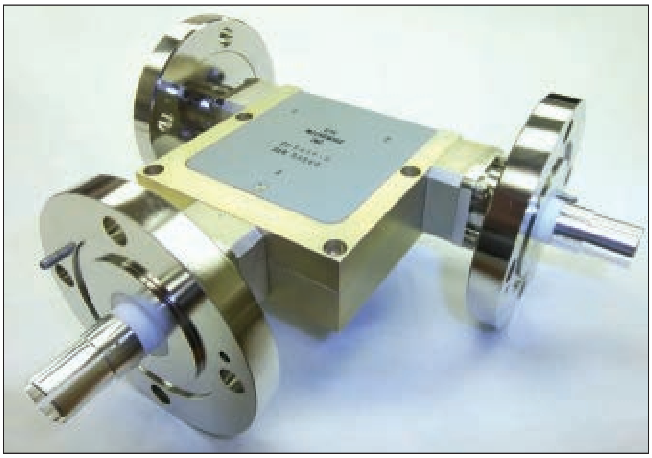

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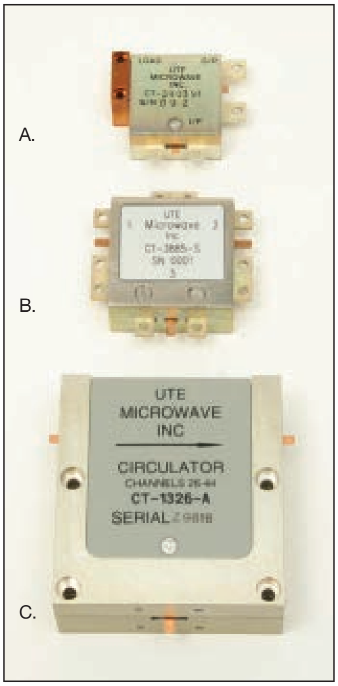

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CT-3838-N	5 Kw Pk 500 W Av	N Conn.	2.7–3.1 GHz
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The continuous class F mode provides formulas for a series of waveforms to overcome the class F mode bandwidth limitation. The waveforms for providing high power and efficiency can be obtained by introducing a varying parameter, γ, to the voltage waveform formula. Its modified voltage waveforms can be described as:

$$V(\theta)=\left(1-\frac{2}{\sqrt{3}}\cos\theta\right)^2 \cdot \left(1+\frac{1}{\sqrt{3}}\cos\theta\right)(1-\gamma\sin\theta) \quad (2)$$

Voltage waveforms for the case $\gamma = 0$ turn into the standard class F mode. The continuous class F mode can maintain the performance of its counterpart, class F, by changing the standard class F drain voltage waveform as the parameter γ varies over the range $-1 \leq \gamma \leq 1$. This leads to a family of voltage waveform solutions. In this way, the corresponding maximum normalized drain voltage amplitude increases from 2 to 3.37 (see ***Figure 1***), sustained by utilizing GaN device technology. It can be seen that when $\gamma = 0$, the waveform corresponds to the class F case.

In practice, harmonic impedances must be calculated from the following equation:

$$Z_n = -\frac{V_n}{I_n} \quad (3)$$

where n represents the order of the harmonic component. R_{opt} is defined as the optimum impedance for the standard class B mode, expressed as:

$$R_{opt} = \frac{V_{dc} - V_{knee}}{I_{max}/2} \quad (4)$$

V_{dc} is the drain bias voltage, V_{knee} is the knee voltage of transistor and I_{max} is the maximum drain quiescent current. The drain current waveform of the continuous class F PA is the same as that of the class F mode PA, which is based on a Fourier series expansion and defined as:

$$i_d(\theta)=\frac{1}{\pi}+\frac{1}{2}\cos(\theta)+\frac{2}{3\pi}\cos(2\theta)-\frac{2}{15\pi}\cos(4\theta)+\ldots \quad (5)$$

The corresponding impedance is determined by equations 2, 4 and 5 as follows:

$$Z_f = R_{opt}\frac{2}{\sqrt{3}} + jR_{opt}\gamma \quad (6)$$

$$Z_{2f} = -jR_{opt}\frac{7\sqrt{3}\pi}{24}\gamma$$

$$Z_{3f} = \infty$$

$$Z_{4f} = jR_{opt}\frac{5\sqrt{3}\pi}{24}\gamma$$

The nature of the impedance curves for $-1 \leq \gamma \leq 1$ is shown in ***Figure 2***. The third harmonic impedance remains in an open state and the second harmonic impedance moves along the R = 0 circle of the Smith chart, while the fundamental impedance moves in the opposite direction.

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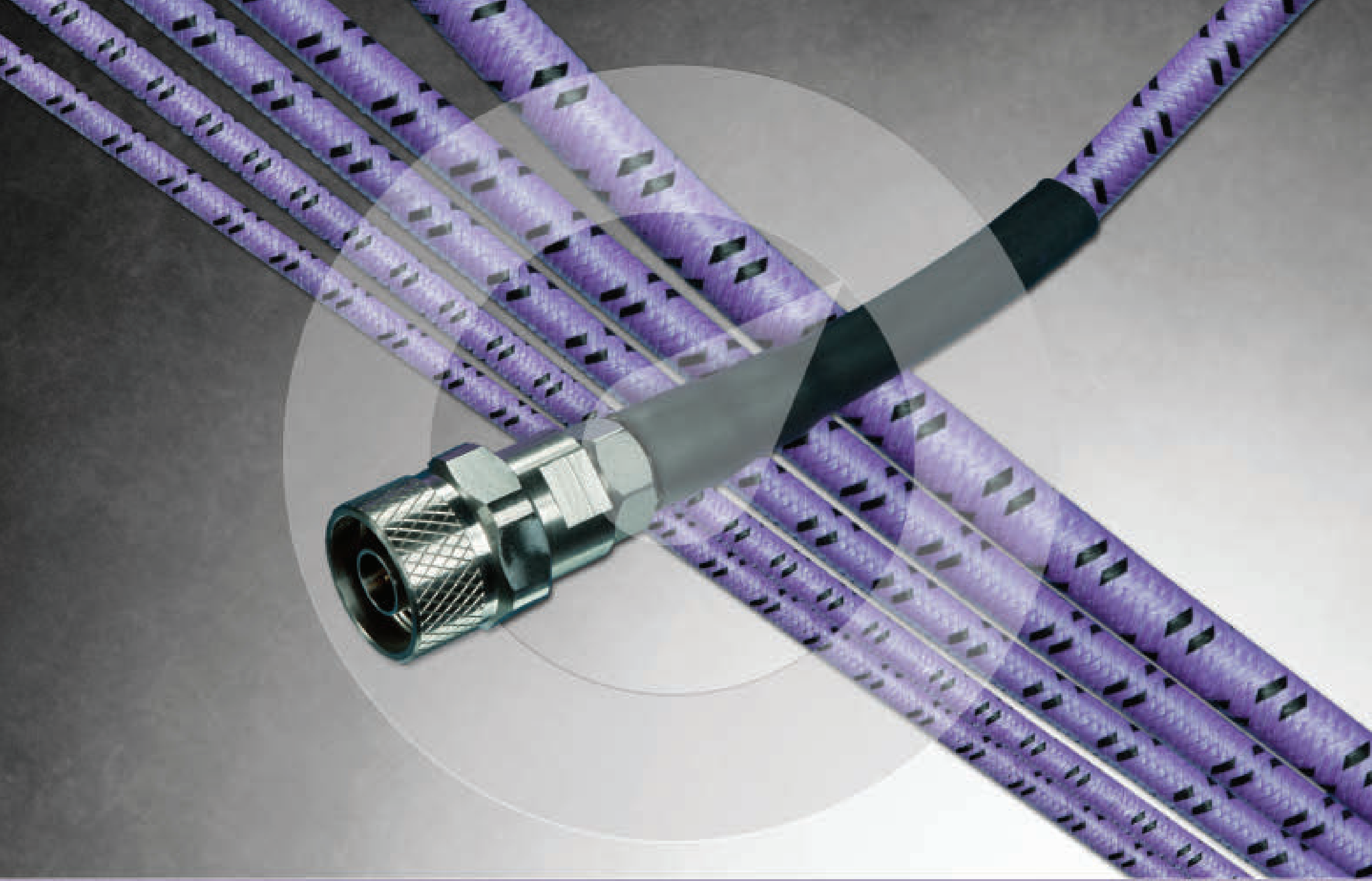


CONTINUOUS CLASS F PA DESIGN

Figure 2 shows that in an ideal case the third harmonic impedance is constrained to be infinite; however, this is extremely difficult to achieve and is not necessary for a practical design. In this article, a simple and practical approach is described for obtaining the harmonic impedances. Through the action of a nonlinear device output capacitance, C_{DS}, as discussed by Tutly, et al.,[9] the third harmonic high efficiency impedance trajectory is made to move along the edge of the Smith chart. This can be done by harmonic load-pull after the second harmonic termination is determined. The position of the $\gamma = 0$ point should be noted. This method of third harmonic load determination guarantees a high efficiency BHPA design.

From Equation 2, the fourth harmonic impedance is also important in the continuous mode; however, design of a broadband continuous class F PA with fourth harmonic control is difficult and will inevitably require a very complicated circuit. The more feasible method is to neglect the fourth harmonic impedance. The effect of neglecting Z_{4f} on continuous class F performance can be calculated. The result is shown in ***Figure 3*** as the parameter γ is varied. Degradation in efficiency is less than 4.5 percent over the range of γ values. The maximum degradation occurs at $\gamma = +1$, which can be avoided by limiting the bandwidth.

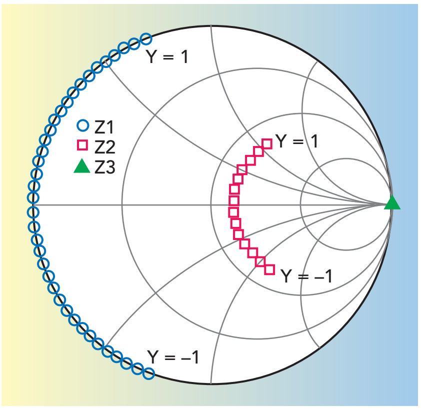
Limitation of Bandwidth

The target bandwidth should be limited to avoid overlapping with the harmonic bandwidth. The target fundamental band is set from

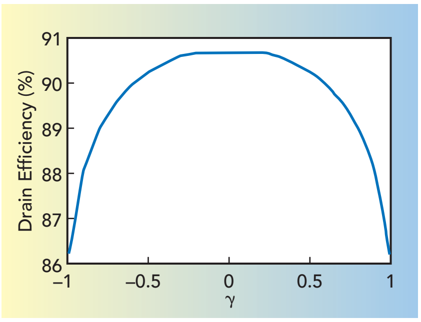
$$f_0 - \frac{\Delta f}{2} \text{ to } f_0 + \frac{\Delta f}{2}$$

and the second and third harmonic bands can be expressed as follows:

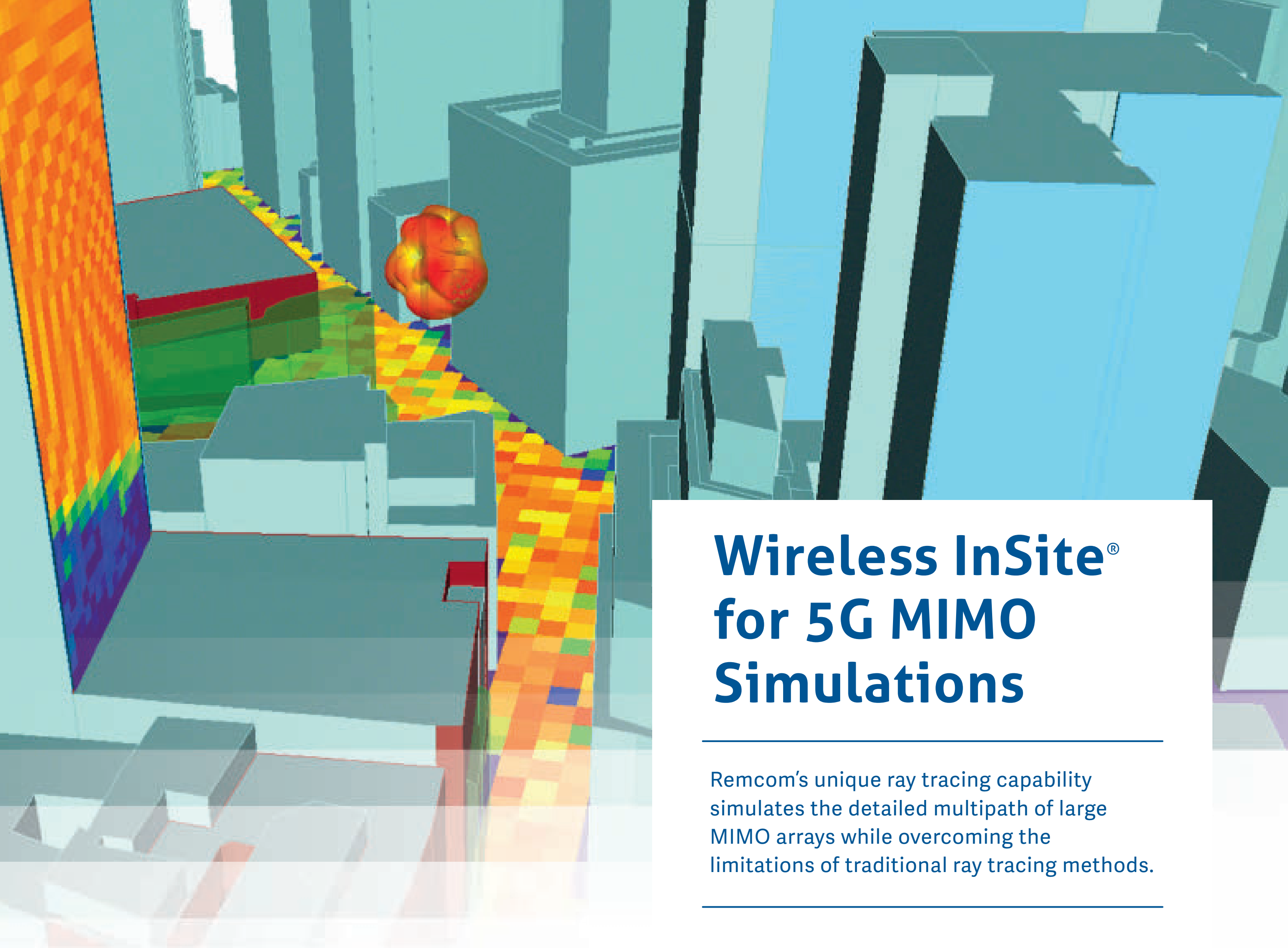
$$\left[f_0 - \frac{\Delta f}{2}, f_0 + \frac{\Delta f}{2}\right] n, n = 1, 2, 3 \qquad (7)$$

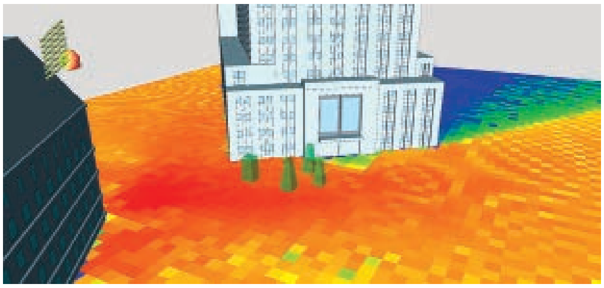


▲ **Fig. 2 Theoretical continuous class F mode impedance curves, showing the fundamental and second and third harmonic loads.**



▲ **Fig. 3 Efficiency degradation vs. γ.**



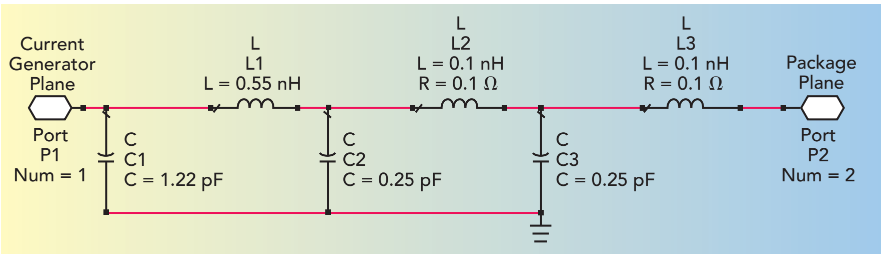


As previously discussed, control of the fourth harmonic is neglected. From Equation 7, bandwidths overlap when

$$\left(f_0 + \frac{\Delta f}{2}\right) = 2\left(f_0 - \frac{\Delta f}{2}\right) \qquad (8)$$

or

$$2\left(f_0 + \frac{\Delta f}{2}\right) = 3\left(f_0 - \frac{\Delta f}{2}\right) \qquad (9)$$



▲ **Fig. 4** Equivalent circuit of the Wolfspeed CGH40010F GaN transistor.

Equation 8 represents the overlapping case for the fundamental and second harmonic bands. Equation 9 represents the overlapping case for the second and third harmonic. For the ideal continuous class F PA where the third harmonic is in an open state, consider the overlapping of the fundamental and second harmonic bands represented by Equation 8. The fractional bandwidth (FBW) of the ideal continuous class F is

$$FBW = \frac{\Delta f}{f_0} = \frac{2}{3} \approx 66.7\% \qquad (10)$$

It is clear that the limitation of Equation 9 is more restrictive than the limitation of Equation 8. The FBW from Equation 9 is:

$$FBW = \frac{\Delta f}{f_0} = \frac{2}{5} = 40\% \qquad (11)$$

Load Impedance with Parasitic Parameters

In a practical design utilizing a packaged GaN device, as described here, parasitic parameters must be taken into account. The parasitic model of the Wolfspeed CGH40010F GaN device is shown in ***Figure 4***.[10]

Due to the impact of parasitics, the load impedance reference plane of the continuous class F PA shifts from the ideal current generator plane to the package plane. This forms a fundamental impedance area and a harmonic impedance area. These areas correspond to a series of solutions. The key to a successful design is to contain the matching load impedances in these areas, respectively, across a wide band. As a consequence, the voltage waves do not strictly follow the variation shown in Figure 1.

Output Matching Network

In this architecture, MRS are used for harmonic control and stepped impedance transformers are used for fundamental matching over a specified range of frequen-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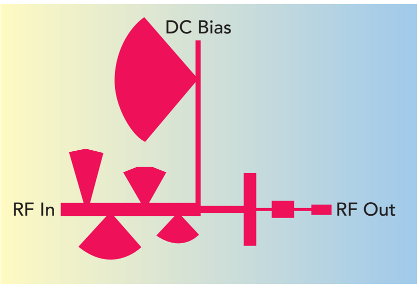
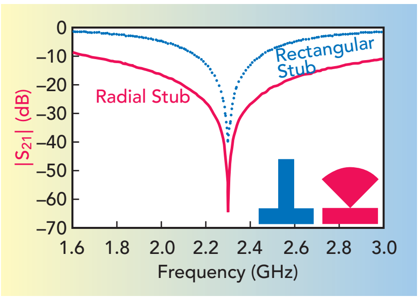


▲ **Fig. 5** Continuous class F output matching network layout.



▲ **Fig. 6** Comparison of a radial vs. rectangular stub.

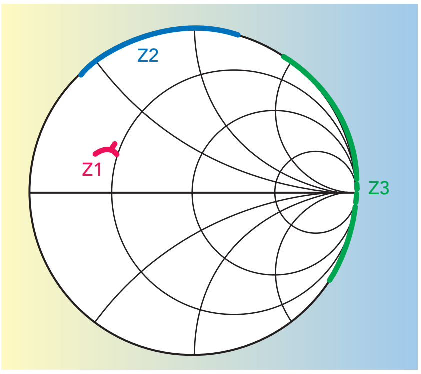
cies. Commercial computer-aided design (CAD) software is used for greater accuracy in determining the harmonic impedances presented to the device. The output matching network used for the continuous class F design is shown in ***Figure 5***.

As ***Figure 6*** shows, a radial stub exhibits wider bandwidth performance and a much deeper resonance than a rectangular stub. More important, however, is that the four radial stub structure can realize a constant 0 Ω resistance over a wide band. In other words, it forms a stable structure that is independent of the fundamental matching network. This harmonic network is the key to separating the harmonic terminations from the fundamental matching. In addition, the structure of up-and-down radial stubs is convenient for fabrication, avoiding overlap when the second and third harmonic matching stubs are closely spaced.

The corresponding target loads and behavior of the output matching network (fundamental and second and third harmonic) are shown in ***Figure 7*** over a band from 1.95 to 2.65 GHz. It is apparent that the second and third harmonic components behave in accordance with the design requirements.

BHPA FABRICATION AND MEASUREMENT

The design is implemented on a Rogers 5880 substrate with ε_r = 2.2, a dielectric thickness of 0.787 mm and a copper thickness of 18 µm (see ***Figure 8***). The Wolfspeed CGH40010F GaN HEMT packaged device has a drain bias of 28 V with a corresponding quiescent drain current of 168



▲ **Fig. 7** Impedance of the continuous class F output matching network, showing the fundamental (Z_1), second (Z_2) and third (Z_3) harmonic components.

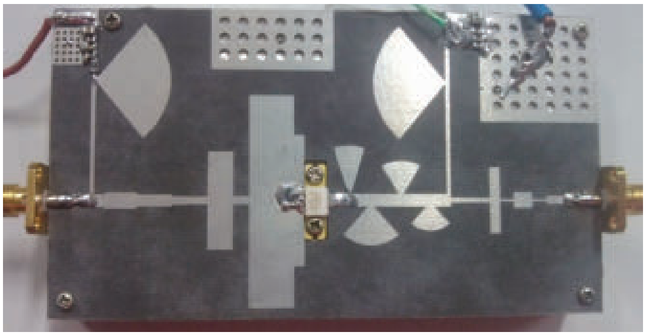


Fig. 8 Fabricated BHPA.

mA. Large-signal continuous wave (CW) PA characterization is conducted from 1.95 to 2.65 GHz. The results in ***Figure 9*** show PA performance in terms of output power, gain, drain efficiency and PAE as a function of frequency. The prototype achieves 39.7 to 41.7 dBm output power and a peak PAE of 60 to 79.9 percent with 30.4 percent bandwidth, extending from 1.95 to 2.65 GHz. The highest PAE is 79.9 percent, but it is nearly impossible to maintain this level throughout the entire operating band (in the upper part of the band, PAE drops to 60 percent).

A 5 MHz WCDMA signal is used to evaluate linearity and adjacent channel power ratio (ACPR) characteristics at 2.14 GHz. The BHPA output spectra with and without digital predistortion (DPD) are shown in ***Figure 10***. The PA achieves an average drain efficiency of 32.1 percent and an output power of 35.3 dBm. The ACPR is -32.8 and -32.7 dBc at ±5 MHz offset, and -50.5 and -50.9 dBc at ±10 MHz offset. After applying DPD, the ACPR significantly improves to -49.7 and -48.6 dBc at ±5 MHz offset, and -59.0 and -55.6 dBc at ±10 MHz offset.

CONCLUSION

A novel method for synthesizing an output matching network consists of a four MRS harmonic control structure and a stepped impedance fundamental matching structure. This method provides an easy approach to BHPA design. A BHPA is implemented using a GaN

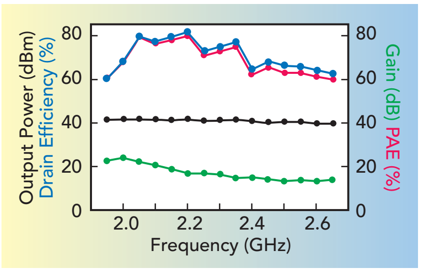


Fig. 9 Measured performance of the BHPA.

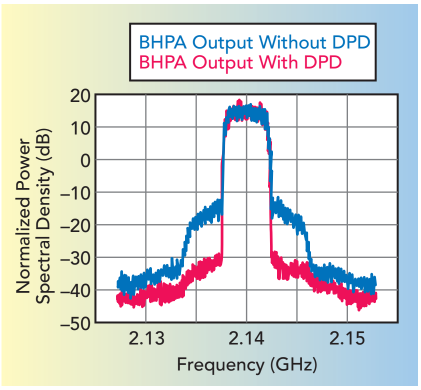


Fig. 10 BHPA output spectra for a 5 MHz WCDMA signal with and without DPD.

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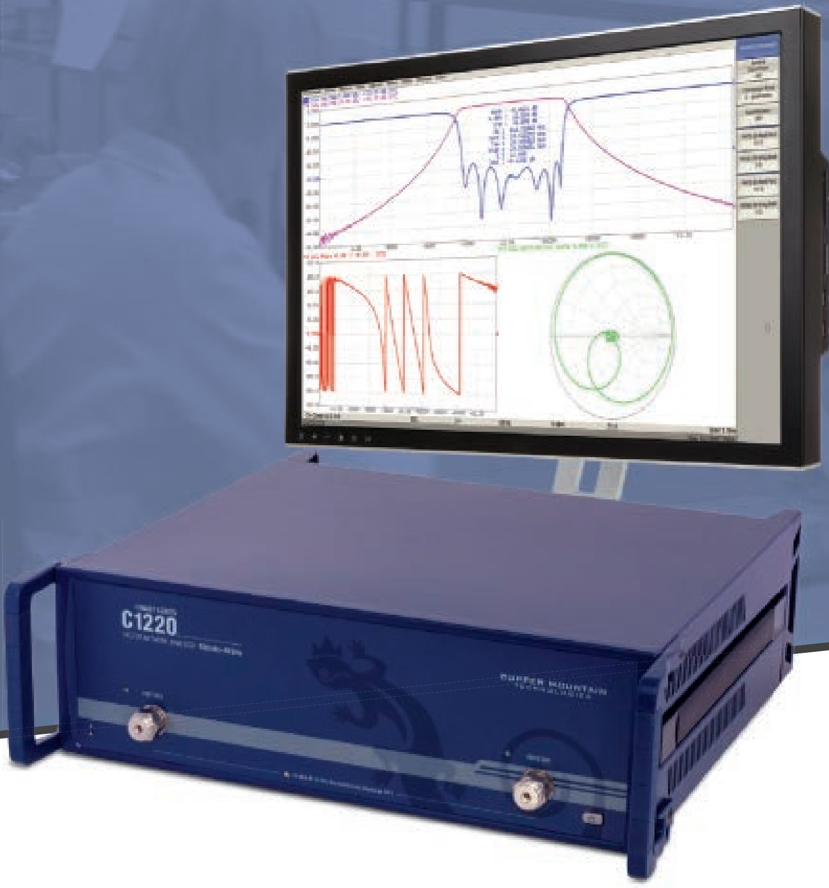

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HEMT over an operating frequency band of 1.95 to 2.65 GHz. Its performance compares favorably with a selection of current state-of-the-art designs shown in ***Table 1***. Analysis shows that the second harmonic is matched well for high efficiency and output power. The theory of third harmonic impedance matching is extended for practical broadband design to mitigate the fact that a fixed third harmonic load (as defined for the continuous class F mode) is extremely difficult to implement over frequency. Test results show that this structure can achieve high efficiency and power gain across a 1.95 to 2.65 GHz band. Linearity improvement is achieved with DPD.■

TABLE 1

BHPA COMPARISON

Ref	Class	Bandwidth (GHz)	Output Power (W)	PAE (%)
11	Class E	2.1 to 2.7	9.3 to 12.7	53 to 63
12	Class J	2.15 to 2.65	10 to 12	57.6 to 65.5
13	Continuous Class F	2.15 to 2.65	11.4 to 15	61 to 71
This Work	Continuous Class F	1.95 to 2.65	9.3 to 14.8	60 to 79.9

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Security in Automotive Radar and Vehicular Networks

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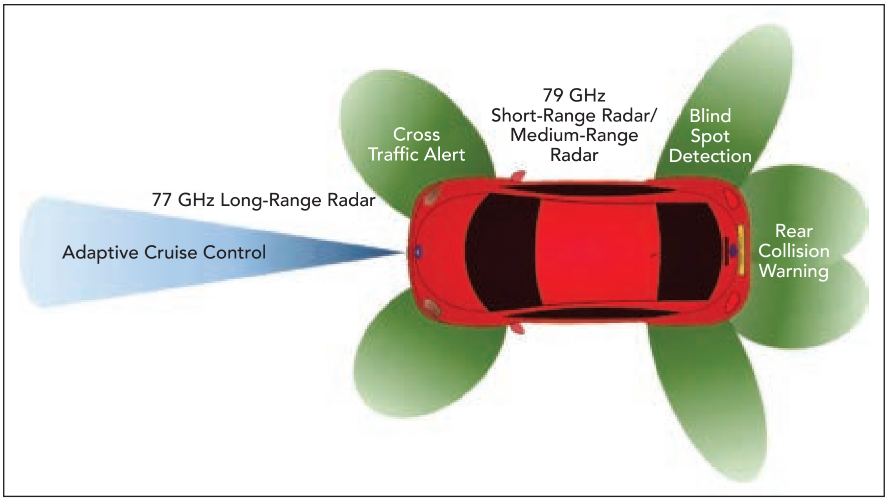
As vehicles become more automated, security issues in automotive systems such as radar and dedicated short-range communication (DSRC) must be thoroughly examined. This article provides an overview and comparison of the inherent security flaws in automotive radar and DSRC technologies. Existing implementations of automotive radar are vulnerable to spoofing attacks from third parties, potentially resulting in fatal accidents. While DSRC exhibits inherent resilience to spoofing attacks, it is still susceptible to similar types of attacks used against traditional Wi-Fi. This article concludes with a discussion on the motivation for combining radar and DSRC into a joint system, and an overview of the potential consequences of an insecure vehicular system.

Many new radio frequency (RF) technologies are being deployed to make driving safer and more automated. Automotive radar is one such technology, where RF signals are used for adaptive cruise control, forward collision warning or blind spot detection. Wireless communication used by cars is also increasing. For example, many models support mobile Wi-Fi hotspots. Going forward, many vehicles will be connected using dedicated short-range communication (DSRC), a wireless communications standard that enables reliable data transmission in active safety applications. Each technology, however, comes with its own security risks. Even isolated security breaches could have a dramatic impact on consumer confidence, resulting in the discontinuation of such technologies. In this article, we present an overview and comparison of security risks associated with both automotive radar and DSRC systems. We make a suggestion about how the industry should respond to these known threats, for example, through joint radar and communication. Furthermore, we describe an instance of a past successful attempt to hack a vehicle and speculate on future hacking attempts.

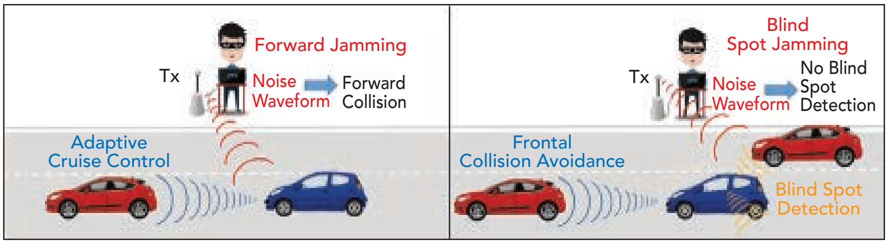
SECURITY RISKS OF AUTOMOTIVE RADAR

The majority of automotive radars on the market today operate in the millimeter wave (mmWave) band.[1] ***Figure 1*** illustrates the major uses of mmWave radar in vehicles. Specifically, long-range radar operates from 76 to 77 GHz, medium-range radar operates from 77 to 81 GHz and short-range radar (previously in the 24 GHz band) operates from 79 to 81 GHz. Additionally, research on leveraging the IEEE 802.11ad standard for automotive radar at 60 GHz is currently being conducted at The University of Texas at Austin.[2]

The types of attacks on vehicular radars are slightly different than the ones targeting radars in other settings due to the mobile nature of vehicular networks. There are three principle attacks (i.e., intentional disruption



▲ **Fig. 1** Uses of mmWave radar in vehicles.



▲ **Fig. 2** Two types of jamming attacks.

of a vehicular system by a third-party) on automotive radar.[3,4] Jamming is the transmission of RF signals to interfere with a radar by saturating its receiver with noise. Spoofing is the replication and retransmission of transmitted radar signals in order to provide false information to the receiver. Interference is the intentional or unintentional modification or disruption of a radar signal by unwanted signals, such as signals from different automotive radars. Note that although some forms of interference may not be considered attacks, we will discuss their implications for the sake of completeness.

Jamming

Figure 2 illustrates two different types of jamming attacks. Both forward and blind spot attacks can effectively disable the functionality of vehicular radar, leaving the driver vulnerable to a collision. Due to the long-term use of mmWave radars in military applications, there is an extensive history of research on jamming in mmWave radars.[3,5] A simple jamming technique uses a tunable scanner to determine the frequency of a radar signal and generates a jamming signal at the same frequency, disrupting the target radar's receivers.[6] More advanced jamming techniques may employ jamming signals with specific polarizations to more effectively disrupt the target radar's antennas.[7,8]

Automotive mmWave radar has a limited range due to small wavelengths and the inability to consistently pass through solid objects.[9] Most radars overcome this with a substantial amount of directivity, which also provides more resistance to jamming compared to systems that operate at lower frequencies. Additionally, since the purpose of jamming is to deny service, it is moderately difficult to conduct an effective jamming attack on an automotive radar in a highly mobile environment. If the jammer is in a static location, even a successful breach will disrupt an automotive radar for only as long as the target is in range, which may be a matter of just a few seconds in a highly mobile environment (i.e., highway). Although the potential consequences of losing a few seconds of operation are significant (i.e., loss of collision detection for that time frame), it is incredibly difficult for a malicious attacker to predict exactly where and

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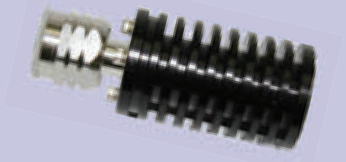

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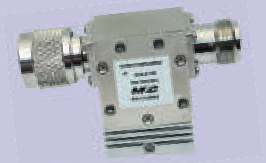

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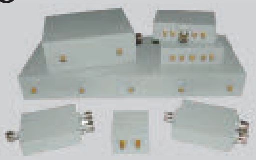

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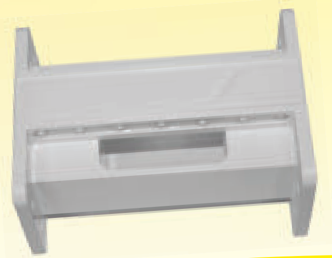
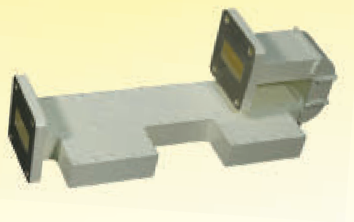
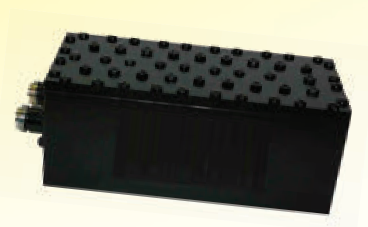

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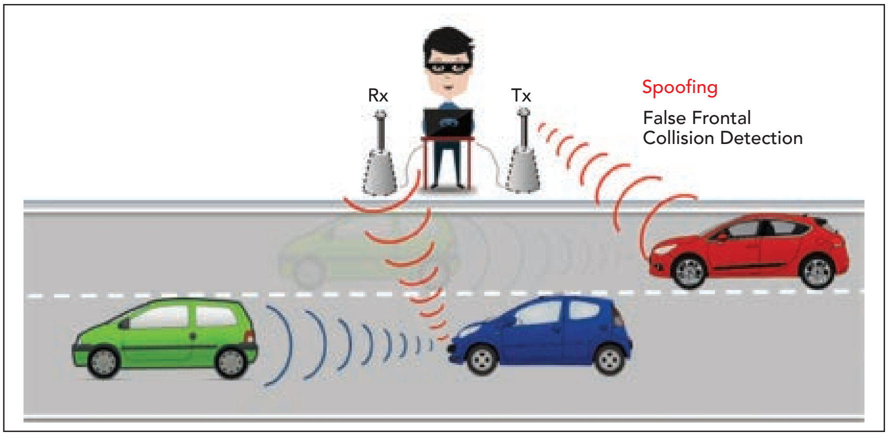

Fig. 3 mmWave spoofing attack.

when the jammer needs to operate to cause an accident. As a result, the attacker is limited to jamming in environments with low mobility (i.e., downtown areas) and does not have the ability to focus an attack on a single radar system.

If the jammer is mobile, much more damage may be inflicted. A jammer located on a vehicle that is currently following the target radar may be able to continuously jam it. Executing a continuous jamming attack requires two major components in order to be successful. First, the vehicle with the jammer must stay within a certain range of the target vehicle without attracting suspicion. Second, the operation requires a jammer that can accurately scan the wireless channel in a highly mobile environment, which is notably complex. To perform the attack, the jammer must be able to scan the target vehicle from any direction and distinguish its radar signals from any other wireless signal. It must also transmit a strong jamming signal in the direction of the target vehicle.

Although jamming attacks have the potential to induce major collisions, current jammers do not have the necessary adaptability to perform in a highly mobile environment, making it very difficult for malicious attackers to target a single vehicle.

Spoofing

Automotive mmWave radars are known to be susceptible to spoofing. ***Figure 3*** illustrates an attack that has the potential to cause the radar to report false information and greatly increases the risk of a collision. A spoofing demonstration was conducted by Chauhan,[10] where the subject radar reported distances significantly shorter than the actual distance to the target. In addition, distance and velocity-falsifying attacks on commercial automotive radars have been shown to be feasible.[10,11]

Automotive radar exploits a specific signal structure that performs well as a radar signal (i.e., has strong autocorrelation properties) but exhibits no inherent authentication capability, leaving it vulnerable to spoofing attacks. Without a means for checking signal integrity, the receiver is unable to verify the spoofed sequences, making it possible to analyze and replicate the signal. Unlike a jamming attack, a spoofing attack is designed to confuse the victim. Ideally, it needs only to breach the vehicle radar for a short period of time to severely influence its behavior, potentially causing it to stop, change direction or, in the worst case, collide. A successful spoofing attack can therefore have a devastating effect on automotive radars in today's market.

Despite this vulnerability, there have been no publicized reports. We believe that this is due to the relatively high implementation complexity inherent in the design of an effective and robust spoofing system. Overall, however, spoofing is the primary security concern for automotive radar due to its feasibility and potential consequences.

Interference

Most automotive radars employ frequency-modulated continuous wave (FMCW) waveforms.[12] They exploit small shifts in signal fre-

quency by transmitting a signal that varies in frequency over a fixed period of time. This provides a measurement of speed and distance. Since the receivers in these radars expect signals with definitive frequency patterns, they can perform more advanced signal cancellation techniques to reduce the effects of interference (including jamming).[13] Despite this, there are some forms of interference, such as a chirp or sweep signal, that cannot be isolated,[14] resulting in performance degradation in the presence of heavy interference. Due to the limited use of automotive radar, interference is not a problem in today's environment; however, as automotive radars become more widespread, we expect that interference between automotive radars in different vehicles will become a major issue.

SECURITY RISKS OF DSRC

In 2017, several newly released vehicles will use DSRC technologies to communicate over designated vehicular networks in the U.S. These networks enable mobilized vehicles to exchange data vehicle-to-vehicle (V2V), as well as vehicle-to-infrastructure (V2I), within range. Information such as velocity and global position can be used by V2V applications that leverage DSRC to perform collision prevention and driver assistance tasks, making it extremely important that DSRC devices be reliable and secure. Additionally, V2I applications that use DSRC can provide more convenient e-parking, vehicle safety inspection and toll payment services. In general, DSRC exhibits low network latency, high-reliability, a priority ranking hierarchy and improved security and privacy.[15]

Current implementations of vehicular communication systems are modeled after existing Wi-Fi communication systems (i.e., IEEE 802.11p, the standard used in DSRC, is a subset of the IEEE 802.11 standard). Thus, in general, DSRC technologies are susceptible to similar types of attacks used against traditional Wi-Fi, which include jamming, spoofing and interference.[16] In addition to these attacks, DSRC technologies are also susceptible to attacks on user confidentiality.

Jamming

In contrast to automotive mmWave radar, DSRC systems operate at relatively low frequencies (5.9 GHz), improving the maximum range of detection but making them more susceptible to jamming attacks. Research has shown that constant, random and intelligent jamming attacks can deny service to DSRC applications to the point of disabling their entire functionalities.[17] In addition, DSRC may potentially experience denial-of-service attacks designed to jam the system from within the vehicular network, such as malware, spamming and black hole attacks.[16] All of these attacks have the potential to disable vehicular communications for extended periods of time, putting a targeted vehicle and its occupants in danger if the vehicle relies on DSRC for collision warning.

To combat potential attacks, considerable research has been conducted to examine solutions such as additional authentication, physical separation of networks within the same vehicle, switching of frequencies when denied service and communication with legitimate DSRC devices to blacklist rogue devices.[17-19] Despite these efforts, jamming is still a major security concern due to the ease of carrying out an attack and the potential consequences it has on targeted systems.

Spoofing

Although DSRC is more susceptible to jamming than automotive radar, it exhibits inherent resistance to spoofing attacks. Since DSRC is a subset of the IEEE 802.11 standard, it has a predefined packet sequence that incorporates packet authentication within its packet headers. Because of this, spoofing a DSRC device requires knowledge of the specific sequences used in the packet headers. In addition, the DSRC standard is capable of incorporating public key cryptography during transmission, further improving security.

Despite these advantages, DSRC is still vulnerable to specific types of spoofing attacks. These include attacks from within the network itself and attacks that modify the signals sent throughout the network. If able


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to determine or obtain the necessary credentials for authentication, then an attacker may be able to impersonate a legitimate device, enabling the transmission of false information.[20] In contrast, spoofing attacks such as replay attacks or man-in-the-middle attacks may allow an adversary to modify signal information by intercepting a transmitted signal and retransmitting a slightly modified version of the signal.

Although DSRC technology is ultimately susceptible to spoofing, its inherent robustness due to predefined packet authentication mitigates the severity of this security risk. Furthermore, several supplementary measures can be implemented to provide additional security such as additional authentication.

Interference

DSRC has been allocated a 75 MHz frequency band at 5.9 GHz by the Federal Communications Commission so it does not experience any (legal) interference from non-DSRC devices, such as Wi-Fi operating in the 5 GHz band. Currently, there are relatively few DSRC devices implemented in vehicles on the road; consequently, mutual interference is a non-issue. In the future, however, when DSRC devices become widespread, interference between devices will be a concern, especially in congested environments such as downtown areas. Although current strategies for reducing mutual interference (such as interference cancellation, power and frequency adaptation and improved MAC layer protocol design) can decrease the effect of interference on DSRC, mutual interference is still a notable security concern that has yet to be completely addressed.[21,22]

Confidentiality

In addition to jamming, spoofing and interference, DSRC devices must also address the issue of confidentiality due to its nature as a communications system. Not only do DSRC devices need to maintain information privacy, but they also need to ensure that unwanted third-parties cannot covertly track the location of the device over an extended period of time. Potential threats to confidentiality include eavesdropping, masquerading and traffic analysis.[23]

Although the consequences of failing to address information and location privacy are not as severe as those due to jamming, spoofing and interference, maintaining confidentiality in vehicular networks is one of the more discussed security topics. This is due to the exceptionally low complexity of conducting an attack. For naïve DSRC technologies, such attacks can be performed by just listening to the data transmissions within a network and analyzing the traffic.

Furthermore, even if the data itself is encrypted, modern traffic analysis techniques can examine traffic patterns of a specific device and extract location information from the analysis. As a result, DSRC technologies need to be designed intelligently in order to prevent attacks on confidentiality. Currently, there are various measures such as device cloaking; however, these solutions introduce considerable complexity to the entire network and are, therefore, sometimes undesirable.

COMPARING AUTOMOTIVE RADAR AND DSRC SECURITY

Both automotive radar and DSRC technologies have inherent security flaws as summarized in ***Table 1***. "High" indicates a security risk with a high potential for major consequences, "moderate" indicates a security risk with a moderate potential for major consequences or a high potential for minor consequences, "low" indicates a security risk with a small potential for both major and minor consequences and "none" indicates no security risk.

On the one hand, DSRC devices are more susceptible to jamming than automotive radars since they are subject to jamming attacks from within the vehicular network. On the other hand, automotive radars are considerably more susceptible to spoofing attacks than DSRC technologies due to their lack of signal verification. Currently, both automotive radar and DSRC devices are not


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TABLE 1
AUTOMOTIVE RADAR AND DSRC SECURITY

	Automotive Radar	DSRC
Jamming	Moderate	High
Spoofing	High	Moderate
Interference	Low	Low
Confidentiality	None	Moderate

significantly impacted by interference. In the future, when the technologies become more widespread, interference will become an important security concern.

In addition, DSRC technology must account for attacks on confidentiality due to its nature as a communications system. Overall, although there are more types of attacks for DSRC systems, DSRC is more secure than automotive radar due to its built-in security mechanisms and its ability to communicate with other legitimate DSRC sources. This does not mean that DSRC equivalents can replace automotive radar, since the functionalities of both technologies are crucial for a variety of vehicular applications.

At The University of Texas at Austin, we are performing research on joint radar and communication. One line of research is to fuse information derived from separate radar and DSRC modules. This has been shown to improve target localization.[24,25] In addition, a joint system is not solely dependent on a single factor, such as sensor quality or degree of noise. Furthermore, while the DSRC aspect of the system remains the same, the radar aspect receives an extra layer of authentication, dramatically reducing the device's vulnerability to a spoofing attack. Joint radar and communications devices operate using the same signal or different time/frequency resources, which does not increase system mutual interference.

One of our primary areas of research is how to incorporate a communications waveform (e.g., IEEE 802.11ad) and its inherent security into the signal structure of automotive radar.[2] By exploiting special data sequences within the IEEE 802.11ad signal structure, radar parameter estimation for both range and velocity detection can be performed with high accuracy. This framework enables joint long-range automotive radar and V2V communication at 60 GHz, improving detection accuracy and reliability.

Another primary area of research is in the development of a cost-effective microwave IEEE 802.11p radar that may be used in tandem with mmWave automotive radars to perform a security check with the received radar waveform.[25] By exploiting a special characteristic of the IEEE 802.11 channel energy, range detection using a communications waveform at microwave frequencies can be performed at meter-level accuracy. The main advantage of performing radar tasks at microwave frequencies is the significantly reduced cost and increased availability of microwave equipment. In addition, by supporting high-accuracy mmWave automotive radars with a joint microwave radar and communications system, the security issues associated with automotive radar (e.g., spoofing) can be eliminated.

HACKING A VEHICLE

In 2014, security researchers published a paper describing a strategy for a remote automotive attack at an international hacker convention.[26] A year later, they took a step further and demonstrated a wireless attack on a Chrysler Jeep being driven on a public highway, posting the footage as a YouTube video.[27] By exploiting a major oversight in Chrysler's network design, they were able to brute force their way into the system and exploit the Linux operating system. From there, they were able to remotely control steering at low speeds, engine status, the air conditioning system and radio from the Internet.

The public reacted quite negatively towards this demonstration. Their angry complaints prompted several changes in the automotive industry, one of them being the release of a best practices paper by Intel (McAfee)[28] outlining all the known ways vehicles can be hacked and the most effective countermeasures, including but not limited to attacks from wireless V2V and V2I receivers, Bluetooth systems and the engine control unit.

Despite the paranoia caused by the video, wireless malicious hacking of a vehicle has been virtually nonexistent. Though the idea has been popularized in movies (such as Disney's® "Tron") or video games (such as Ubisoft's® "Watch Dogs"), there has only been one documented instance of malicious hacking of a car. In 2010, an angry former employee bricked hundreds of cars at a dealership,[29,30] destroying several million dollars' worth of cars, but injuring no one in the process. Additionally, although Miller and Valasek[26] provided a substantial list of vehicle models susceptible to the same type of attack they performed, there have been no reported attacks on any of these vehicles.

This recent public outburst can be explained by the heavy consequences of allowing vulnerable vehicles to drive on public roads. Although the threat of hacking vehicles is real, with the proper precautions these threats can be avoided. Like any other networking protocol, vehicular networks will always be subject to attack. But as long as security concerns are addressed in an ethical, appropriate and timely manner, there is no reason to prevent or delay the integration of communication networks in vehicles.

CONCLUSION

As automotive radar and vehicular networks grow more and more widespread, it is crucial that the security risks of each technology are examined and addressed. Automotive radar and DSRC technology both exhibit inherent security flaws, motivating the development of a joint radar and communications system. In addition, a documented instance and demonstration of hacking a vehicle on the road has greatly increased public awareness of the topic. Although the security breach demonstrated was not due to the flaws of automotive radar or DSRC technology, it more than sufficiently demonstrated the potential of an attack that can result in severe consequences.

To perform many of the attacks introduced in this paper, attackers need only to attach a device that can intercept and/or scan a signal to a centralized computer, and in some cases, a signal generator and transmitter. Some of the more complicated attacks discussed (such as spoofing a DSRC device) may require more sophisticated equipment that enables the attacker to gain access to well-protected information. As a result, the majority of malicious hackers will likely seek a simplistic security breach that allows them to gain considerable access, similar to the Chrysler Jeep hacking demonstration.

Due to cost and complexity, many hackers will likely avoid attacking a vehicular system using a sophisticated strategy. As black hat research advances, however, conducting spoofing attacks on automotive radar will become more and more feasible, encouraging more malicious hackers to consider spoofing and dramatically increasing the risks associated with unprotected devices in vehicular environments. The observations presented in this paper should be considered as a sober warning to automobile companies, motivating them to address the security risks of both automotive radar and DSRC technologies as soon as possible.■

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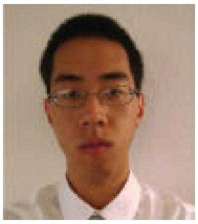

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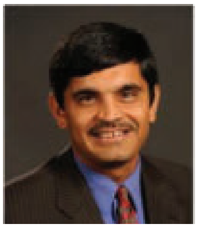

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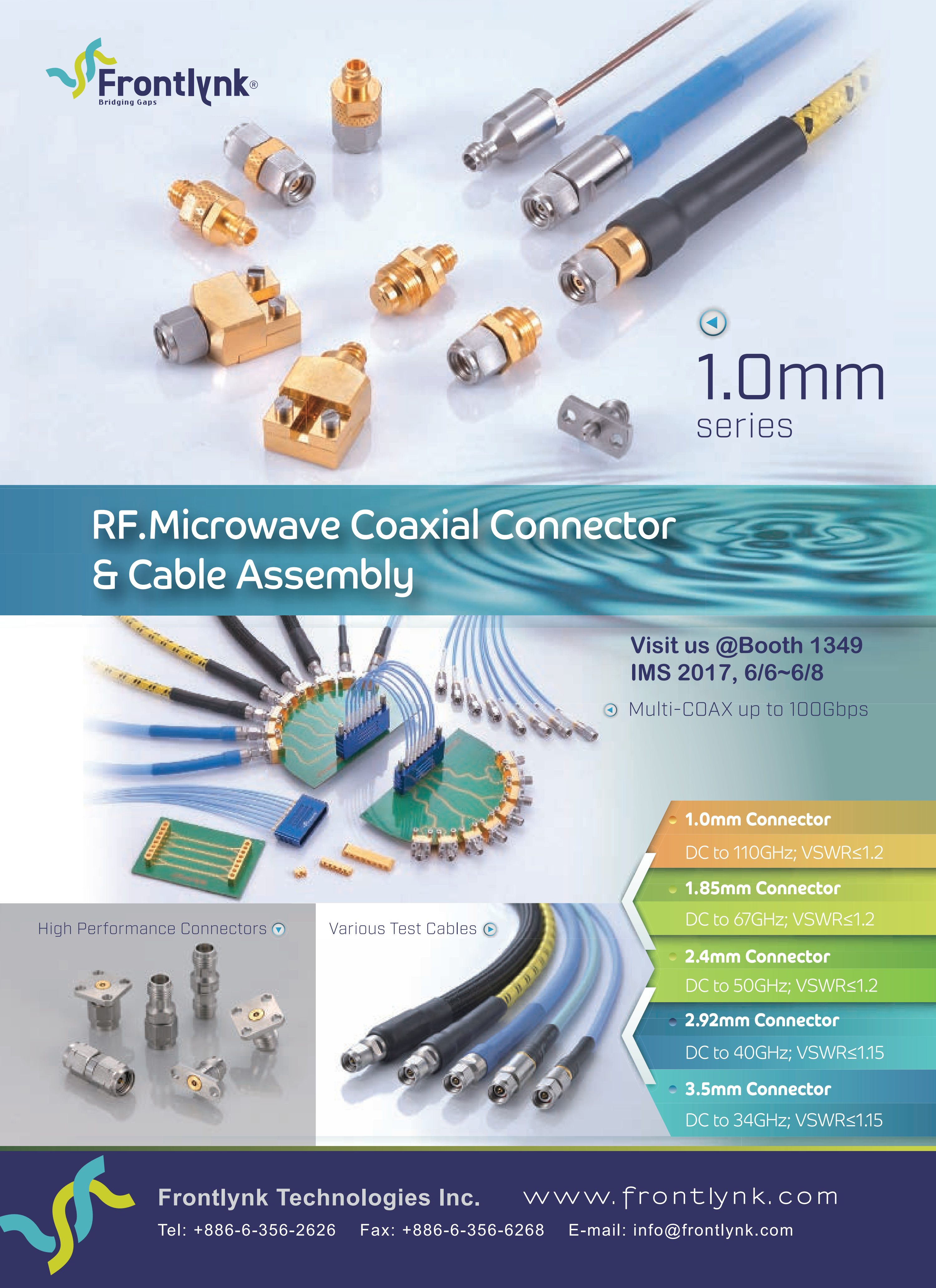
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Registration Opens for EDI CON USA

Janine Love
Event Director and Contributing Editor, *Microwave Journal*

This fall, the Electronic Design Innovation Conference (EDI CON) USA 2017 comes to the Hynes Convention Center in Boston, Mass. EDI CON USA is the only industry event for RF & microwave engineers in the continental U.S. in 2017 and the largest high-speed design conference on the East Coast. The event planning team is putting together another robust technical program this year, as well as a 2-day exhibition of the latest products and tools from leading suppliers to the RF, microwave and high-speed digital industries.

The event begins on Monday, September 11 with an all-day training day (special registration required, free to conference pass holders). Designed to give you in-depth training like you can get nowhere else, the day includes 3-hour short courses on topics including radar, PCB design and power integrity, as well as sponsored tool-specific training sessions from companies such as Teledyne LeCroy. In addition, EDI CON USA's Diamond Sponsor, Rohde & Schwarz, is hosting a full day of four workshops on Wednesday, September 13.

If you live or work around the Boston area, you can reserve a spot on one of our charter buses to take a stress-free ride in and out of Boston every day of the event. Buses are available Monday, Tuesday and Wednesday, serving points outside of the city. Seats must be reserved in advance through our registration process. If you will be staying in the city for the event, we have specially-priced hotel room blocks for our attendees. September is a beautiful time to be in Boston. Consider bringing your partner or family. We have arranged partner day trips for Tuesday and Wednesday, including a Boston trolley tour and trip to the JFK Library & Museum, as well as a whale watching tour. You can sign up for these special events at ediconusa.com.

For those with an interest in high-speed digital applications, we are launching our High-Speed Zone on the show floor, complete with demo pods of some of the latest equipment for SI/PI/EMC/EMI work. In addition, Eric Bogatin, *Signal Integrity Journal* editor, is hosting a High-Speed Digital Symposium on Tuesday, September 12.

On the exhibition floor, the Frequency Matters Theater features informative talks as well as speed training opportunities. These presentations typically provide details on strange and complex applications, state of the art technology, rules of thumb and pitfalls to avoid during the design cycle. While exploring the exhibits, you can drop in and see what others in your field are up to.

Networking opportunities abound this year. On Monday, short course and sponsored training session attendees can enjoy a luncheon and end-of-day reception. On Tuesday, join everyone on the exhibition floor for a Welcome Reception party for dinner. (Tuesday, the exhibition is open until 7 p.m. to accommodate local attendees who wish to come in at the end of the day.) Coffee breaks all three days ensure chances for meetings with other engineers, friends, customers and potential customers.

EDI CON USA is the first industry event in the U.S. to bring together RF, microwave, EMC/EMI and high-speed digital design engineers and system integrators for networking, product demonstrations, trainings and learning opportunities. It celebrates the interaction between analog and digital, what's similar, what's different and how we can learn from each other. Got a design challenge? Bring it to EDI CON USA and ask your peers and industry experts about it. Chances are, you will come away with an entirely new perspective on the problem, and some immediate ways to move forward.

The goal of the conference is to provide actionable information to practicing engineers that they can use today. Plan to spend the day, or spend all three, meet with your peers, colleagues and competition and let's all work together to advance the state of the art!

Registration is open now. Take advantage of early bird rates and lock-in your space in the Monday training sessions today! Go to ediconusa.com. EDI CON USA is organized by *Microwave Journal* and *Signal Integrity Journal*. Make sure to stay connected with us on Facebook and Twitter @ediconusa, with #ediconusa.■

INVITED PAPER

Transformation to 5G: PCB Advantage

Tony Mattingly
Rogers Corp., Chandler, Ariz.

Hard to believe it has been over 30 years since 1G was introduced to the world, back when there were no official requirements and analog technology was being used. The 1990s brought 2G, with the introduction of digital technology and the ability to transmit text messages via your cellular device. Ten years later, in 2000, an upgrade to 3G brought IEEE WiMAX standards that were designed to support 30 to 40 megabit per second (Mbps) data rates. Then, 4G was introduced a mere seven years ago and, although it brought to the world a much higher spectral efficiency, exponential consumer demand for wireless data is now driving a need for substantially higher mobile network capacity and performance. Let's take, for example, the primary driver for data usage on smartphones: video streaming. Just an hour a day of mobile video at 1 Mbps throughput—which is typical of applications supporting streaming video like YouTube or Netflix—consumes 13.5 GB per month. The demand for data will continue to grow as the 5G and IoT ecosystems are created in the coming years (see ***Figure 1***), and we will all eventually live in a world that depends on billions of devices communicating with one another. The connectivity of these devices will be expected to be instantaneous and without interruption.

▲ **Fig. 1 Our world is increasingly connected, which is driving the growing demand for wireless data.**

Adding capacity is not cheap, and space for additional antenna towers is limited. In the U.S., most towers are not owned by carriers, rather companies such as American Tower, Crown Castle and SBA. Carriers lease space on these towers and, as strict permitting processes make it difficult to build new sites, carriers are forced to replace antennas


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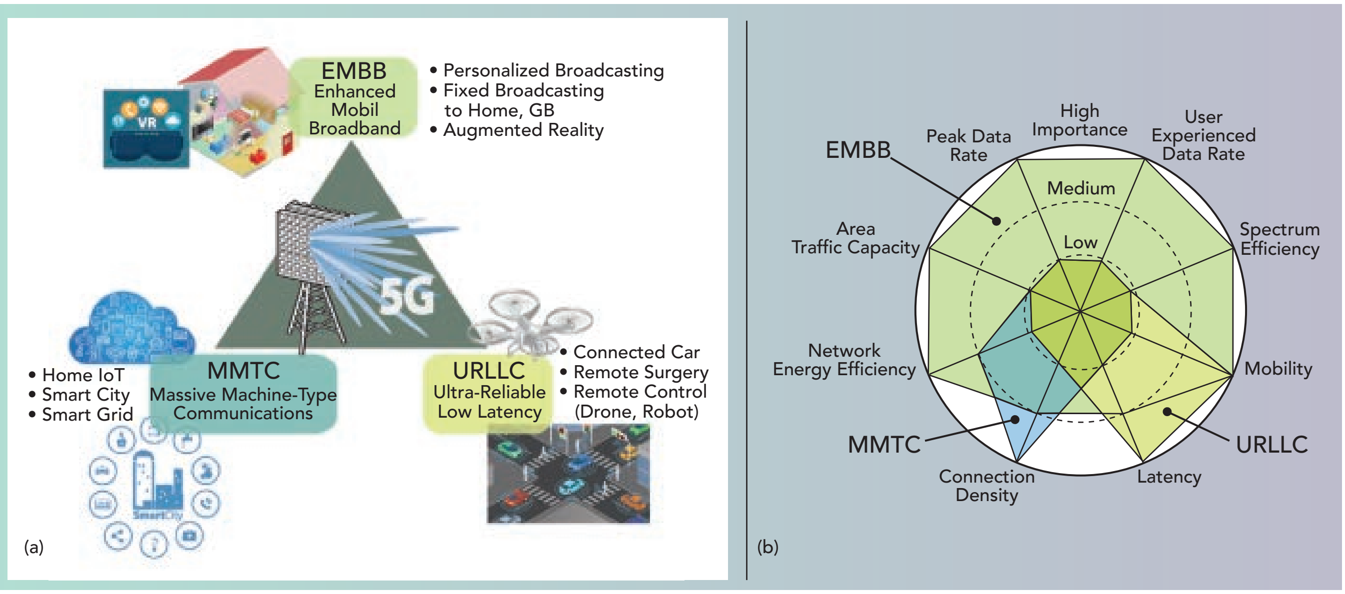

▲ **Fig. 2 5G is envisioned to support three general use cases: high data rate, low latency and massive numbers of connections (a), and these use cases define the performance requirements of the network (b).**

with newer and more efficient ones. Arguably, the cost for operators to deliver data is proportional to the spectral efficiency of the wireless technology. LTE networks have the highest spectral efficiency of any technology to date, but it is not going to be enough to serve consumer desire to always be connected. So how is capacity added in an already saturated wireless infrastructure? One answer is advanced antenna designs employing new technologies that operate within current frequencies. Another answer is adding wireless infrastructure that operates at new and higher frequencies, where plenty of spectrum exists. Early in 2015, U.S. carriers spent more than $40 billion on spectrum! Because much of the spectrum below 2.5 GHz is limited, frequency bands around 3.5, 28, 39 and 77 GHz are gaining interest because of the availability of bandwidth.

5G COMING SOON

We should start by clarifying the conceptual goals for 5G (see ***Figure 2***). Cost to deliver data is crucial to the success and survivability of the carriers, so the 5G infrastructure will need to support a greater number of devices at lower average revenue than with 4G systems. The infrastructure must also provide peak data rates of multi-gigabits per second (Gbps), facilitate a user experience that is uniform throughout the coverage area—no matter the device density—support numerous frequencies (including cellular bands and frequencies above 6 GHz), use both licensed and unlicensed bands and follow advanced spectrum sharing rules.

The 5G networks of the future will require infrastructure that has a wide range of capabilities and operates both below 6 GHz and at millimeter wave frequencies. These networks will use massive MIMO antenna structures and massive carrier aggregation and will need to operate "lightning fast" with very low latency. Massive MIMO comprises hundreds of antennas at the base station that enables spatial multiplexing and beamforming. These systems provide three times the spectral efficiency of today's LTE-Advanced antennas. Carrier aggregation, which is a key LTE-Advanced feature that operators are deploying globally, uses spectrum more effectively, increases network capacity and user throughput rates and provide new ways to integrate unlicensed spectrum. Frequency band allocations for 5G focus heavily on bandwidth availability and seem to center around three groups: below 6 GHz, 15 to 40 GHz and above 60 GHz. The combination of lower and higher frequencies is crucial for 5G operation. Lower bands can be devoted to coverage and control, while the higher bands enable high data rates. While millimeter wave frequencies suffer from characteristics such as higher propagation loss—even with line-of-sight conditions and no obstructions—this challenge can be overcome with beamforming antenna arrays or massive MIMO.

Regulatory policies around the world are striving to keep pace with these changing technologies. Some of the complex issues to be addressed: allocating and managing the new spectrum, maintaining neutrality within the networks and preserving privacy. Spectrum is considered a precious commodity within the industry. This could be seen during the U.S. auction for the 3.5 GHz small cell band last year, spectrum the FCC is now enabling. As advancements in technology provide a path for small cell operation between 6 and 100 GHz, a vast amount of available spectrum is introduced. Wider radio channels operating at higher frequencies enable much higher data rates. Small cells offload data from macro cells, inherently increasing capacity, and can offer improved signal quality in places with a higher concentration of users or where the signal from a macro tower is weak. Millions of small cells will eventually be deployed, leading to massive increases in capacity. The industry is slowly overcoming challenges that have impeded small cell deployments. These include

government regulations, acquiring real estate for the antennas and managing and preventing interference. Another challenge relates to spectrum sharing. Future wireless systems may interface with a planned spectrum access system that manages spectrum among primary users—government agencies, in some cases—and secondary or tertiary users. This will enable more efficient use of spectrum for scenarios in which incumbents use spectrum lightly.

Many countries have started 5G trials, focusing on various applications and using different frequencies. Major carriers in the U.S. are conducting trials in 2017 with a focus on fixed broadband at 28 GHz. South Korea is also conducting trials at 28 GHz to prepare for the 2018 Olympic Games in Seoul. Japan plans to start trials in Tokyo during 2017, using both sub-6 GHz and 28 GHz, and they will likely scale up the trials significantly during 2018 and 2019. China has announced ongoing 5G trials at 3.5 GHz, with a major carrier testing seven experimental base stations in several cities throughout 2017. Additionally, the European Commission recently published their 5G action plan, with preliminary trials starting in 2017 and pre-commercial trials in 2018; they will use 3.4 to 3.8 and 24.25 to 27.5 GHz. However, all these trials will be very targeted and limited in scale, constrained by the pace of 5G standards, technology development and economic justification. This view has also been confirmed by the November 2016 forecast from ABI Research, estimating 5G subscribers will reach 4 million in 2020 and 349 million in 2025, accounting for only 0.04 percent of all subscribers in 2020 and 3.6 percent in 2025.

PCB ANTENNAS

With all that said, there is no doubt antennas for next-generation wireless systems (e.g., LTE-Advanced and 5G) are becoming more complex. With demand for mobile data projected to grow at approximately 53 percent compound annual growth rate through 2020, active antennas and small cells will continue to be deployed to handle the data throughput. These trends and the associated growth are expanding the use of printed circuit board (PCB) materials in antenna designs. The material requirements will be different from the traditional cellular network. At the same time, 5G designs are completely new to the designers of wireless infrastructure. These designers need to overcome the many challenges and understand what performance properties are needed to meet their design goals.

With the use of additional frequency bands and consumer demand for better performance and lower latency, PCBs have advantages compared to competing technologies, such as bent metal and cable. Designers at antenna original equipment manufacturers (OEM) find that PCB-based designs shorten the design iteration cycle and enable the development of

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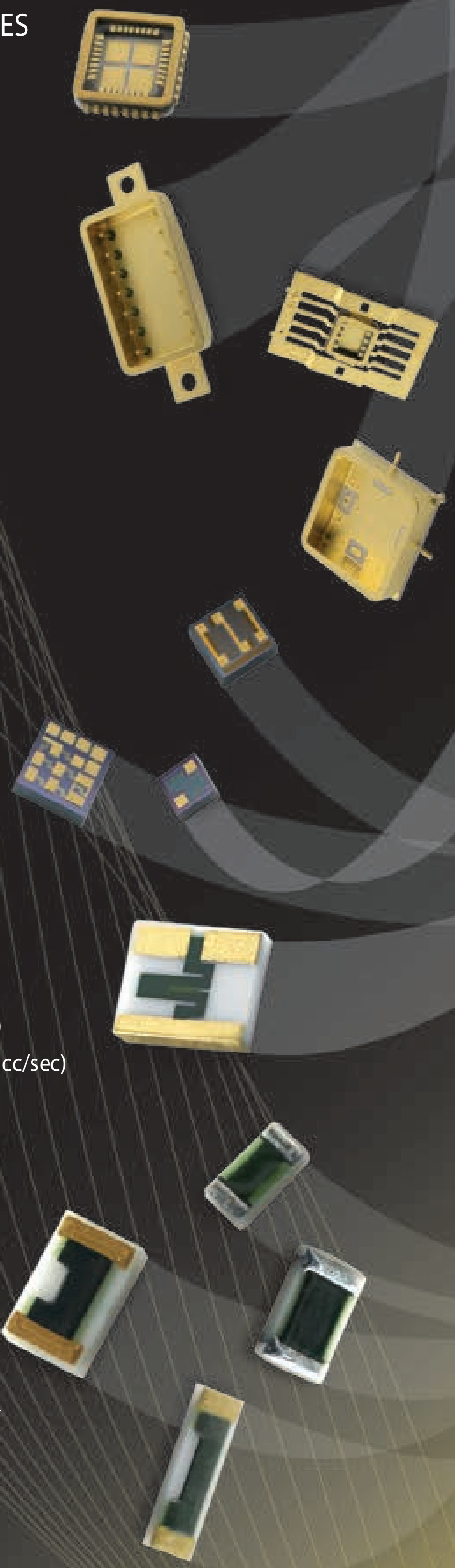

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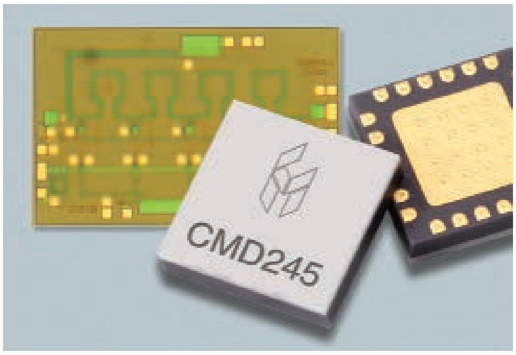
complex, multilayer board (MLB) designs. However, PCB-based designs have challenges: integration of the power amplifier (PA) and antenna into one structure for active antennas and higher fabrication and assembly costs of MLB approaches using PTFE materials. While thermoset high frequency materials are ideal for MLB designs, there are limited thermoset materials that have low loss, low passive intermodulation (PIM) and are flame retardant, meeting the sought after UL 94 V-0 designation.

To address these challenges, PCB materials companies like Rogers have launched new antenna grade laminates. Rogers' solution combines a flame retardant, low loss thermoset dielectric with low profile copper foil and incorporates a proprietary filler system. The material has a dielectric constant (Dk) of 3.0, a popular choice for antenna designers, and a dissipation factor (Df) of 0.0023 at 2.5 GHz. The laminate possesses a low thermal coefficient of dielectric constant (TCDk), which gives consistent circuit performance over a range of temperatures. It has low passive modulation (PIM < -160 dBc), because it is constructed using a patented LoPro copper foil, and it incorporates low density microspheres, yielding a laminate that is 30 percent lighter than PTFE materials. The coefficient of thermal expansion (CTE) is matched to copper in the X and Y directions, which minimizes bow and twist and allows for hybrid MLB construction, and the material has a low Z-axis CTE of 30.3 ppm/°C from -55°C to +288°C, for reliable plated through holes (PTH) in multilayer circuit assemblies. These laminates offer a practical, cost-effective circuit material for active antenna arrays and PCB antennas, whether for current wireless systems or those on the horizon. With the right combination of materials, these laminates provide the optimum blend of price, performance and durability.

Rogers, like other PCB materials companies, continues to focus on market trends and material needs of the future. Under development is a whole family of thermoset laminates with multiple thicknesses, low dielectric constant and low insertion loss for emerging PA and small cell point-to-point backhaul radio applications operating at millimeter wave. Rogers will soon add a thermoset solution designed to meet the growing RF needs within the carrier grade Wi-Fi and distributed antenna system (DAS) markets, where better loss, improved Dk over frequency and more controlled thickness tolerance are desired. These product offerings will only serve to enhance an already comprehensive portfolio of the highest reliability and highest quality product offerings. PCB manufacturers are meeting the needs of the antenna market with new products aimed at the performance criteria needed to meet 5G performance goals.■



Low Phase Noise Amplifiers and Doublers

Custom MMIC
Chelmsford, Mass.

Phase noise is rapidly becoming the most critical factor in sophisticated radar and communication systems. This is because it is the key parameter defining target acquisition in radars and spectral integrity in communication systems. There are many papers detailing the mathematical derivation of phase noise; few mention the reasons for its importance.

Phase noise is commonly used as a measure of the frequency stability of an oscillator. This noise is inherently different than the general background noise of any electrical system, which is defined as kTB, where k is Boltzmann's constant, T is the temperature and B is the bandwidth. Phase noise is a secondary effect related to the topology and construction of the oscillator (see ***Figure 1***). The figure shows the output power of an oscillator versus frequency, comparing an ideal oscillator, with power at a single frequency, to an oscillator with phase noise, which shows power across a spectrum of frequencies very close to the desired output. These skirts, as they are called, are always present and are due to thermal noise within the active devices of the oscillator. The power level of the skirts is dependent upon the quality of the oscillator and is measured in dBc/Hz at an offset frequency from the desired signal, typically called the carrier.

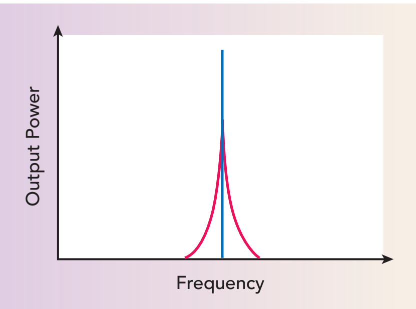
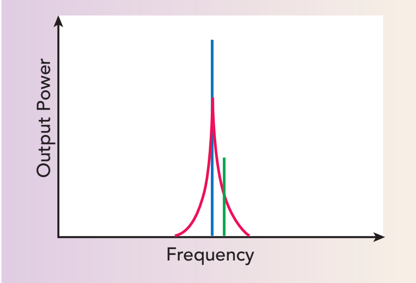


Fig. 1 An ideal signal (blue) and a signal with phase noise (red).

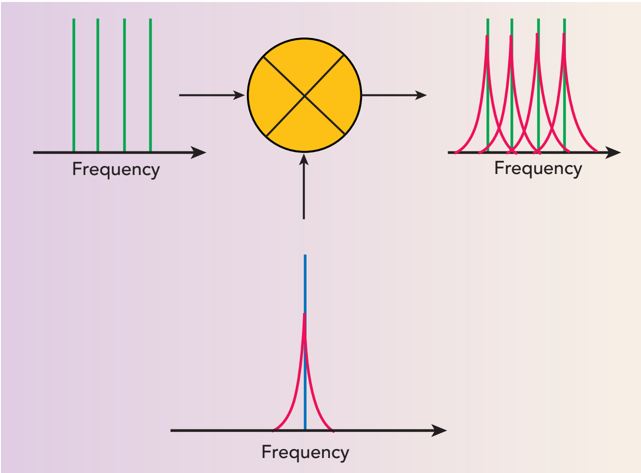
Phase noise affects the performance of many microwave systems, seen by considering direct down-conversion receivers and radars. Direct down-conversion is a type of receiver used in microwave communications systems. One benefit of direct down-conversion is the simplicity of the circuit, which is essentially a single mixer driven by a local oscillator (LO) that converts the input RF signal to a baseband or very low frequency signal. This baseband is applied to an analog-to-digital converter for subsequent digital processing. A common expression for this architecture is "RF in, bits out." One problem with direct down-conversion, though, is that the input RF signal can be very close in frequency to the LO, which makes the conversion process susceptible to phase noise, especially if the signal strength is low. With radar, the problem is similar. Radar systems operate by transmitting a pulse at one frequency, then measuring the frequency shift of the returned pulse. The shift, called the Doppler effect, is related to the velocity of the object being imaged. Objects moving very slowly will generate a return pulse very close in frequency to the transmitted pulse; if the cross section of the object is also small, the power level of this received signal will be very low. This return pulse is converted to baseband to recover the velocity informa-

tion, and phase noise can obscure the data.

An illustration of the dilemma faced by direct-conversion receivers and radar systems is shown in ***Figure 2***. If the power level of the RF signal falls below the phase noise spectrum of the LO signal, the baseband information is not recoverable, as the signal is in the noise. Reducing the phase noise increases receiver sensitivity. A second example of how phase noise negatively impacts communications systems is shown in ***Figure 3***, which illustrates a multi-carrier orthogonal frequency-division multiplexed (OFDM) signal. If the phase noise of the LO is too high, the noise will be converted into adjacent channels of the baseband data and ruin the integrity of the information.



▲ Fig. 2 A close-in RF signal to be converted to baseband (green) may fall within the skirts of the LO's phase noise (red).

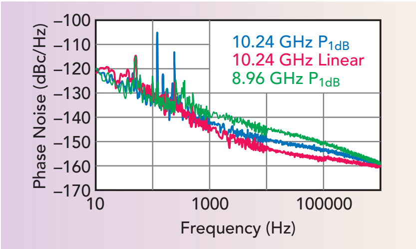


▲ Fig. 3 Phase noise issues with OFDM systems. LO signal with phase noise (red) can impair the fidelity of the RF signal (green).

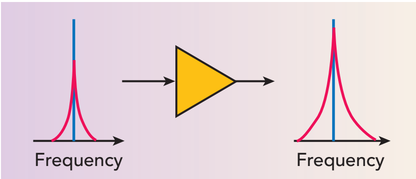
AMPLIFIERS AND PHASE NOISE

One obvious place to limit phase noise is with the choice of oscillator, by spending considerable time and money to design or procure a low noise oscillator. However, most oscillators do not generate sufficient output power to drive the LO port of a mixer and are followed by an amplifier. For example, an oscillator's output of +5 dBm needs to be amplified to a level of 15 to 17 dBm to drive the mixer.

Does the amplifier affect the phase noise of the LO signal? In an ideal situation, the answer is "no," as the amplifier simply raises the desired LO signal and its skirts by the same level. In reality, microwave amplifiers add noise of their own to any signal. All electronic devices exhibit a phenomenon called 1/f or pink noise, which is noise power that is added to the spectrum of the input signal but falls off proportionally to the inverse of the offset frequency. ***Figure 4*** shows the phase noise versus offset frequency of a low noise amplifier (LNA) that covers 10 to 17 GHz. The phase noise of the incoming signal has been cancelled out, so the plot represents only the noise generated by the amplifier. Note that the phase noise falls off linearly on the logarithmic scale with increasing frequency offset, which is characteristic of 1/f noise. If this noise is greater than the phase noise of the input signal,



▲ Fig. 4 Phase noise of the CMD167 low noise amplifier.



▲ Fig. 5 An amplifier can degrade system phase noise, increasing the skirts of the input signal (red) more than the gain of the amplifier.

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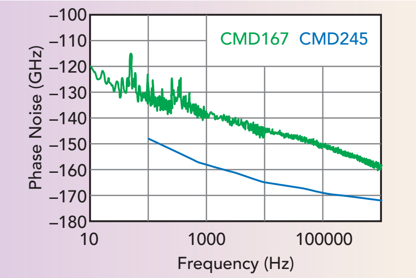

▲ **Fig. 6** **Phase noise comparison of the GaAs HBT CMD245 and the GaAs FET CMD167 MMIC amplifiers.**

then the amplifier noise will dominate the output noise spectrum. In this example, the low phase noise of the oscillator would be replaced by the higher phase noise of the amplifier, defeating the purpose of the low phase noise oscillator. ***Figure 5*** illustrates that the skirts of the signal at the input of the amplifier are increased after passing through the amplifier.

One obvious question is what can be done to lower the phase noise of amplifiers? The answer lies in device physics. The 1/f noise is caused by random and thermal charge movement in the channel of an active device. The CMD167, with the phase noise shown in Figure 4, is manufactured on a GaAs PHEMT process with a gate length of 0.13 μm. The FET devices on this process typically have a high 1/f corner due to their high electron mobility. GaAs bipolar devices, in comparison, tend to have lower electron mobility, which means a much lower 1/f noise. As they are considerably better for phase noise than their FET counterparts, one solution to lowering additive phase noise is to use a GaAs HBT process.

Custom MMIC used their extensive knowledge of amplifier design techniques to develop a family of low phase noise amplifiers designed on a GaAs HBT process. The three amplifiers in the family span 5 to 40 GHz (see ***Table 1***). ***Figure 6*** shows the phase noise versus offset frequency for one of the amplifiers, the CMD245, which is available in a 4 mm QFN-style package. For comparison, the phase noise of the CMD167 GaAs FET LNA is included. The phase noise of the CMD245 is 15 to 20 dB lower than that of the CMD167.

TABLE 1
LOW PHASE NOISE AMPLIFIER FAMILY

	Frequency (GHz)	Saturated Output Power (dBm)	Phase Noise (dBc/Hz @ 10 kHz Offset)
CMD245	6 to 18	20 to 22	−165
CMD246	8 to 22	18 to 20	−165
CMD247	30 to 40	15	−160 max

OTHER COMPONENTS

Other components in addition to oscillators and amplifiers can contribute to phase noise, including frequency multipliers. Many microwave systems utilize a lower frequency oscillator that is multiplied to produce a higher frequency. One common approach for multiplication is to use a harmonically terminated amplifier to generate the required output frequency. Unfortunately, such an approach will add the amplifier's phase noise to the multiplied signal, which will degrade the phase noise of the original oscillator. A second approach is to use passive multiplication, which has the potential to add minimal phase noise to the multiplied signal.

Custom MMIC has created a family of passive HBT-style frequency doublers that do not add to the phase noise of the input signal (see ***Table 2***).

TABLE 2
PASSIVE DOUBLER FAMILY

	Output Frequency (GHz)
CMD225	8 to 16
CMD226	14 to 22
CMD227	16 to 30

VENDORVIEW

Custom MMIC
Chelmsford, Mass.
www.custommmic.com

Compact USB-Controlled Synthesizers for Lab and Field

Pasternack Enterprises
Irvine, Calif.

Since it was introduced in the 1990s, the Universal Serial Bus (USB) has become the defacto interface for almost every type of device, relegating the bulky 36-pin Centronics parallel bus and RS-232 serial bus to the back stage. In the last few years, the list of applications has extended to another domain: RF and microwave instruments, such as frequency synthesizers. Although synthesizers powered and controlled by USB and a computer do not have the performance or full array of features of benchtop instruments, they are not intended to—instead providing basic functions that, in many cases, are all that is required. They also cost a fraction of the price, are basically plug-and-play, take up virtually no space and require only a computer and software.

Pasternack Enterprises has introduced a family of USB 2.0-based synthesizers that collectively cover frequencies from 25 MHz to 27 GHz. Their most likely use is in the lab or on the desktop, sometimes in combination with other instruments for testing during the design and prototype phases of development. However, their compact design makes them usable virtually anywhere, including measurements in the field. In addition to providing the measurement interface, a laptop computer powers them, so a basic frequency generation setup can fit comfortably in a laptop bag. Each unit is supplied with a USB cable and a coaxial cable with a female SMA connector on one end and a male MMCX connector on the other.

There are six models in the PE11S390X series, beginning with the PE11S3900,


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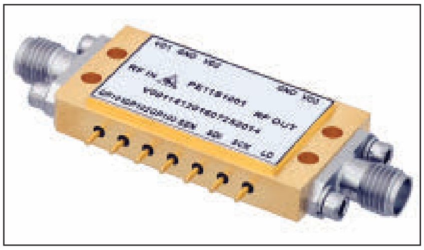


▲ **Fig. 1 Two broadband synthesizer modules cover 2 to 6 GHz and 5.5 to 10 GHz (shown).**

TABLE 1

SYNTHESIZER SPECIFICATIONS

Model	*Frequency Range (GHz)*	*RF Output Power (dBm)*	*Phase-Lock Speed, < 3°*	*Phase Noise, Offset (dBc/Hz)*
USB				
PE11S3900	35 MHz to 4.4	−20 to +10	2.44 step: fractional, 1 ms	@100 kHz: −103
PE11S3901	25 MHz to 6	−20 to +10	1 ms	@100 kHz: −86
PE11S3902	5 to 10	−15 to +18	1 MHz step: 1 ms	@100 kHz: −72
PE11S3903	10 to 20	−19 to +18	200 MHz (integer) or 1 MHz (fractional): 60 μs	@100 kHz: −80
PE11S3904	21 to 24	−17 to +17	400 MHz (integer) or 1 MHz (fractional): 1 ms	@100 kHz: −88
PE11S3905	24 to 27	+17	40 MHz (integer) or 1 MHz (fractional): 1 ms	@100 kHz: −75
Modules				
PE11S1001	5.5 to 10	+21	20 MHz step: 150 μs 5 GHz step: 15 ms	@100 Hz: −78 @1 MHz: −117
PE11S1002	2 to 6	+14 to +17	10 MHz step: 500 μs 4 GHz step: 15 ms	@100 Hz: −83 @1 MHz: −122

which covers 35 MHz to 4.4 GHz. At the high end, the PE11S3905 covers 24 to 27 GHz. The phase noise of the various models, at 100 kHz offset, ranges from -103 dBc/Hz at 4.4 GHz to -75 dBc at 27 GHz. The RF output power can be adjusted in 1 dB steps from -20 to +18 dBm. The synthesizers operate from an internal 50 MHz clock, although an external reference from 10 to 70 MHz can be used. An external reference is supplied via the MMCX connector on the cable, the other end connecting to the synthesizer. The MMCX connector also allows the unit to be synchronized with other test equipment. LEDs on each synthesizer confirm the USB connection, PLL lock and RF output power. Non-volatile memory in the synthesizer saves the last setup for future use. The synthesizers can be controlled via Windows, Mac or Linux platforms. The units are designed to operate from 0°C to +55°C.

The phase-locked loop operates in integer mode, by default, or fractional N mode, if desired. In integer mode, the output frequency is an integer multiple of the frequency of the reference oscillator divided by the reference divider. If the reference frequency is 20 MHz, for example, and the reference divider is two, in integer mode the synthesizer can generate frequencies of 9.0 GHz and 9.010 GHz, but not 9.005 GHz (assuming 10 MHz tuning resolution). Advantages of the integer mode are lower phase noise and the ability to phase-synchronize modules. When operated in fractional N mode, any frequency can be produced at the output; using the above example, the synthesizer can generate an output of 9.005 GHz.

The PE11S390X series is virtual instrument software architecture (VISA) compliant, requiring only a VISA library installed on the computer. VISA is a standardized test and measurement API that acts as an interface between an instrument and various communication buses, such as USB, GPIB and PCI/PCIe. The library can be obtained from National Instruments, Keysight Technologies, Tektronix and other test equipment manufacturers. The synthesizers automatically configure as a USB test and measurement class (USBTMC) device, which allows GPIB-like communication over USB with no need for additional drivers. The synthesizers are also compliant with standard commands for programmable instrumentation (SCPI), the common interface language between computers and test instruments. VISA, USBTMC and SCPI make it possible for the PE11S390X series to communicate with almost any instrument, as well as test application environments within MATLAB.

In addition to the USB synthesizers, Pasternack has introduced two broadband synthesizer modules in its PE11S series (see ***Figure 1***), with frequency ranges of 2 to 6 GHz and 5.5 to 10 GHz. Output power is between 14 and 17 dBm for the 2 to 6 GHz synthesizer, and 21 dBm for the 5.5 to 10 GHz module. The two modules are well-suited for defense and commercial applications. They integrate SiGe, GaAs PHEMT or InGaP HBT MMICs with low noise voltage regulators and an output buffer amplifier in a hermetic package measuring 1.4 in × 0.75 in × 0.35 in. The PE11S series can operate in either integer or fractional N modes. A step size of only 0.6 or 1.2 Hz can be achieved in fractional N mode, depending on the model. Both use an external clock reference of 10 MHz and operate from a +3.3 V bias.

Specifications for the USB-based synthesizers and synthesizer modules are summarized in ***Table 1***.

VENDOR**VIEW**

Pasternack Enterprises
Irvine, Calif.
www.pasternack.com

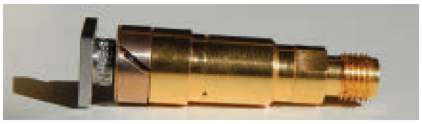
Push-On RF Probe for SMA Connectors

INGUN USA Inc.
Lake Wylie, S.C.

Spring-loaded coaxial probes to test SMA (and other RF) connectors are not that new. For several years, they have met the demand for having a test solution that can be used beyond the mating cycles of a regular RF connector and can be utilized inside a test fixture for semi or fully automated testing.

These probes must be used in such a test fixture because there is no locking feature for hand probing. More and more companies with RF applications, however, need to manually test large arrays of RF connectors. The SMA series is one of the most widely used miniature connectors worldwide. One solution to test these connectors is to use the mating connector. This usually yields the best RF performance. However, that is not only time consuming (each SMA needs to be tightened with the proper torque) but also limits the lifetime of the test connector drastically, as SMA connectors are usually limited to 500 to 1,000 mating cycles, depending on the base material and other material properties.

To address this issue, INGUN decided to develop a product that combines the advantages of a spring-loaded test probe—long lifetime, versatility and robustness—with the qualities of a mating connector—best return and insertion loss performance. The design engineers added a spring-loaded locking feature that makes the probe usable by hand without the need for a test fixture. The result is the HFS-ADA-QSMA-M-SMA-F Push-On RF Probe for SMA connectors with locking mechanism that can withstand more than 100,000 mating cycles.



▲ **Fig. 1 The probe mated with the SMA connector.**

DESIGN AND PERFORMANCE

The HFS-ADA-QSMA-M-SMA-F features three spring-loaded pins with serrated heads, for the best contact on various quality SMA connectors, that mate with the outer conductor upon compression of the part. This yields to a slight impedance discontinuity, due to the air gap; however, the losses are negligible up to 12 GHz, and the probe keeps a return loss of 20 dB or better (VSWR $\leq$ 1.22) for most of that range, up to approximately 11 GHz. A touchdown on the inner ring of the female SMA would increase the return loss but, at the same time, decrease mechanical mateability.

The center conductor has a cone shape and mates with the slotted center conductor of the SMA connector. The cone shape allows for a firm, concentric contact on all sides, yet is soft enough to withstand a high number of disengagement cycles. Three small beads are used as a retention feature and hold the SMA connector. On insertion of the SMA, a leaf-spring acts as the counterforce and presses against the beads. ***Figure 1*** shows the probe mated with the SMA connector. The force which is applied to the beads is surprisingly low: 0.5 N per bead. However, even the low force locks the probe securely, with no risk of damaging the outer threads. ***Figure 2*** shows the mechanical dimensions of the HFS-ADA-QSMA-M-SMA-F push-on RF probe.

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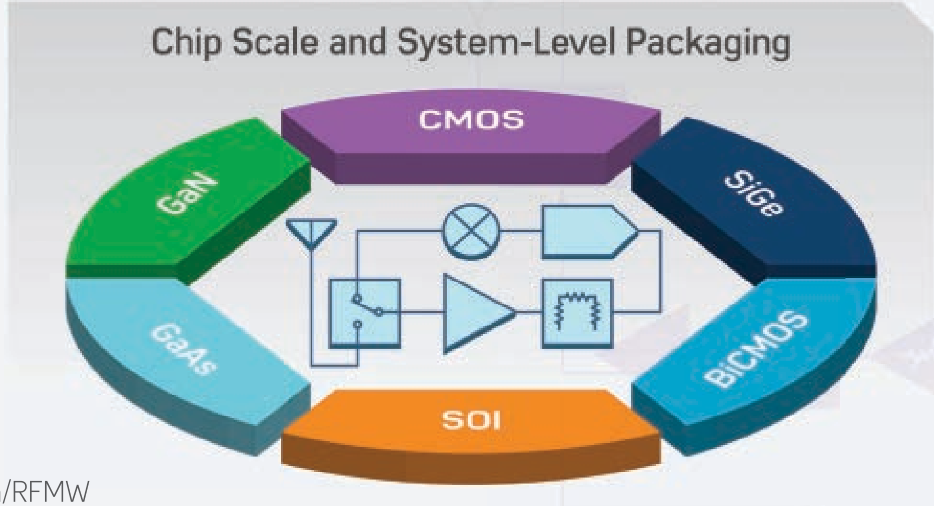

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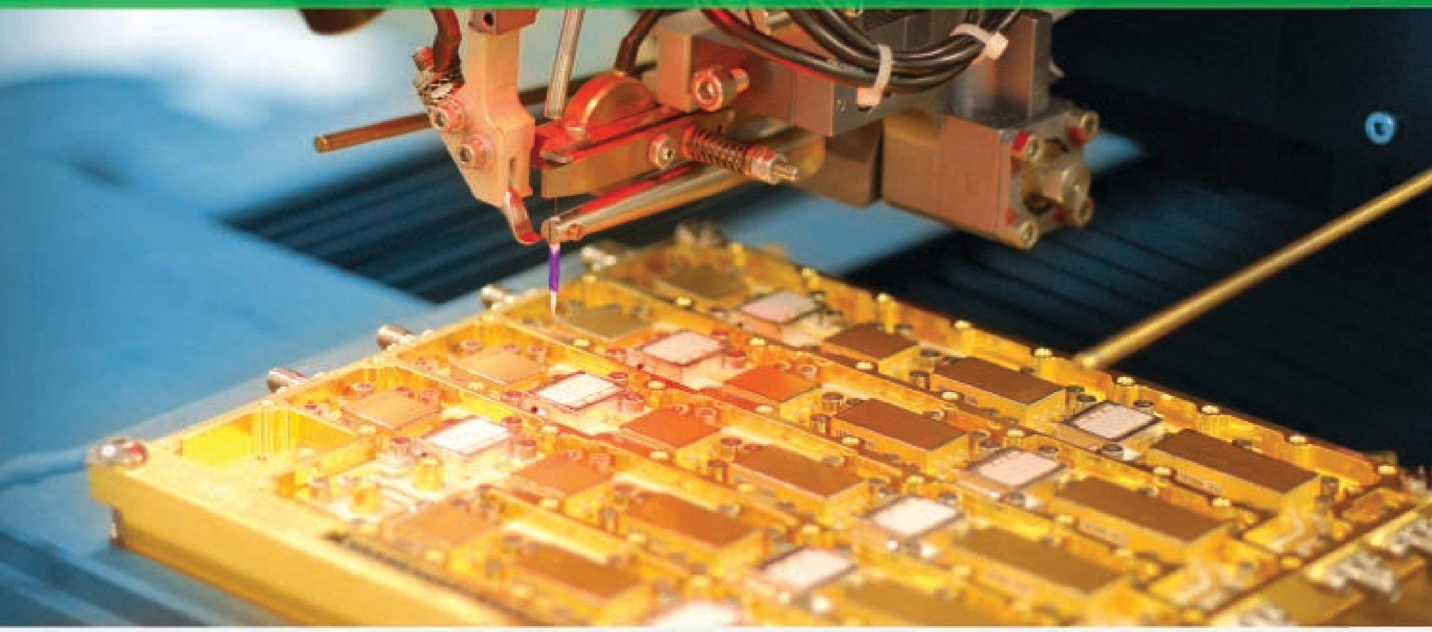

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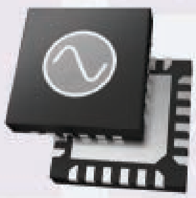
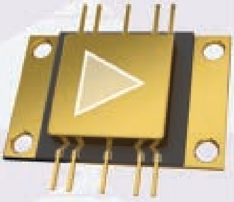


HMC5356

Wideband Freq Synthesizer

- RF output frequency range: 53.125 MHz to 13,600 MHz



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GaN Power Amplifier

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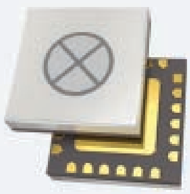
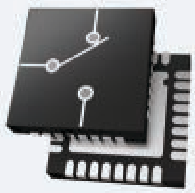


HMC8191

Wideband Mixer

- Passive, wideband I/Q mixer
- RF and LO range: 6 GHz to 26.5 GHz



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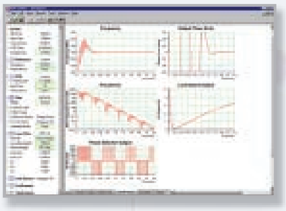

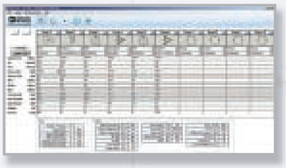

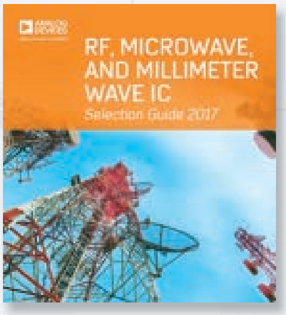

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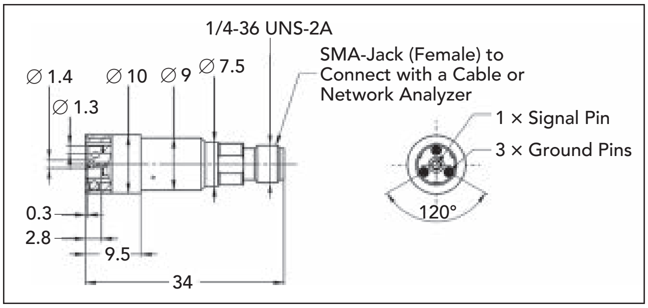
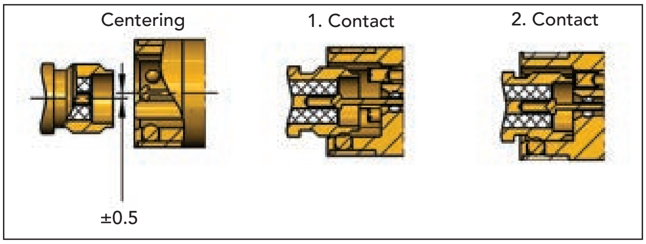
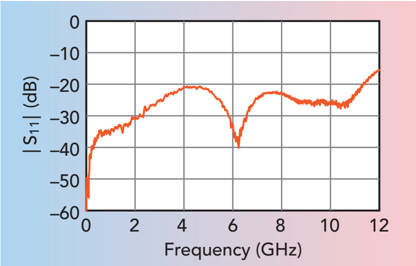


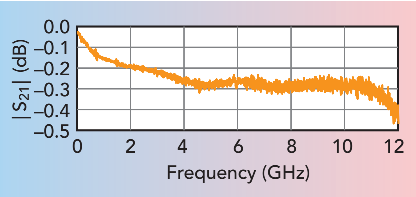
▲ **Fig. 2** Mechanical outline of the push-on RF probe.



▲ **Fig. 3** Contacting sequence.



▲ **Fig. 4** Typical probe $|S_{11}|$.



▲ **Fig. 5** Typical probe insertion loss ($|S_{21}|$).

RF PERFORMANCE

INGUN carried out extensive testing of the new product. Up to 11 GHz, the probe shows a return loss value of 20 dB or better, while the insertion loss is around 0.3 dB at that frequency. ***Figure 3*** shows the contacting sequence, while ***Figure 4*** and ***Figure 5*** show the return and insertion losses, respectively.

As a result of development and testing, the company has produced a versatile contacting solution for push-on connection of female SMA connectors. The design allows the operator to quickly attach and test rack systems or individual RF modules. Significantly too, the concept of the probe has the facility to accommodate different connector applications. For instance, similar designs could help to quickly connect to and disconnect from type N or other connectors, even bulkier types such as 7/16 connectors. However, it is critical to note that the probe should not be used for metrology grade testing or for applications where phase stability is of utmost importance. The main arena for the HFS-ADA-QSMA-M-SMA-F probe is for power level and similar test applications for test laboratories, production line testing or troubleshooting.

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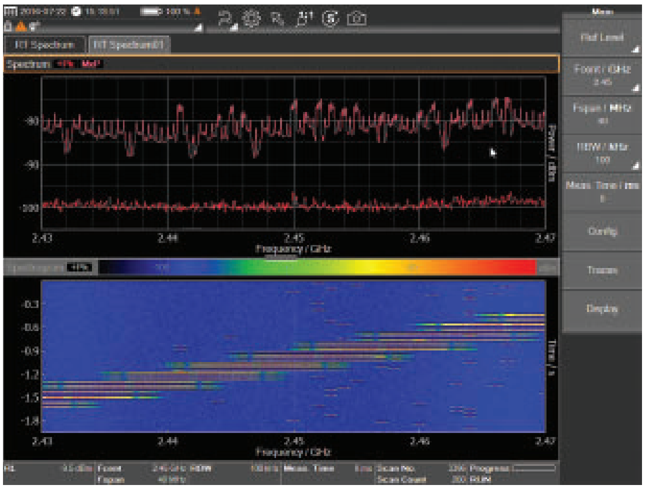
In light of the rapid development in new technologies, such as the Internet of Things (IoT), machine-to-machine (M2M) and car-to-car (C2C) communications, together with expanding 4G/5G mobile networks, increasing numbers of devices have to share the available frequency ranges. Therefore, Narda has developed the SignalShark real-time handheld analyzer to provide comprehensive measurement solutions for the increasingly complex RF spectrum. Applications include, making a wideband measurement of an entire frequency range, detecting hidden signals, reliably capturing very short impulses and localizing interference signals.



▲ **Fig. 1** **40 MHz RTBW spectrum and spectrogram, showing Bluetooth and Wi-Fi.**

Designed for the measurement of RF signals between 9 kHz and 8 GHz, the analyzer features a sweep rate of up to 40 GHz/s, a 40 MHz real-time instantaneous bandwidth, powerful, live persistence spectrum to find hidden signals, fully automatic direction finding (DF) and a high dynamic range receiver. It is applicable for mobile and stationary use.

Its 40 MHz real-time bandwidth captures the spectrum of even very short pulsed signals of > 3.125 µs with a probability of intercept (POI) of 100 percent. This guarantees a consistent awareness of all spectrum events. Due to its distinguished analysis functions like real-time spectrum, spectrogram, persistence and channel analysis and its large integrated I/Q recorder, measured signals are analyzed with a very high frequency and time resolution. ***Figure 1*** shows a 40 MHz real-time bandwidth (RTBW) spectrum and spectrogram–Bluetooth and Wi-Fi.

SignalShark supports manual bearing with Narda's directional antennas (shown in ***Figure 2***) as well as fully automatic DF in combination with the company's automatic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▲ **Fig. 2** **SignalShark manual directional antenna.**

▲ **Fig. 3** **SignalShark automatic direction finding antenna.**

DF antennas (see ***Figure 3***). A live map view shows the current position, bearings and localizations.

OPERATING MODES & TASKS

The SignalShark has two basic operating modes. The scan mode supports the measurement of the spectrum with a full frequency span of 9 kHz up to 8 GHz within one measurement and a maximum measurement speed of 40 GHz/s, while the real-time fixed frequency mode enables real-time spectrum measurements with a frequency span of up to 40 MHz.

This frequency span will be acquired simultaneously in frequency and also gapless in time with 75 percent of overlapping of the fast Fourier transform (FFT) frames. For frequency spans $\leq$ 20 MHz, the overlapping of the FFT frames increases to 87.5 percent. At the same time, a second digital downconverter is used to analyze and demodulate the I/Q data of a separate channel with selectable frequency and bandwidth within the 40 MHz real-time bandwidth.

Also, predefined measurement tasks are stored in the analyzer in advance, facilitating consistent, effective and reliable measurements for both beginners and experts alike. Measurement tasks are represented by a tab on the 10.4 inch touch screen, like a website within a web browser. Users can add up to six measurement visualizations (Views) to a task, to adapt it to specific user needs. SignalShark is supplied with several predefined tasks, so users can immediately begin making measurements.

VIEWS

Measurements are visualized within different kinds of views. The frequency domain and time domain can be examined at the same time, for example, by adding a spectrum view and a high time resolution (HTR) Magnitude view to a measurement task. The individual views are:

- Spectrum (scanned or real-time) shows level over frequency.
- Peak Table (of spectrum) provides a list of relevant signal peaks in the measured spectrum.
- Spectrogram offers a visual representation of recorded spectra over time with colors represent-

ing the signal level. The smallest selectable time resolution is 31.25 μs and detectors are used to compress the high speed real-time spectra to the selected time resolution.

- Level Meter (& Compass) shows the channel level as a bar graph and compass values.
- I/Q (versus time) displays the measurement data as I (in-phase demodulated signal) and Q (quadrature demodulated signal) components versus time for determining modulation type and interference.
- HTR Magnitude displays signal power versus time.
- HTR Spectrogram displays signal as a spectrogram with an arbitrary high time resolution. Colors represent the signal level.
- Persistence (of real-time spectrum) displays spectra as level versus frequency. Sporadic signals are detected easily and color indicates the rate of occurrence.
- Bearing (& Level Meter) shows azimuth and level of an automatic DF antenna.
- Horizontal Scan shows the signal level over azimuth angle in a polar diagram.
- Map view visualizes the current position, bearings, located transmitters and selectable measurement data within a geographical map.

Note: I/Q, HTR Magnitude, HTR Spectrogram and Horizontal Scan will be available in a later firmware version.

AUTOMATIC DF ANTENNAS

Another significant feature is that SignalShark can be connected to an automatic DF antenna, which translates signals from several antenna segments into a single channel DF signal. The antenna is controlled by the analyzer, which automatically calculates bearings out of the single channel DF signal.

The antenna can be mounted to an antenna mast or can be attached to the rooftop of a vehicle via a magnetic mount adapter. The measurement results contain bearings, as well as omnidirectional level and spectrum values. In its omnidirectional mode, the antenna can be used for real-time measurements too.

40 MHz REAL-TIME BANDWIDTH (RTBW)

The SignalShark's ability to make powerful real-time measurements with a real-time bandwidth of 40 MHz in a handheld design will not only help accelerate the development of mobile technologies within the industry, it will also assist mobile service providers and authorities to ensure interference free networks and support regulators in providing protection from illegal transmitters and hidden signals.

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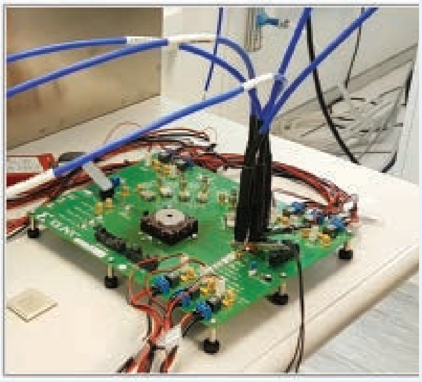
www.narda-sts.com



Programmable SoC with RF Data Converters for 5G

Xilinx has monolithically integrated RF-class analog technology into its 16 nm UltraScale+™ multi-processing system on a chip to create the world's first hardware and software programmable RF SoC (RFSoC). Based on an ARM-class processing subsystem merged with FPGA programmable logic, the all programmable SoC has 12-bit, 4 GSPS RF sampling analog-to-digital converters and 14-bit, 6.4 GSPS direct RF digital-to-analog converters, along with built-in digital down-conversion and up-conversion. RFSoCs enable a 50 to 75 percent reduction in system power and footprint for LTE-A Pro and 5G active antenna systems and massive MIMO radios.

Because massive MIMO radio systems have large antenna arrays that use many analog chains, they create a significant challenge for connecting digital front-end devices to many data converters. Typically, high speed transceivers—leveraging the JESD204B protocol—are needed both in digital and analog components to build such systems, dissipating significant power and increasing footprint. Integrating RF-class analog into the digital front-end radio device eliminates expensive interconnects, reduces the footprint and dramatically lowers power dissipation, making massive MIMO systems commercially viable.

Using a 16 nm FinFET process node for direct RF sampling data converters improves analog device performance at a much lower power compared to traditional data converters that are built on older nodes. Integrated RF sampling data converters simplify the signal chain by eliminating the intermediate frequency stage. Built-in digitally assisted analog design brings much needed programmability to the analog domain, addressing the extensive range of cellular bands with the same architecture and building blocks and reducing the growing number of radio form factors that must be maintained today.

Xilinx
San Jose, Calif.
www.xilinx.com/rfsoc

mmWave Frequency Extenders for Handheld Spectrum Analyzers

To extend the use of handheld spectrum analyzers into the millimeter wave bands, OML developed the portable mixer series, MxxHxDC. The harmonic mixers in the series are designed to attach to a handheld spectrum analyzer, such as Keysight Technologies' FieldFox. The mixer uses the tracking generator in the spectrum analyzer as the LO source and taps into 5 V from the analyzer's built-in DC supply. The mixer enables a "one box" solution for portable field measurements for applications such as backhaul radio, automotive radar and WiGig. Three versions of the MxxHxDC are available, for waveguide bands WR-12 (60 to 90 GHz), WR-15 (50 to 75 GHz) and WR-10 (75 to 110 GHz).

The M12H6DC model covers the 60 to 90 GHz RF band and downconverts to an IF output between DC and 2 GHz. The spectrum analyzer's tracking generator is set between 9.92 and 14.92 GHz, with the sixth harmonic used for the LO. The M12H6DC's conversion factor is typically −6 dB with the IF at 500 MHz. Typical noise figure is 26 dB, which includes the IF amplifier, and the output 1 dB compression point is typically −5 dBm, with a maximum input power drive of +20 dBm. The extender uses a WR-12 waveguide interface for the RF signal and SMA female connectors for the LO and IF. The extender draws a maximum of 250 mA from the spectrum analyzer's 5 V supply. The operating temperature range is +20°C to +30°C.

The MxxHxDC portable mixer series from OML is the first truly portable measurement system that extends the measurement capabilities of handheld spectrum analyzers into the millimeter wave bands.

OML
Morgan Hill, Calif.
www.omlinc.com

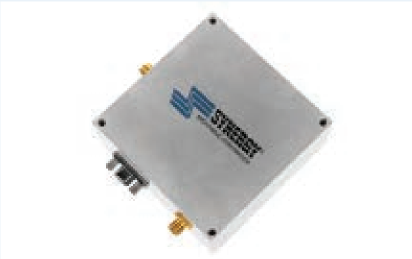
High Power SPDT RF Switch

Two trends continue in recent Wi-Fi system developments. One is the increase in RF transmitter power to improve coverage range and signal quality, the other is the use of more complex modulation to boost data throughput. Both trends place more stringent requirements on the power handling and linearity of the RF components in the transmission path to meet regulatory and signal integrity requirements. The RF switches at the antenna ports are critical components, as they can limit system performance. While more integrated front-end-modules are increasingly being used, particularly for applications with limited space, discrete MMIC switches still offer the most flexibility, for both performance and system configuration.

To address these demanding requirements, CEL developed the CG2409X3, a high power single pole double throw (SPDT) GaAs MMIC switch. Intended for wireless systems where high power capability is required, the CG2409X3 covers 50 MHz to 6 GHz and has a 0.1 dB compression point of 37.5 dBm at 3 V control voltage. The second and third harmonics are −80 dBc and −85 dBc, respectively, with 26 dBm input power. Insertion loss is 0.3 to 0.6 dB, while isolation ranges from 32 to 28 dB over the frequency range. The switch operates with a control voltage from 1.8 to 5 V and is available in a compact 6-pin XSON package measuring 1.5 mm x 1.5 mm x 0.37 mm.

The CG2409X3 is manufactured using state-of-the-art PHEMT technology and is assembled and tested in Japan, assuring high quality and reliability. The switch is a drop-in replacement for the Renesas uPG2409T6X, which is being phased out.

CEL
Santa Clara, Calif.
www.cel.com



1 GHz, Ultra-Low Noise, Phase-Locked OCXO

Synergy Microwave has released a new 1 GHz, ultra-low noise, phase-locked oven controlled crystal oscillator (PLOCXO) that is ideal for low jitter analog-to-digital and digital-to-analog converter or local oscillators applications. The PLOCXO features a user-programmable input reference of 1, 5, 10, 20 or 50 MHz, with other frequencies available if requested. This programmability enables the source to be tailored to the requirements of various applications in radar, instrumentation and test equipment.

The PLOCXO provides a sine wave output of +13 dBm into 50 Ω, typical, and very low phase noise of −110 dBc/Hz at 100 Hz offset, −153 dBc/Hz at 10 kHz offset and −165 dBc/Hz at 10 MHz offset. Harmonics are −30 dBc maximum, with sub-harmonics suppressed to −40 dBc maximum. Phase-locked loop spurious products are down at least 60 dBc, and all other spurious are down at least 80 dBc. Free running, long-term aging is within ±200 ppb after 30 days of operation.

Two SMA connectors are used for the reference input and RF output, with a 9-pin D-connector for DC bias. A "lock detect" signal is provided on the 9-pin connector to show status, with 2.3 to 3.3 V indicating "locked" and 0 to 1 V if the oscillator is "unlocked." The unit is powered with +15 V, drawing a warm-up current of 600 mA maximum and a steady-state operating current of 300 mA maximum at 25°C. The oscillator measures 2.4" x 2.4" x 1.2" and weighs 7 oz.

With an operating temperature range from −10°C to +60°C and meeting the shock and vibration requirements of MIL-STD-810F and MIL-PRF-55310D, as well as IEC60068 and IEC60679-1, this commercial off-the-shelf source is excellent for both military and commercial applications.

Synergy Microwave Corp.
Paterson, N.J.
www.synergymwave.com

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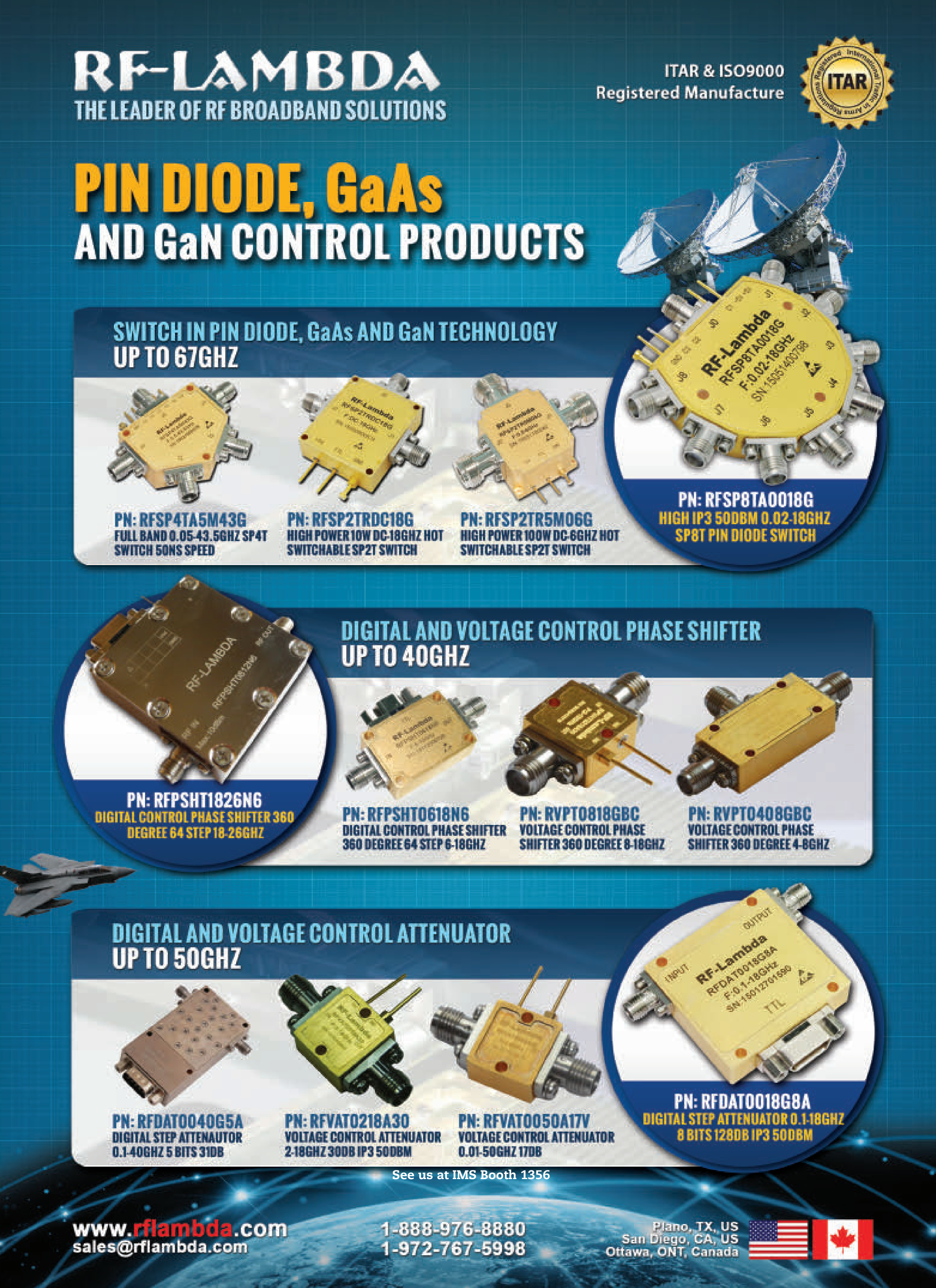
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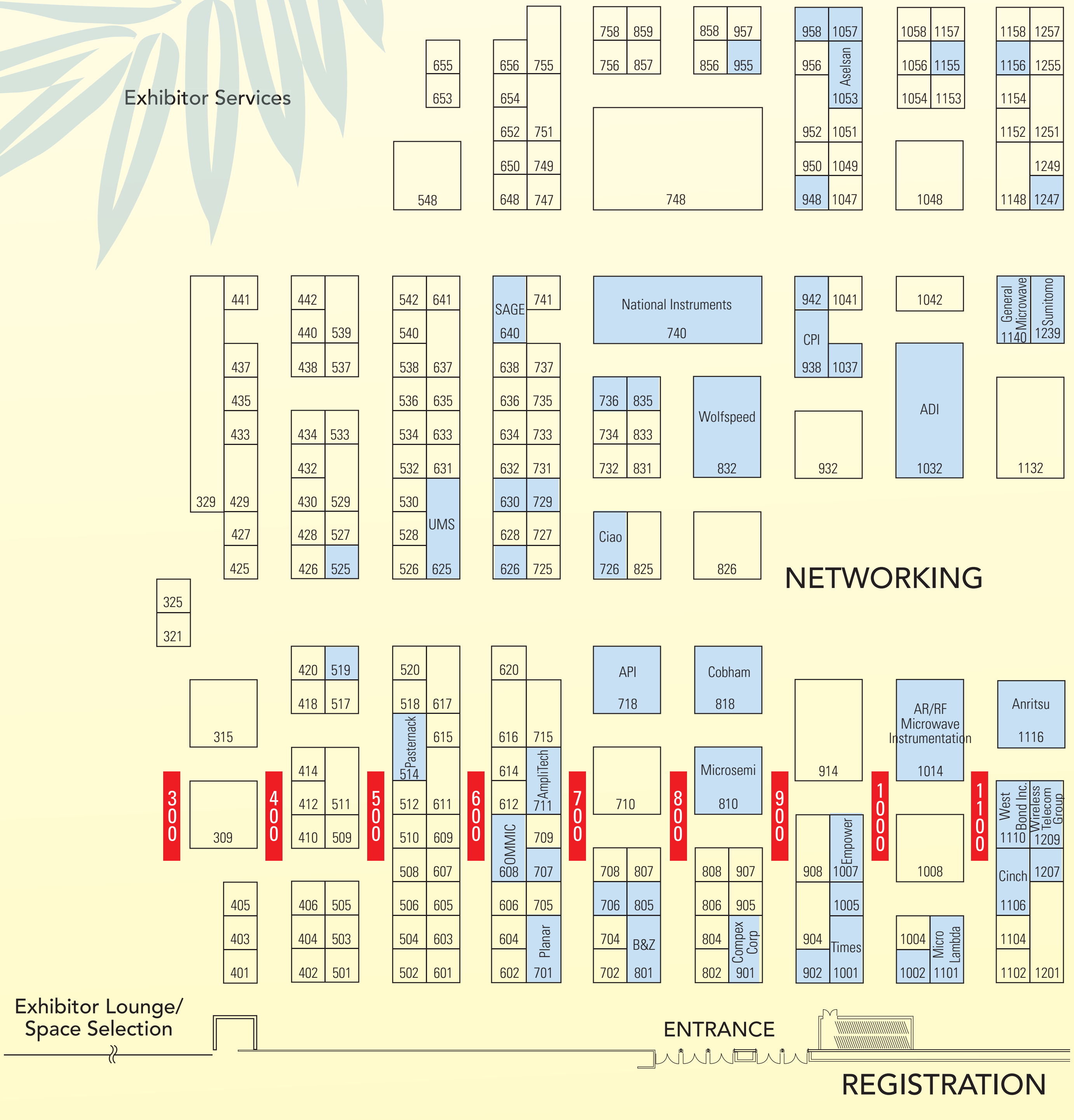
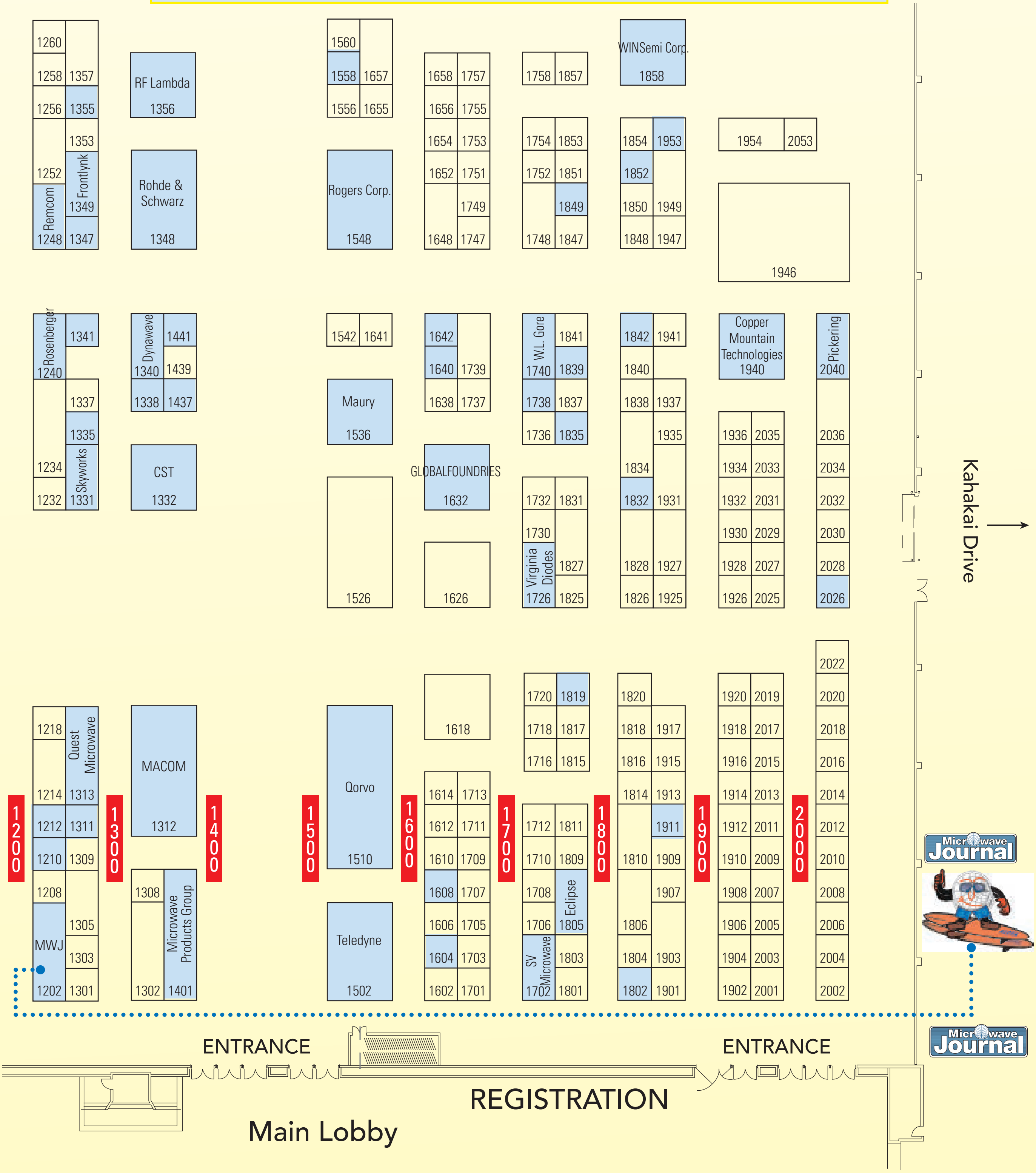
PN: RFVAT0050A17V
VOLTAGE CONTROL ATTENUATOR 0.01-50GHZ 17DB
PN: RFDAT0018G8A
DIGITAL STEP ATTENUATOR 0.1-18GHZ 8 BITS 128DB IP3 50DBM
See us at IMS Booth 1356
www.rflambda.com
sales@rflambda.com
1-888-976-8880
1-972-767-5998
Plano, TX, US
San Diego, CA, US
Ottawa, ONT, Canada

IMS FLOOR PLAN

Your Product Guide to The Show Floor

Shaded exhibitors have an ad featured in this IMS Show Issue.





RF Lambda 1356
Rohde & Schwarz 1348
Remcom 1248
Frontlynk 1349
Rogers Corp. 1548
WINSemi Corp. 1858
Rosenberger 1240
Dynawave 1340
Maury 1536
CST 1332
Skyworks 1331
GLOBALFOUNDRIES 1632
W.L. Gore 1740
Virginia Diodes 1726
Copper Mountain Technologies 1940
Pickering 2040
1946
Quest Microwave 1313
MACOM 1312
Qorvo 1510
Microwave Products Group 1401
Teledyne 1502
MWJ 1202
Eclipse 1805
SV Microwave 1702
1200
1300
1400
1500
1600
1700
1800
1900
2000
Microwave Journal
ENTRANCE
ENTRANCE
REGISTRATION
Main Lobby
Kahakai Drive

The following booth numbers are complete as of April 5, 2017.

Pasternack — Booth 514

Voltage Variable Attenuators

Pasternack's portfolio of voltage variable attenuators includes models covering octave broadband frequencies from 400 MHz to 18 GHz while boasting low insertion loss and wide dynamic range. These modules display excellent VSWR over all attenuation levels. CW input power is rated up to +23 dBm and each unit is designed into rugged coaxial packages to meet MIL-STD-202 environmental conditions.

Waveguide Direct Read Attenuators

Pasternack's direct read attenuators are available in WR-42 to WR-10 waveguide standards operating in seven waveguide bands within the 18 to 110 GHz frequency range. They feature ±2% typical attenuation accuracy and feature an easy-to-read drum scale and military standard UG-style flanges. Minimum attenuation range is 0 to 50 dB with an insertion loss of 0.5 to 1 dB depending on the frequency range.
www.pasternack.com

CTT Inc. — Booth 519

Pulsed and CW SSPAs

GaN-based SSPAs for pulse operation have design criteria somewhat different than those for continuous waveform (CW) operation. CTT's proprietary designs result in pulse GaN power amplifiers that are compact, reliable and with the ability to be operated in any of three pulse modes, depending on the customer applications, i.e.: radar, data links and UAV.
www.cttinc.com

KRYTAR — Booth 525

Broadband Directional Coupler 0.5 to 20 GHz

New coupler model 152006 offers superior performance ratings including nominal coupling (with respect to output) of 6 dB, ±1 dB and frequency sensitivity of ±1 dB. The directional coupler exhibits insertion loss (including coupled power) of less than 2.1 dB, directivity of greater than 12 dB, maximum VSWR (any port) is 1.35, input power rating is 20 W average and 3 kW peak. The directional coupler comes with industry-standard SMA female connectors. SMA male and N-type female connector options are available. The compact package measures just 4.49 in x 0.53 in x 0.71 in, and weighs only 3.1 ounces. Operating temperature is -54°C to +85°C.
www.krytar.com

IW Insulated Wire Microwave Products Division — Booth 626

Cable Assemblies

For 2017, IW extends the available range of cable assembly availability for 50 Ω small signal and high power applications and 75 Ω products. 1-5/8 and 7/8 EIA flanges are new for 4806 cable, providing high-power performance to 3 GHz; for 0471, interconnect options are extended with size 20 contacts for multiport configurations, including Micro-D; to support high performance broadcast applications, 75 Ω assemblies with precision N-type and BNC operating to 18 GHz are now available.
www.iw-microwave.com

SAGE Millimeter Inc. — Booth 640

Frequency Extender for 5G and E-Band Communication

Model STE-SF612-03-S1 is an E-Band frequency extender that uses an input frequency of 10 to 15 GHz at +0 dBm and harmonic generation to produce a 60 to 90 GHz RF signal at +3 dBm. The extender is designed and manufactured to extend low-frequency synthesizers or sweepers without losing their other functionalities. The extender features adjustable legs for an easy test setup. In addition to this model, W-Band frequency extenders are also available.

Waveguide Diplexer for E-Band Communication

Model SWY-74384355-12-I1 is an E-Band waveguide diplexer with a low passband of 71 to 76 GHz and a high passband of 81 to 86 GHz. The nominal insertion loss of the diplexer is 0.5 dB and the minimum isolation is 55 dB. Since both low and high passband frequencies can be changed by modifying the design, custom designs are available under different model numbers.
www.sagemillimeter.com

Planar Monolithics Industries Inc. — Booth 701

10 Bit Programmable 50 dB Attenuator

PMI Model No. DTA-18G40G-50-CD-1 is a 10 Bit programmable 50 dB attenuator with step resolution as low as 0.05 dB over the frequency range of 18 to 40 GHz. This model is offered in a slim line housing measuring only 0.5" in height with 2.92 mm female connectors. Other specifications include insertion loss of 8.5 dB typical–measured 10.4 dB, flatness ±1.5 dB typical, attenuation accuracy ±2 dB typical, VSWR of 2.5:1 max–measured 2.27:1 and power handling of +24 dBm CW maximum.
www.pmi-rf.com/Products/attenuators/DTA-18G40G-50-CD-1.htm

MIcable — Booth 706

T26 Cable Assemblies

T26 series is high reliable and durable test cable up to 26.5 GHz, ideal for high precision and frequent tests. The cable construction is very rugged, which can be qualified by over 150K harsh flex cycles without changes in electrical performance till to 26.5 GHz. T26 series can be built with a wide range of stainless steel connectors, such as 3.5 mm, SMA and N types.

VNA Cable Assemblies

MIcable is providing VNA cable series, which is rugged and flexible test cable for Vector Network Analyzers from frequency through 50 GHz. MIcable VNA test cable assemblies maintains negligible changes of phase and amplitude over flexure to guarantee repeatable and constant operations. Cable was armored with extreme rugged braid and NMD-style connectors are applied to ensure excellent reliability by withstanding repetitive mating, flexure and bending.
www.micable.cn

AmpliTech Inc. — Booth 711

100 W Wideband Power Amplifier

The AMTHPA-00700270-100W is a 100 W high gain power amplifier operating in the 0.7 to 2.7 GHz frequency band. The amplifier offers 100 W typical saturated power and 50 dB minimum small signal gain with ±1 dB typ. gain flatness. The amplifier

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Whether you're working in production test or R&D, Mini-Circuits' modular test systems give you a solution that's flexible, reliable, affordable and fast! Choose from either a rack-mountable chassis or a space-efficient, bench-top module, and configure your system with any combination of extra-long-life SPDT, SP4T, SP6T and transfer switches and programmable attenuators with attenuation ranges from 0 to 30, 60, 90, 110 and 120 dB. We'll build and ship a system tailored to your requirements within just 2 weeks! Define your system with our online configuration tool for a fast quote today!

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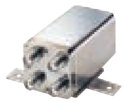
SPDT Switches
DC – 18 GHz

SP4T Switches
DC – 18 GHz

SP6T Switches
DC – 12 GHz



Transfer Switches
DC – 18 GHz

0 – 30, 60, 90, 110 or 120 dB
Programmable Attenuators
1 MHz – 6 GHz

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operates from a 32 V DC power supply with a 30% PAE. The connectorized module operates over a temperature range of 0°C to 50°C and is 50 Ohms input and output matched for unconditional stability. The unit comes with built-in heat sink and fans for efficient cooling.
www.amplitechinc.com

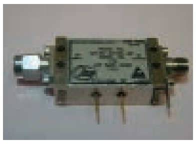
API Technologies Corp. Booth 718

Configurable Octave Band Synthesizers

This synthesizer product platform by API Technologies provides an adaptable design solution for engineers requiring a small surface-mount package and the adaptability to meet a number of varying system configurations. Application-specific changes can be achieved without the need for hardware modifications. This affordable design features low phase noise performance and fast switching speeds.
www.apitech.com

Ciao Wireless Inc. Booth 726

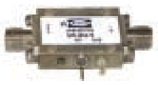
1 to 40 GHz AMP with Detected Output



Ciao Wireless Inc. has introduced an ultra-broadband amplifier which features an integrated wideband detector for communication applications. This amp comes with two min gain options of 30 dB min (35 dB typ.) and 15 dB min (20 dB typ.). The gain flatness is ±3.25 maximum. The typical output power is +13 dBm across 1 to 28 GHz. The input and output VSWR is 2.3 or better. The typical noise figure is six across the full band (1 to 40 GHz).
www.ciaowireless.com

Herotek Booth 729

Detector for Low Signals



Herotek introduces a new series of detectors for very low signals for direct measurement of microwave signals down to -80 dBm over 1 to 40 GHz. The DTA182670A operates from 18 to 26 GHz with very high sensitivity of 100 mV/mW, TSS of -70 dBm, stable and quite low I/F noise operation and extremely fast pulse response (1 nsec rise time typical). Its max input VSWR is 2:1, is hermetically sealed for military application and has removable connectors for MIC assembly.
www.herotek.com

Norden Millimeter Booth 736

Frequency Up and Down Converters

Norden Millimeter is a leader in the design and manufacture of frequency converters, transceivers, frequency multipliers and amplifiers operating in frequencies between 500 MHz to 110 GHz. Norden supplies a wide range of frequency up and down converters which are used in EW and ELINT systems. Custom assemblies can include frequency multiplication, filtering, LNA's and power amplification. Norden's products include VME, VPX and 3U configurations. Norden's quality system is ISO 9001:2008 and AS9100C certified.
www.nordengroup.com

National Instruments Booth 740

Vector Signal Transceiver

VENDORVIEW

Visit NI's booth #740 to see a demonstration of their second-generation Vector Signal Transceiver (VST) used in applications such as RF power amplifier test, MIMO test and more. This PXI instrument combines an RF signal generator, RF signal analyzer, high-speed digital interface and LabVIEW-programmable FPGA into a single PXI module. This latest VST features up to 1 GHz of instantaneous bandwidth for technologies including 802.11ax, DPD, 5G and radar.
www.ni.com/vst

NI AWR Booth 740

NI AWR Design Environment V13

VENDORVIEW

The latest V13 release of NI AWR Design Environment accelerates product development of RF/microwave circuits and systems. V13 offers new and expanded technology for circuit and system simulation as well as design automation and assistance. Specific enhancements include new capabilities to automate PCB, MMIC and module design flows, expanded design synthesis and addition of import/export of file format standards. V13 also features speed and functionality improvements to its harmonic balance, system-level and EM simulation engines.
www.awrcorp.com

NI Microwave Components Booth 740

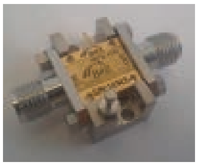
QuickSyn X

VENDORVIEW

The QuickSyn X joins the popular QuickSyn line of very fast-switching, very low-noise frequency synthesizers by extending its frequency range down to 250 kHz, making its total operating range 250 kHz to 20 GHz. The QuickSyn X now includes the highly requested amplitude-leveling-control (ALC) feature for users who require power accuracy, and the AM option on the QuickSyn X is calibrated across its entire frequency range, delivering truly instrument-grade quality.
www.ni-microwavecomponents.com

B&Z Technologies Booth 801

Microwave Amplifiers



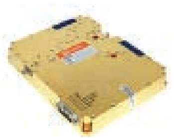
B&Z Technologies manufactures a full line of state-of-the-art microwave amplifiers spanning from 100 KHz to 50 GHz. B&Z offers ultra-low noise, high dynamic range, medium power (up to +30 dBm) amplifiers for military, SATCOM and commercial markets. The company's in-house designing, machining and manufacturing capabilities allow them great flexibility to custom design amplifiers with quick turn-around time with option of waveguide and weatherproof housing. Stock amplifiers are routinely updated on the website along with data and can be shipped within three to five days.
www.bnztech.com

Exodus Advanced Communications Booth 805

GaAs Hybrid SSPA Module

VENDORVIEW

Exodus Advanced Communications announced the release of its Class SSPA model AMP3060–a 32 to 40 GHz, 10 W GaAs Hybrid SSPA Module. It provides 10 W CW Psat over the full band with 4 dB Peak to Peak flatness. Additional features include high reliability and ruggedness along with suitability for all single channel modulation standards. This amplifier is designed for any application that requires wide band coverage such as EMI/RFI, Ka-Band radar, EW and high power millimeter testing.



www.exoduscomm.com

IMS PRODUCT SHOWCASE

AISLES 800-900

Holzworth Instrumentation — Booth 835

Real Time Phase Noise Analyzer

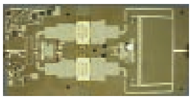
VENDORVIEW

The HA7062C real time phase noise analyzer is a dual channel, cross correlation system that was designed to address both the needs of R&D engineering as well as high volume manufacturing. The versatile design can collect data to unprecedented noise floor levels with industry leading data acquisition speeds at the touch of a button. The reconfigurable analog front end eliminates issues common to digital phase noise test systems while boasting numerous extended capabilities.

www.holzworth.com

Integra Technologies Inc. — Booth 902

1 KW L-Band Radar Pallet



Integra Technologies, a designer and manufacturer of high-power multi-stage, multi-band RF pallets (up to 2 KW) and transistors (up to 1.4 KW), is proud to feature IGNP1214M1KW-GPS for L-Band radar applications. GaN-SiC, > 1000 W, 50 V, 12.7 dB, 60% at 300 microseconds, 10% pulse conditions. Pallet includes gate biasing and sequencing circuitry for easier system integration. Custom versions of this product (and other VHF/UHF, L, S, C, X-Band standard products) are available upon request.

www.integratech.com

CPI Beverly Microwave Division — Booth 938

High Power, Solid State Power Amplifier

VENDORVIEW

The VSC3645 is a C-Band 4 kW+ modular GaN high power, solid state power amplifier. The HPA operates from 5.2 to 5.9 GHz at 10% duty and has integral air cooling, amplifier health monitoring and designed to be modular building blocks for 16 and 32 kW applications. The VSC3644 is easy to maintain, with high gain, excellent pulse fidelity, and outstanding spectral performance. Applications: maritime, defense and high resolution weather radars.

www.cpii.com

Besser Associates Inc. — Booth 942

RF and Wireless Training

BESSER ASSOCIATES

Besser Associates is a worldwide leader in RF and wireless training. Besser's instruction combines theory with hands-on practice, the latest tools and technology and the most appropriate training media (online and traditional classroom) for individualized, meaningful participant experiences. Besser chooses its instructors from the best and brightest in their fields around the world; they carry an average of 20 years of field and applied teaching experience. Courses can be presented on-site and customized to meet the specific needs of the client.

www.besserassociates.com

Berkeley Nucleonics — Booth 955

Low Phase Noise Signal Generator

VENDORVIEW

The BNC Model 855 is a phase coherent multi-output ultra-fast switching and low phase noise signal generator with frequency ranges from 10 MHz to 6.2, 12.5 or 20 GHz, with excellent phase noise and spurious and harmonic rejection. A high-stability OCXO reference provides excellent frequency accuracy and stability. The Model 855 provides two to eight independent outputs in a 1U or 3U enclosure. Various control interfaces: USB, LAN or GPIB, and a rich library of APIs are provided.

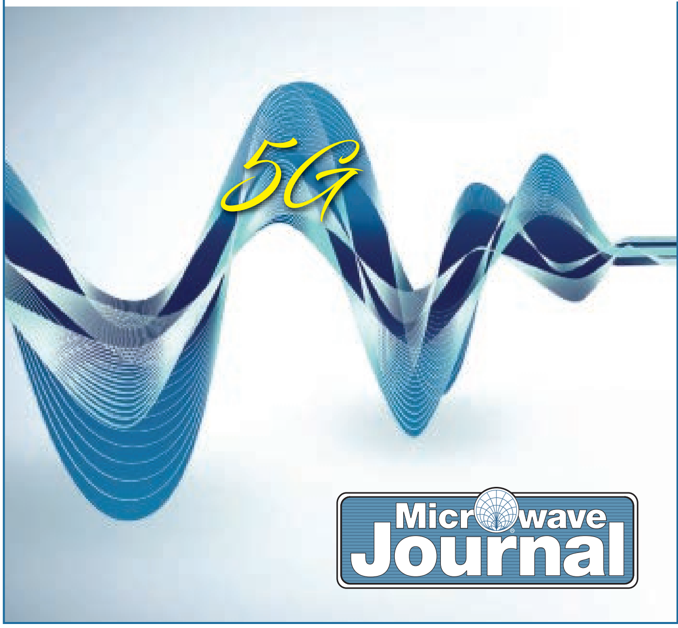
www.berkeleynucleonics.com

IMS2017 MicroApps Keynote Panel Session

Wednesday, June 7 ■ 12:00-1:00 p.m. ■ MicroApps Theater

The Future of RF Semiconductor Test

This panel of test & measurement and semiconductor experts will cover topics such as on-wafer mmWave testing, low power/low cost approaches for IoT testing, RFFE module testing challenges and OTA testing, and their role in the future of semiconductor testing.



Panelists:

Steve Reyes, VNA Product Manager, **Anritsu**

Jason White, Director of Marketing, RF & Wireless Test, **National Instruments**

Chris Scholz, North American Product Manager for VNAs, **Rohde & Schwarz**

Greg Peters, Vice President and General Manager, Aerospace/Defense/Government Solutions, **Keysight**

Brad Nelson, Director of Engineering RF Components and Sources, **Qorvo**

Rene Rodriguez, Senior Antenna Engineer, **Skyworks**

Moderator:

Pat Hindle, Editor, **Microwave Journal**

E LEARNING CENTER

Presented by: Microwave Journal

May Short Course Webinars

Technical Education Training 5/2
Phase Noise: A New Frontier for Amplifier MMICs
Sponsored by: Custom MMIC

Innovations in EDA 5/4
Four Ways to Boost Simulation Data Processing Using Python
Presented by: Keysight Technologies

Technical Education Training 5/4
Five Things to Know About WLAN 802.11ax and Why Testing is More Important than Ever Before
Sponsored by: Rohde & Schwarz

Technical Education Training 5/10
Sponsored by: Richardson RFPD / NXP

Technical Education Training 5/11
IP Connection Security
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RF/Microwave Training 5/16
RFMW Filters
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Technical Education Training 5/18
Recent Radar and Phased-Array Breakthroughs
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Signal Integrity Journal's Webinars

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Laminate Materials Characterization for High Speed Applications 5/17
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www.signalintegrityjournal.com

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Benefits of Modular RTSA

Sponsored by: RADX Technologies, Inc

Presented by: Ross Q. Smith, RADX Co-Founder and CEO & Robert W. Lowdermilk, RADX Co-Founder and CTO

microwavejournal.com/Webinar_12apr17

Register to attend at mwjournal.com/webinars

See us at IMS Booth 1202

Wenteq Microwave **Booth 958**

6 to 18 GHz Wide Band Coaxial Circulator

Model F2700-1300-A0 is a wide band SMA connectorized circulator operating over 6 to 18 GHz frequency range. It features 1.5 dB maximum insertion loss, 10 dB minimum reverse isolation and 1.9:1 maximum VSWR. This circulator can handle 10 W of forward CW power. The package size of the circulator is 0.748 in × 0.787 in × 0.512 in and its weight is only one oz.
www.wenteq.com

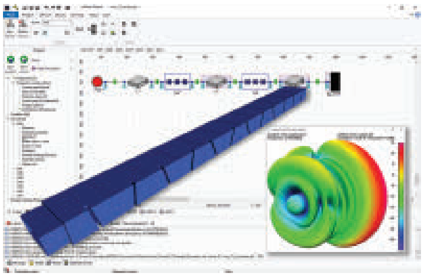
Times Microwave Systems **Booth 1001**

High Frequency Coax Cable Assemblies

SilverLine®-VNA Flex Supreme™ 50 & 67 GHz are extremely flexible, very high frequency coax cable assemblies designed for vector network analyzer use. The high flexibility is ideal for use with small or delicate circuitry. "Light" armoring helps reduce accidental damage without adding excess weight and/or inhibiting flexibility. A Nomex®, abrasion resistant outer braid improves feel and handling characteristics.
www.timesmicrowave.com

Mician GmbH **Booth 1002**

μWave Wizard Version 8.1



Mician, recognized as a leading developer of EM software tools for the analysis, synthesis and optimization of passive components like feeding networks, couplers, multiplexers and horn antennas, including reflectors, will preview the latest release of their hybrid software tool μWave Wizard, version 8.1. The tool combines the flexibility of fast and powerful numerical methods with an appealing and ergonomic GUI that enables flexibility and openness including CAD export formats interfacing with most mechanical design tools.
www.mician.com

Werlatone **Booth 1005**

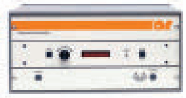
New High Power In-Line Power Meter

Werlatone's®RMS Digital In-Line Power Meters allow accurate, instantaneous and simultaneous local and/or remote monitoring and alarm capability. With a 40 dB dynamic range, the power meters provide measurement and alarm capability of forward and reverse power, load VSWR and two external temperature sensors. Includes six general purpose inputs/relays and is powered by AC power adapter or POE. Remote interface through TCP-IP (with SNMP and browser interface via LAN), RS232 and RS485 form addressable serial network. User ID and password protection provides secure, off-site monitoring. Multiple units can be networked and simultaneously monitored.
www.werlatone.com

AR RF/Microwave Instrumentation **Booth 1014**

Single Band Amplifier

VENDORVIEW



AR's new 40S6G18B is a self-contained, air-cooled, broadband, class A solid-state amplifiers designed for applications where instantaneous bandwidth, high gain and linearity are required. The Model 40S6G18B, when used with a sweep generator, will provide a minimum of 40 W of RF output power instantaneously from 6 to 18 GHz. This single band amplifier is suitable for radiated immunity testing, TWTA replacements and EW applications.
www.arworld.us/html/18200.asp?id=1343

Analog Devices Inc. **Booth 1032**

Digital-to-Analog Converter

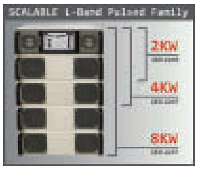
VENDORVIEW

Based on 28-nanometer CMOS technology, the AD9172 dual, 16-bit digital-to-analog converter (DAC) sets new performance benchmarks in signal bandwidth synthesis, dynamic range and low power consumption. At a total power consumption of only 1.5 W per channel, the converter's superior analog core achieves spurious-free dynamic range performance of 70 dBc providing the ability to realize Direct-to-RF synthesis within a first Nyquist zone of 6 GHz. The rich-suite of digital signal processing functions moves complex filtering and frequency up-conversion stages from the analog to the digital domain.
www.analog.com/en/products/digital-to-analog-converters/high-speed-da-converters/ad9172.html

Empower RF Systems Inc. **Booth 1041**

1 to 2 GHz for Radar, EW and Radiated Susceptibility

VENDORVIEW



Empower RF's scalable pulsed L-Band amplifier family gives you a lower initial cost and inexpensive upgrade path while offering AGC and ALC operating modes that simplifies your overall system integration by eliminating the need to build your own costly external feedback loop for exciter control. This family offers an inherently rugged design, based on Empower's patented NEXT GENERATION architecture that virtually eliminates every internal connector.
www.empowerrf.com

R&D Interconnect Solutions **Booth 1057**

Invisipin®

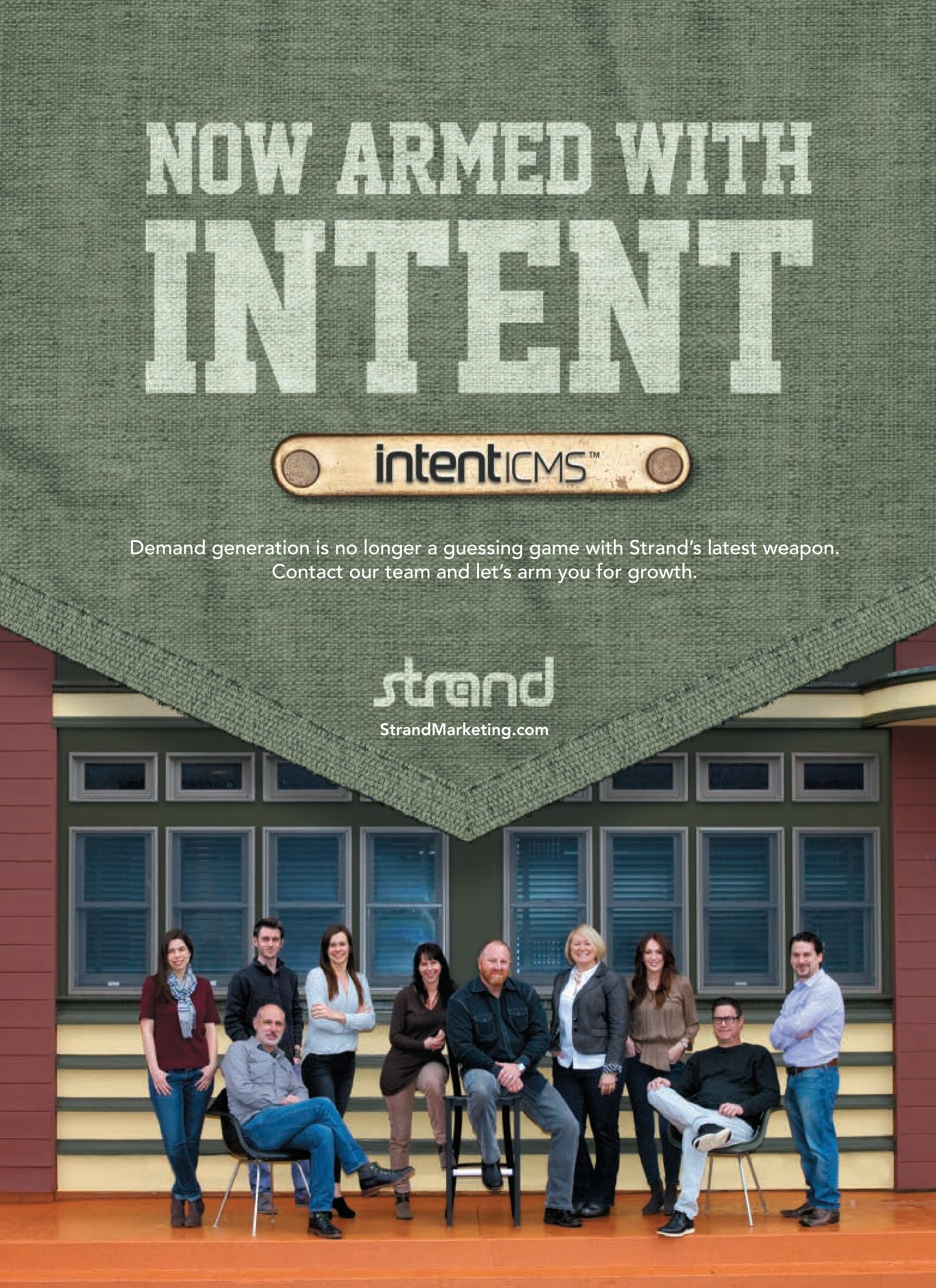
Invisipin is the world's first solderable, individual conductive elastomer pin. Invisipin stands apart by allowing unparalleled flexibility and performance with < 25 m Ω contact resistance (typical), high compliance range, RF loss at 50 GHz < 0.45 dB (Coax, 1 pin), socket RF loss < 1.15 dB between 76 to 77 GHz and two amps continuous current capacity. Invisipin offers standard pin configurations of 0.23 mm to 0.64 mm diameter supporting pitches from 0.4 mm to 1 mm. Invisipin is pick and place/solder reflow compatible, infinitely configurable, individually replaceable and 100% electrically tested.

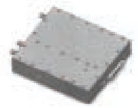
www.rdis.com

Micro Lambda Wireless **Booth 1101**

MLVS-Series Frequency Synthesizers 50 MHz to 20 GHz

Smaller and lower phase noise frequency synthesizer. The first in a series of standard


NOW ARMED WITH
INTENT
intentICMS™
Demand generation is no longer a guessing game with Strand's latest weapon.
Contact our team and let's arm you for growth.
strand
StrandMarketing.com



frequency models covering 50 MHz to 20 GHz phase noise at 10 GHz is specified at -124 dBc/Hz at 10 kHz offset with a switching speed of 10 uSec full band. Standard models are specified to operate over the 0°C to +60°C. This series of frequency synthesizers have been designed in a miniature package with dimensions of 4 in × 3.6 in × 0.9 in tall.
www.microlambdawireless.com

West·Bond Inc. **Booth 1110**

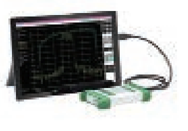
Wire Bonders

Introducing the most flexible, complete wire bonders system available today. 7KE and 4KE series wire bonders: bonding at 45 degree feed for tail control, 90 degree for ribbon and deep access and ball bonding without changing heads. Wedge bonding Au, Al, Cu; ball bonding Au, Cu, automatic, semiautomatic and manual all ESD protected. Ultrasonic, thermosonic and thermocompression wire/ribbon bonders; eutectic and epoxy die bonders, insulated wire bonders and pull testers.
www.westbond.com

Anritsu Co. **Booth 1116**

Ultraportable mmWave Spectrum Analyzers

VENDORVIEW



The Anritsu Co. Spectrum Master™ MS2760A family features the world's first ultraportable, mmWave spectrum analyzers. Leveraging Anritsu's patented state-of-the-art NLTL Shockline technology, the MS2760A shatters the cost, size and performance barriers associated with traditional large form-factor instruments. The MS2760A ultraportable, mmWave spectrum analyzers improve test procedures and lower the cost-of-test in high frequency applications such as 5G, E-Band, 802.11ad/WiGig, satellite communications, electronic warfare and automotive radar.
www.anritsu.com

Kratos **Booth 1140**

Indirect Synthesizer

Kratos General Microwave enhanced its family of indirect synthesizers with the addition of the model SM6218 with frequency modulation

capability. It can provide a frequency deviation of 1 GHz at up to a 10 MHz rate and can be controlled with either analog or digital inputs. Of special significance; the synthesizer output frequency remains fully locked even while in the FM mode. Its small size and high reliability make it ideal for use in demanding airborne environmental conditions as well as test systems.
www.kratosmed.com

Pivotone **Booth 1155**

Wide Band Twin TMA Filter Design

Pivotone will feature the new wide band twin TMA filter design at IMS2017. The new TMA filter is capable of handling high-power with a compact size for a wide range of the frequency band. The other characteristics of the product include low PIM, low insertion loss and high Q.
www.pivotone.com

L3 Technologies **Booth 1201**

RF and Microwave Components, Subsystems and Vacuum Electron Devices

Join L3 Technologies (Narda-MITEQ, Narda-ATM and Electron Devices) in booth 1201 as L3 will showcase the most advanced lineup of RF and microwave components, subsystems and vacuum electron devices. On display will be the extensive lineups from each division with the support staff to answer any questions you have. L3 will be located right inside the show floor across from registration.
www.L3T.com

L3 Electron Devices **Booth 1201**

80 W Ka-Band MPM

L3's M1292 MPM provides over 80 W of saturated power and 50 W of linear power in Ka-Band. This amplifier is ideal for defense applications requiring high output power and high efficiency in an ultra-compact, fully airborne-qualified package. Covering both communications and radar bands, this MPM is suitable for communications, radar and EW applications. The M1292 operates from conventional +28 VDC prime power, measures 9.75 in × 8.5 in × 1.5 in and weighs less than eight pounds.
www.L3com.com/edd

Huber+Suhner **Booth 1207**

Plug, Test, Smile with HUBER+SUHNER

VENDORVIEW

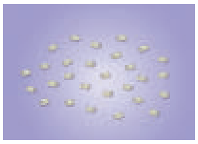
When it comes to test and measurement, SUCOFLEX 500 assemblies guarantee the

IMS PRODUCT SHOWCASE
AISLES 1200-1300

highest level of satisfaction. Not only are they extremely flexible and easy to use, thanks to their unique design, they also deliver best-in-class phase and amplitude stability with flexure, movement, temperature and tensile stress. SUCOFLEX 526V is the only 26.5 GHz VNA microwave cable assembly worldwide with a 50 ppm phase variation vs. temperature in standard test lab environment, guaranteeing accurate measurements with longer calibration intervals.
www.hubersuhner.com

American Technical Ceramics — Booths 1212, 1311
RF/Microwave SMT Capacitor

ATC's new 400 W Series EIA 01005 precision tolerance NPO RF/microwave SMT capacitor offers the tightest tolerances available (± 0.01 pF), greatly reducing the need for end process tuning, adding an extra benefit in reduced manufacturing cost. It is superior for critical tuning applications through millimeter-wave where exact capacitance values and ultra-low loss are required. Ultra-stable performance and reliability make it ideal for a full range of critical tuning applications as well as DC blocking and bypassing applications.



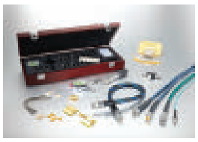
www.atceramics.com

Sumitomo Electric Device Innovations — Booth 1239
X-Band Pulsed Radar Devices

VENDORVIEW

Sumitomo Electric introduces new devices to its line of high power GaN products for X-Band radar applications. SGM6901VU is a compact two-stage hybrid module SMD with 22 dB gain, 30 W power, ideal as driver or phased array radar element. The SGC0910-300A-R is a 300 W IMFET. These add to the existing line of 50, 100 and 200 W IMFET devices.
www.sei-device.com

Rosenberger North America LLC — Booth 1240
Test and Measurement Equipment



As a renowned supplier of high-quality and high-precision test and measurement equipment and services, Rosenberger of North America highlights its latest developments at the IMS show. The company will have available test and measurement equipment and products for microwave and VNA measurements, such as calibration kits (full and industrial versions), with a wide range of coaxial interfaces, as well as compact calibrations kits such as MSO (open, short, load) and MSOT (open, short, load, thru) versions.
www.rosenberger.com

Delta Electronics Mfg. Corp. — Booth 1247
VITA 67 Product Release

Delta Electronics Manufacturing Corp. introduces 4 position (VITA 67.1) and 8 position (VITA 67.2) RF connector housings designed for 3U and 6U formats within the OpenVPX™ architecture. Ideal for blind mating daughtercards to motherboards, the SMPM RF contacts provide ± .010" radial misalignment tolerance and excellent return loss up to 65 GHz. Precision machined from either stainless steel or aluminum, the 4 and 8 position housings are available with pre-loaded SMPM adapters or a cost effective, direct snap-in, cable mount SMPM contact.
www.deltarf.com

Remcom Inc. — Booths 1248, 848
Wireless InSite for 5G MIMO Simulation

Wireless InSite MIMO is a unique ray tracing tool that simulates the detailed multipath of large numbers of MIMO channels. The MIMO capability predicts accurate path data between each transmitting and receiving element with precision and reveals key channel characteristics in a timely manner. With optimizations that minimize runtime and memory constraints, Wireless InSite efficiently simulates even the large arrays present in Massive MIMO systems. Visit Remcom's booth for a demonstration.
www.remcom.com

MACOM — Booth 1312
GaN, MMICs, Space & Hi-Rel and Diodes Based Devices

VENDORVIEW

MACOM is leveraging over 65 years of unparalleled design and application expertise, and is committed to delivering industry leading design and applications specific solutions for its customers worldwide. MACOM will showcase its industry leading GaN, MMICs, Space & Hi-Rel and Diodes based devices at IMS2017. MACOM design and application engineers are continuing its legacy and commitment of leadership with next-gen wideband RF solutions for mission-critical applications.
www.macom.com

Quest Microwave **Booth 1313**

Ferrite Devices

Quest Microwave provides a broad range of ferrite devices for the global microwave electronics marketplace. Standard and custom designs are available for both commercial and military applications. With over 60 years of combined experience, the company's engineering staff can design and develop ferrite devices for virtually any application. They are there to provide you with a world class microwave components solution.
www.questmw.com

Spectrum Elektrotechnik GmbH **Booth 1313**

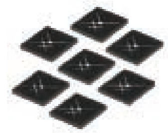
Phase Adjusters DC to 63 GHz

Phase adjusters are needed at applications where the phase adjustment of components or cable assemblies is necessary. Phase adjusters are designed for constant impedance over the whole adjustment range. They are employed to adjust the electrical separation of other components without introducing additional mismatch. All step discontinuities have been carefully compensated. Locking screws are provided to comfort the sliding tension and to lock at the desired adjustment. The best materials have been used for ruggedness, low weight and best performance.
www.spectrum-et.com

Skyworks Solutions **Booth 1331**

Family of Solutions for Rapidly Growing Small Cell Market

VENDORVIEW



Skyworks Solutions is showcasing its new family of industry leading power efficient amplifiers that meet stringent data rate and power consumption requirements for indoor and outdoor network systems. The SKY6629X amplifiers support the world's most popular frequency bands and can be incorporated in FDD and TDD 4G LTE, 4.5G and 5G systems, as well as the recently launched Citizen's Broadband Radio Service (CBRS).
www.skyworksinc.com

CST of America Inc. **Booth 1332**

CST STUDIO SUITE®

VENDORVIEW

CST STUDIO SUITE®, its flagship 3D EM software features tools for a wide range of applications. Antenna coupling for the asymptotic solver offers an efficient way to simulate multiple antennas on very large platforms. This feature is especially useful for system integrators because data from a wide variety of sources can be brought together in a single system-level simulation. With the nearfield monitor, users can identify and visualize the coupling paths between antennas, and the Interference Task can identify potential EMC issues caused by co-site interference.
www.cst.com

LPKF Laser and Electronics **Booth 1338**

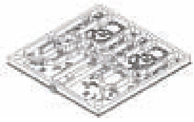
ProtoMat E-Series Rapid PCB Milling System

Reduce your PCB prototype development cycle from days/weeks to only minutes with

advanced LPKF PCB milling and direct laser etching equipment. LPKF's entry level ProtoMat E44 enables production-on-demand processing and conveniently solves complex and diverse design needs. LPKF will also show samples on Flex DuPont Pyralux TK, AP and A1203 fired ceramics completed with the latest ProtoLaser systems. LPKF offers a wide range of high precision PCB milling and laser etching systems that enable super high frequency (SHF) and extremely high frequency (EHF) applications.
www.lpkfusa.com

Mercury Systems **Booth 1341**

BGA-based Quad Channel RF Receiver



At just 1.4 in × 1.4 in, this RF receiver is an environmentally sealed device with a BGA interface making it ideal for rugged applications that require a very small form factor. It is ideal for SWaP-constrained EW applications. Features include RF input frequency: 2 to 18 GHz through SMPS connector, high dynamic range, 55 dB typical, input HPF for UHF/VHF rejection, two 32 dB analog variable attenuators and two tunable notch filters, 1.4 in × 1.4 in BGA package and 500 Sn63Pb37 solder balls.
www.mrcy.com

Rohde & Schwarz **Booth 1348**

FSW Signal and Spectrum Analyzer

VENDORVIEW

Rohde & Schwarz is expanding the internal analysis bandwidth of its R&S FSW signal and spectrum analyzer to 1.2 GHz. It enables research and development for next generation

mobile standards, especially in the 28 and 39 GHz bands for 5G, as well as characterization of wideband amplifiers. Typical applications include the demodulation of wideband OFDM and single-carrier digitally modulated signals or measuring the linearization and predistortion of amplifiers. For applications that need more than 1.2 GHz analysis bandwidth, the FSW already supports 2 GHz using an external.
www.rohde-schwarz.com

Custom MMIC **Booth 1355**

GaAs and GaN MMICs

VENDORVIEW

The Custom MMIC standard product portfolio of performance-driven gallium arsenide (GaAs) and gallium nitride (GaN) MMICs is gaining a new ultra-wideband distributed amplifier, a family of low phase noise amplifiers (LPNA) and a family of high P1dB mixers. The CMD201P5 distributed amplifier offers +38 dBm IP3 from DC to 20 GHz. The LPNA family spans 6 to 40 GHz with phase noise figures as good as -165 dBc/Hz. Lastly, a new high linearity mixer family features high P1dB from 4 to 40 GHz.
www.custommmic.com

RF-Lambda USA LLC **Booth 1356**

6 to 18 GHz, Broadband Power Amplifier

RAMP06G18GF is an ultra-wide band solid state benchtop power amplifier covering 6 to 18 GHz with a saturated output power of 140 W. The nominal gain is 45 dB, with a gain adjustment range of 20 dB with a 0.1 dB step size. The units come equipped with multiple protection features such as input over drive, over current and over temperature shutdown making them ideal for EMC, vsat, test and radar applications.

Ultra Low Phase Noise RF Signal Generator 0.039 to 22 GHz with USB Control

RSGLP0120GA is a wide band USB controlled signal generator covering 0.04 to 22 GHz with an output range of -20 to 10 dBm. The frequency step tuning speed is < 100 us with the tuning step at 0.001 Hz and the phase noise at 10 KHz offset -116 dBc/Hz (10 GHz). It uses the advanced VCO and DDS based phase lock technology to provide T&M instrument level of phase noise. The unit uses the internal temperature compensated crystal oscillator as the reference signal of PLL. The unit can also be locked to an external 10 MHz reference source. Accurate calibrated output power. Ideal for ultra wide band radio and test applications.

Absorptive 0.05 to 20 GHz Coaxial SP160T Switch

RFSP160TA0020G is a filter bank switch matrix with 160 channels covering 0.05 to 20 GHz with isolation of 60 dB and speed of 50 ns. This switch comes equipped with a rotary joint and a standard epoxy sealed package for controlled environments up to 30,000 feet. As an added option the switch is also available in a hermetically sealed package up to 60,000 feet that is available on request. Ideal for phase array radar systems.
www.rflambda.com

Dow-Key Microwave **Booth 1401**

Coaxial Switches

Dow-Key's versatile family of 40 GHz products provides users with a wide selection of coaxial switch options. Offered in SP6T Multiposition, DPDT (Transfer) and SPDT, it can be configured for a variety of ATE and military applications. With 2.9 mm RF connectors, the SP6T is available with latching or normally open actuator, while the DPDT and SPDT is offered with latching or failsafe. All models are designed with 12, 24 or 28 V control lines.
www.dowkey.com

K&L Microwave **Booth 1401**

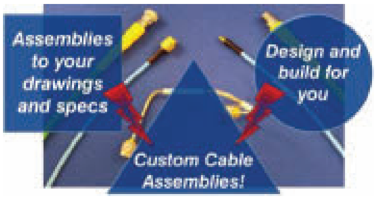
Thin Film Lumped Element

K&L Microwave has launched a Thin Film Lumped Element (TFLE) product line utilizing sputtering deposition on Alumina that applies discrete component expertise to build on the classic quarter-wave-length (λ/4) edge-coupled approach, supporting bandpass, highpass, lowpass and bandreject responses and offering powerful advantages, such as skirt skew control and transmission zeros for enhanced localized rejection. Direct-coupling schemes allow realization of bandpass filters with an operational frequency range exceeding 2 to 20 GHz and relative percentage bandwidth from 3% to 65%.
www.klmicrowave.com

Pole/Zero Corp. **Booth 1401**

Tunable Bandpass Filter

Pole/Zero's HF-ERF™ tunable bandpass filter covers the entire HF tactical radio band of 1.5 to 30 MHz while fitting in a low-profile package measuring 2 in × 2.78 in × 0.6 in (50.8 mm × 70.61 mm × 15.24 mm). It has SMT capability with tune time and has remarkable selectivity for a compact device. These bandpass filters are commonly used in applications where small size, low power and high performance are needed for military handheld radios, radar systems, SATCOM and additional commercial applications.
www.polezero.com



MiniRF **Booth 1437**

SMD Splitters

VENDORVIEW

Are your passives getting performance only some of the time? Then "split" quickly to the MiniRF line of high performance splitters "peas in the pod" performance from first one to the next > 10 K units built. MiniRF offers wide bandwidth, excellent isolation, low insertion loss and excellent I/O return loss for superb matching between components. Look for these products and a full line of transformers/combiners/couplers on MiniRF's website.

www.MiniRF.com

TRAK **Booth 1441**

Ku-Band 25 W Transceiver

VENDORVIEW

TRAK'S latest high power transceiver (HPT) is a modular, high performance TXRX designed for commercial airborne applications with advanced system interoperability features. In a compact package, Model MFC170 delivers a complete Satcom solution with integrated high power solid state power amplifier (SSPA), wideband block upconverter, dual-band downconverter, digital control, status interfaces and all necessary power conditioning circuitry. The modular design approach for this high power transceiver enables multiple built-in-test functions, quick troubleshooting, easy field replaceability and high reliability and survivability gallium nitride (GaN) devices.

www.trak.com

Maury Microwave **Booth 1536**

Product Showcase

Exceptional companies have superior labs–complete your lab with Maury Microwave. Maury, a leader in measurement and modeling device characterization solutions, VNA calibration accessories and interconnections, will be showcasing active and hybrid-active harmonic load pull solutions, LXI-certified mechanical impedance tuners, pulsed IV/RF compact transistor modeling as well as coaxial and waveguide VNA calibration kits and metrology adapters, in-stock color-coded precision and daily-use adapters and test-port, phase-stable and value cable assemblies. Visit Maury for details, demos, deals and NPIs.

www.maurymw.com

Teledyne Labtech **Booth 1502**

RF/Microwave PCB Solutions

VENDORVIEW

Teledyne Labtech develops the most complex, demanding RF/microwave printed circuit board (PCB) specialist solutions for military and commercial markets. Drawing from a 30-year pedigree in PCB manufacturing expertise, Teledyne Labtech offers metal-backed RF/MW PCBs, precision single sided and double sided PCBs, multilayer PCBs and more. Labtech's expansive PCB capabilities feature wire bondable surface finishes; embedded component capability; bonded wave guide structures and components; large format capability; and assembly and microwave testing to 40 GHz.

www.teledynemicrowave.com

Teledyne Relays **Booth 1502**

Electromechanical Relay

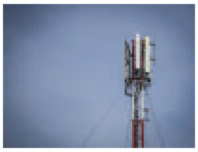
Teledyne Relays introduces the GRF121 electromechanical relay. This magnetic-latching SPDT relay is perfect for broadband, high repeatability, RF and digital applications—where RF performance from DC to 18 GHz or signal integrity up to 40 Gbps is required. This relay is ideal for ATE, semiconductor/IC testing, high-frequency communication and medical imaging devices, RF switch matrices and other applications requiring broadband signal fidelity and high digital throughput. The GRF121 now includes reversed-polarity coil and ungrounded open-contact options for design flexibility.

www.teledynerelays.com

Rogers Corp. **Booth 1548**

94 V-0 Antenna Grade Laminates

VENDORVIEW



RO4730G3™ circuit laminates have been engineered for next-generation wireless PCB antennas, including in 4G and 5G cellular base stations and IoT networks. These low-loss, cost-effective circuit materials are lead-free process compatible and flame retardant. RO4730G3 laminates support broadband antenna designs with excellent PIM performance, outstanding dimensional stability and multilayer board design capability. These thermoset resin/ceramic/woven glass materials expand Rogers' antenna grade product family.

www.rogerscorp.com/acs

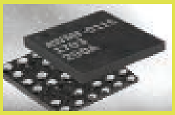
Anokiwave **Booth 1558**

VENDORVIEW

Element Phased Array Innovator Kit

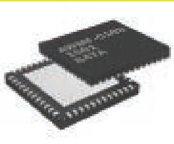
Ready for 5G? The AWMF-0129 is the world's first commercially available electronically scanned active array enabling fast prototyping and evaluation of 28 GHz 5G applications. Based on highly integrated Si ICs with embedded functions for remote telemetry and low-latency steering™, the AWMF-0129 allows for real-time active beam-steering. With 50 dBmi of EIRP and full flexibility for the user in the choice of waveform stimulus and timing-control, the array is an enabling technology for the evaluation and development of 5G networks.

Multi-Function Core ICs



Introducing flexible multi-function silicon ICs for mmW communication and sensing applications. The ICs are for active arrays intended for SATCOM, RADAR and TDD/FDD applications. The devices have switchable outputs and can support half-duplex operation. The AWMF-0117 operates at 10.5 to 16 GHz with +12 dBm Tx P1dB and 4 dB Rx NF. The AWMF-0116 operates at 26 to 30 GHz with +10 dBm Tx P1dB and 5 dB Rx NF. Both ICs feature six bit phase/gain control in a 2.5 mm × 2.5 mm package.

Active Antenna ICs



The world's most advanced active antenna solutions for 5G, RADAR, SATCOM. Anokiwave offers a family of active antenna ICs at X and K/Ka-Bands for 5G, commercial RADAR and SATCOM markets. Supported with expert systems engineering and optimal technology solutions, the company's highly integrated core ICs and system-in-package solutions provide its customers the fastest-time-to-market. Anokiwave's patent-pending IP blocks implemented in silicon technology enable low-cost hybrid beam forming for 5G multi-antenna arrays with high energy efficiency and low latency beam steering™.
www.anokiwave.com

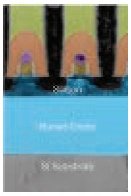
JFW Industries Inc. **Booth 1608**

Rack-Mounted Attenuation Systems for 5G/Millimeter Wave Development and Test

The 50PA-1019-XX 2.9 MM is available with up to 16 attenuators. This new series of Ethernet-controlled RF attenuator systems was specifically developed for testing mmWave and 5G radios in a laboratory environment. A 100 MHz to 40 GHz bandwidth and attenuation from 0 to 62 dB x 1 dB are ideal for receiver testing and network emulation of fixed 5G and mobile 5G wireless network components. A simple ethernet/RS-232 interface and standard 2.9 MM RF connectors make integration simple as well.
www.jfwindustries.com

GLOBALFOUNDRIES **Booth 1632**

45RFSOI Technology

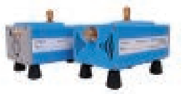


45RFSOI is a future-ready, 45nm RF SOI technology targeted for 5G mobile communications. For improved power handling in next-generation devices operating in the GHz frequency range, 45RFSOI incorporates a high resistivity substrate that maximizes the quality factor for passive devices, reduces parasitic capacitances and minimizes disparity

in phase and voltage swings. 45RFSOI includes RF-centric features and enablement, and supports operation in the 24 to 100 GHz mmWave spectrum bands, 5x more than 4G operating frequencies.
www.globalfoundries.com

OML Inc. **Booth 1640**

WR-05 Signal Generator Frequency Extension Module



The S05MS from OML offers a solution to connect to the RF of your existing signal generator to extend microwave outputs to millimeter and sub-millimeter frequencies of 140 to 220 GHz. With a typical output power of -9 dBm; the S05MS offers options for variable attenuation (S05MS-A) and electronic attenuation (S05MS-EA) which offers up to 60 dB of electronic controlled attenuation. Contact OML for more details.
www.omlinc.com

Modelithics **Booth 1642**

The Modelithics® COMPLETE Library

Modelithics Inc. has released v17, of the COMPLETE Library for Keysight ADS and NI AWR Design Environment. Over 15,000 electronic components are now represented in the library of scalable parasitic advanced simulation models. The Modelithics COMPLETE Library includes passive component and non-linear active device models from 65 of the most popular vendors. Included in version 17 are Modelithics Microwave Supermodels™. A Supermodel is developed by combining all the latest available data into one model that contains the most complete part value range and scalability ranges for all parameters.
www.modelithics.com

SV Microwave **Booth 1702**

High Frequency Coaxial PCB Connectors

SV Microwave offers a complete line of high frequency coaxial PCB connectors that meet the industry need for high-performing, easy-to-use threaded and blindmate/push-on designs. Current configurations include single-port and multiport 2.92 mm, 2.4 mm, SMA, SMP, SMPM and SMPS edge launch, board mount and thru-hole connectors. Additionally, SV now offers a line of pre-tinned coaxial edge mount, surface mount and through hole PCB connectors which eliminate a step during the soldering process. COTS versions are readily available through distribution.
www.svmicrowave.com

Reactel Inc. **Booth 1802**

Filters, Multiplexers and Multifunction Assemblies

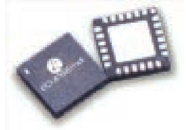
VENDORVIEW

Reactel manufactures a line of filters, multiplexers and multifunction assemblies covering up to 50 GHz. From small, lightweight units suitable for flight to high power units capable of handling 10 kW, connectorized or surface-mount Reactel's talented engineers can design a unit specifically for your application.
www.reactel.com

Eclipse Microwave Products **Booth 1805**

Low Noise Amplifier

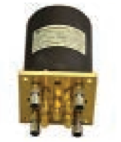
Eclipse Microdevices EMD1715 is a GaAs MMIC PHEMT distributed general purpose low noise amplifier. This LNA has a small signal gain of 14 dB with noise figure less than 1.8 dB at 6 GHz. This device is ideal for applications



that require a typical P1dB output power of +20 dBm up to 12 GHz, while requiring only 103 mA from a +5 V supply. The EMD1715 comes in a small RoHS compliant 4 mm QFN leadless package which has excellent RF and thermal properties.
www.eclipsemicrowave.com

Ducommun **Booth 1819**

RF Coaxial Switch



Ducommun's high reliability Single Pole Four Throw (SP4T) is for space applications. The operating frequency range is from DC to 40 GHz with K connector. Low power input with operating voltage from 22 to 34 VDC (28 VDC nominal) at extreme temperatures of -30°C to +85°C. The SP4T coaxial switch is latching type and equipped with suppression diodes, telemetry circuitry and 50 ohms terminations. They feature multiple output RF transmission lines, robust and compact design and reliability.
www.ducommun.com

RLC Electronics **Booth 1842**

High Power Cavity Bandpass Filters

RLC Electronics manufactures high power cavity bandpass filters for military and commercial applications. These filters exhibit sharp attenuation and low loss. The unit pictured above is a 1280 MHz bandpass filter with 65 dB rejection at 1000 and 1800 MHz. The filter is rated for 400 W cW and 2000 W peak (20% duty cycle) and has low loss (0.3 dB). RLC also offers other high power products such as switches, couplers, power dividers and filters (highpass, bandpass, band reject and lowpass filters, including absorptive designs).
www.rlcelectronics.com

Ulbrich Stainless Steels & Special Metals Inc. **Booth 1849**

Specialty Wire Products

Ulbrich Specialty Wire Group specializes in the production of specialty wire products for various markets, including high performance RF cable applications. These products include custom manufactured helical wrap wire, braid wire and center conductors. Ulbrich's precision controls allow for aspect ratios up to 350:1. Customized mechanical properties enable wrap optimization and variability control. Ulbrich has in-house FFT analysis, as well as in-line statistical process controls that ensure high CPK and PPK values and low standard deviation values. Special alloys available.
www.ulbrich.com

Copper Mountain Technologies **Booth 1940**

Cable and Antenna Analyzer

New R180 1-port VNA (Cable and Antenna Analyzer) from Copper Mountain Technologies is the first 18 GHz 1-port VNA that can connect directly to DUT, improving measurement accuracy by eliminating practical limitation of RF cables. R180 can be controlled and powered through a USB-C port or through an external 5 VDC power supply. Unit delivers high accuracy results in a wide variety of measurement formats including time domain measurement. Frequency range is from 1 MHz to 18 GHz.

www.coppermountaintech.com

IMS PRODUCT SHOWCASE
AISLES 1900-2000

VIDA Products **Booth 1953**

DOMIC VCO

VIDA Products announces DOMIC—Differential Oscillator Ultimate YIG Oscillator featuring performance, broadband sustainability and state of the art low phase noise. Features: Single frequency, YIG-based VCO, center frequency - 10 GHz, minimum RF power: 7 dBm, power - 8 V at 130 mA typ., at 100 KHz to 120 dBc/Hz, at 1 MHz to 140 dBc/Hz and tune - 0 to 10 V = -15 to +15 MHz.

www.VIDAProducts.com

Morion US LLC **Booth 2026**

Ultra-Stable OCXO

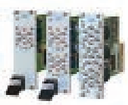
Morion released the MV336, ultra precision OCXO with ultra low short-term stability, phase noise and excellent temperature stability in a 92 mm × 80 mm × 50 mm package. Available with a frequency of 10 MHz, the MV336 has phase noise of < -93 dBc/Hz at 0.1 Hz and -120 dBc/Hz at 1 Hz, short-term stability < 1E-13 at 1 sec and < 3E-13 until 100 sec which is accompanied by temperature stability of < 2E-11 vs. -10°C to +55°C. The MV336 OCXO has 10 MHz SIN output. Works at 12 V.

www.morion-us.com

Pickering Interfaces **Booth 2040**

PXI Microwave Multiplexer Modules

VENDORVIEW



PXI Microwave Multiplexer Modules (40-784A) are from Pickering Interfaces. These multiplexers have a characteristic impedance of 50 Ω and are capable of switching signals up to 40 GHz. Available in single, dual or triple, SP6T or SP4T formats, they are suitable for constructing complex microwave switching networks. These multiplexers are compatible with any PXI chassis and can be used in Pickering's LXI (Ethernet) modular chassis for users preferring control via an Ethernet port. Connection is by a high performance front panel mounted SMA or SMA-2.9 connectors.

www.pickeringtest.com

Mini-Circuits

VENDORVIEW

Ultra-Wideband Coaxial 2-Way 0° Splitter/Combiner

Mini-Circuits' ZN2PD-02183+ is a 2-way 0° ultra-wideband splitter/combiner supporting a wide range of applications from 2 to 18 GHz. This model is capable of handling up to 10 W RF input power as a splitter with 0.5 dB insertion loss, providing excellent signal power transmission from input to output. It delivers nearly equal output signals with 0.05 dB amplitude unbalance and 0.15° phase unbalance, with 20 dB isolation, minimizing interference between channels. The ZN2PD-02183+ comes housed in a rugged, compact aluminum alloy case measuring 1 in × 2.25 in × 0.38 in with SMA-female connectors.

High-Power Surface-Mount Bi-Directional Coupler

Mini-Circuits has expanded its offering of surface-mount couplers with a new series of stripline-based models providing extremely high power handling in a miniature, low-profile printed laminate form factor. New model BDCH-35-272 is a bi-directional coupler which achieves 150 W RF power handling for applications from 700 to 2700 MHz including DAS, transmission signal monitoring, antenna reflection monitoring and more. The coupler measures only 1 in × 0.5 in × 0.051 in and provides 0.2 dB mainline loss, 23 dB return loss and 18 dB directivity. The unit has a wide operating temperature range from -55°C up to +105°C, making it suitable for use near high power componentry where high temperature is common.

90 W, Surface-Mount, 2-Way, 90° Hybrid, 600 to 3900 MHz

Mini-Circuits' QCH-392+ is a high-power, surface-mount 2-way 90° hybrid capable of handling up to 90 W RF input power for applications over a > 2 octave bandwidth from 600 to 3900 MHz. This model provides low insertion loss of 0.6 and 14 dB port-to-port isolation. With 0.8 dB amplitude unbalance and 5° phase unbalance, the hybrid produces nearly equal output signals with 90° phase shift, ideal for I/Q systems, balanced amplifiers, antenna feeds, phase shifters and many more applications. The splitter is designed into a miniature printed laminate measuring only 1 in × 0.5 in × 0.2 in with wraparound terminations for good solderability and easy visual inspection.

Ultra-Thin Coaxial 8-Way 0° Splitter/Combiner

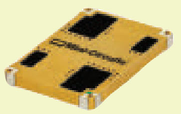
Mini-Circuits' ZN8PD-272SMP+ is a coaxial 8-way 0° splitter/combiner supporting a wide range of applications from 690 to 2750 MHz. This model is capable of handling up to 10 W RF input power as a splitter and provides 0.8 dB insertion loss, 23 dB isolation, 2° phase unbalance, 0.1 dB amplitude unbalance and DC current passing up to 1.4A (175 mA each port). The splitter features blind-mate SMP snap-on connectors and comes housed in an ultra-thin, aluminum alloy package measuring only 6.6 in × 3.28 in × 0.3 in, saving space and allowing easy cable connections in crowded layouts.

Tiny High-Power MMIC SPDT Switch

Mini-Circuits' HSW2-272VHDR+ is a MMIC SPDT reflective switch with an internal driver designed for wideband operation from 30 to 2700 MHz. This model is capable of handling up to 32 W pulsed RF power and 20 W CW power with 0.25 dB typical insertion loss. It provides high linearity with +85 dBm IIP3, minimizing unwanted intermods and 41 μs switching time. The switch is produced using a unique CMOS process on silicon, offering the performance of GaAs with the advantages of conventional CMOS devices. Housed in a tiny 5 mm × 5 mm 32-lead MCLP package HSW2-272VHDR+ provides a high level of ESD protection and excellent repeatability. It operates on a single positive supply voltage with very low current consumption of 120 μA (typical).

High-Power Surface-Mount, Dual-Directional Coupler

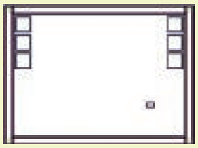
Mini-Circuits' DDCH-50-521+ surface-mount, high-power, dual-directional coupler provides 50 dB coupling on the through path and reflected path with very high power handling up to 300 W for a wide variety of applications from 20 to 520 MHz. This model provides low insertion loss of 0.07 dB, 35 dB return loss and 21 dB directivity. The coupler is designed into an open printed laminate (1 in × 1.5 in × 0.128 in) with wraparound terminations for good solderability and easy visual inspection.



Cavity Filter

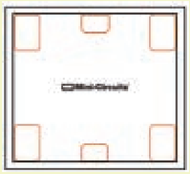
Mini-Circuits' ZVBP-12445HR+ is a bandpass cavity filter with a passband from 2400 to 2490 MHz, supporting a number of applications including satellite earth stations, radar and more. This model provides < 0.6 dB passband insertion loss, 1.1:1 passband VSWR, high rejection with excellent selectivity, reaching 45 dB rejection at 2160 and 2900 MHz. The rugged design can handle up to 10 W RF input power and includes a mechanical feature which prevents accidental detuning that might otherwise require costly replacement or return to factory for re-tuning. It comes housed in a powder-coated aluminum alloy case (2.36 in × 0.79 in × 1.02 in) with SMA-F connectors.

Reflectionless Low Pass Filter Die, DC to 12200 MHz



Mini-Circuits is pleased to offer its revolutionary reflectionless filters in bare die form from stock, allowing customers to integrate the filters directly into their hybrids with minimal space requirements. Mini-Circuits' XLF-123-D+ is a reflectionless high pass filter die with a passband from DC to 12200 MHz and stopband from 18100 to 29000 MHz. The filter provides 1.8 dB passband insertion loss, 1.3:1 passband VSWR, 20 dB stopband rejection and 1.3:1 stopband VSWR. It can handle RF input power up to 2 W in the passband and 50 mW in the stopband. Fabricated using IPD process technology on GaAs, the filter comes housed in a tiny 3 mm × 3 mm QFN package.

Ultra-Wideband Precision Fixed Attenuator Die, DC to 26.5 GHz



Mini-Circuits' YAT-9-D+ is a fixed value, absorptive MMIC attenuator die providing 9 dB attenuation with ±0.6 dB attenuation flatness from DC to 26.5 GHz. A simple modification to the ground plane enables excellent performance all the way up to 40 GHz, supporting requirements for applications in the millimeter wave region such as 5G systems. This model provides RF power handling up to 2 W, and unpackaged die form enables users to integrate the attenuator directly into hybrids where small size and light weight are critical. The die contains through-wafer Cu metallization vias to realize low thermal resistance and very wideband operation. YAT attenuator dice are available from stock with nominal attenuation values from 0 to 10 dB (in 1 dB steps), and 12, 15, 20 and 30 dB.

Wideband, Surface-Mount Limiter

Mini-Circuits' RLM-63-2W+ is a passive PIN diode surface-mount limiter ideal for protecting LNAs and other sensitive receiver circuitry from unwanted high power signals and reducing amplitude variations in IF circuits for satellite receivers and other applications. This model covers a wide range of applications from 30 to 6000 MHz. It provides a wide input power range from +12 to +32 dBm, low output power of +11.5 dBm, 0.4 dB Δ output / 1 dB Δ input (typical), 10 ns recovery time, 0.3 dB insertion loss and 1.2:1 VSWR. It comes housed in a miniature, 6-lead package (0.25 in × 0.31 in × 0.16 in), with wraparound terminations for excellent solderability.

www.minicircuits.com

Reflectionless Filters

Matthew A. Morgan

We all know what a filter does: passes a certain frequency range and attenuates—blocks, ideally—frequencies outside the so-called passband. In RF/microwave systems, where transmission line effects cannot be ignored, the signals outside the passband are usually reflected back from whence they came. If not properly handled, this reflected energy can degrade the performance of the system, often in unexpected ways: spurs, ripple, suck-outs and oscillations.

These challenges provide the motivation for this book. Matthew Morgan wondered why filters cannot be designed to provide a match in the stopband, so the energy is absorbed rather than reflected. Not a filter expert, Morgan surveyed the literature, for others have tried to solve this same problem. He concluded that while the literature does not reflect practical solutions, it is possible to design "reflectionless" filters—networks that present a fixed, real impedance at their inputs, one that matches the characteristic impedance of the system (usually 50 Ω). The challenge is finding the few circuit topologies that meet this criteria.

"Reflectionless Filters" develops the tools needed to identify these "magical" topologies, applying a set of rules—what Morgan terms a "bag of tricks"—that will guarantee the circuit is reflectionless. He accomplishes this in 10 chapters and three appendices, first building a foundation of passive microwave networks and classical absorptive filters before thoroughly developing the concept of reflectionless filters. He concludes the book with applications in up- and down-converters, multiplier chains, broadband amplifiers and analog-to-digital converters. While the book seems steeped in network theory, Morgan says his goal is that the book be accessible to the layman and appealing to "hobbyists."

The author received his M.S. and Ph.D. degrees in electrical engineering from the California Institute of Technology and currently heads the integrated receiver development program at the Central Development Lab of the National Radio Astronomy Observatory in Charlottesville, Va.

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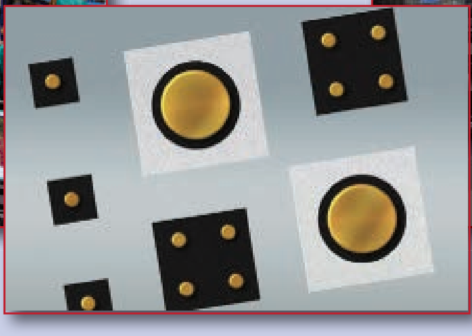
FABS and LABS

From Baker's Ovens to Semiconductor Foundry to Integrated Microwave Assembly



Jim Morgan is an entrepreneur. His persona exudes that passion, a passion that emerged early in life and led him to start a bakery at 18. It was an inauspicious venture, as the business burned cash quickly. With no realistic path to profitability, Jim traded the flour and ovens for a different process. He joined MACOM as an engineering assistant, working with his father and learning about RF diodes. He took to the technology but not to being an employee. After less than two years, Jim convinced his father to leave MACOM and start their own diode company. MicroMetrics grew and prospered over 20 years; then, Jim sold it to Aeroflex. He followed the business to Aeroflex, serving as the chief operating officer, but in two years, the entrepreneurial itch was back.

SemiGen is his second baby — third if you include the bakery. Formed in late 2009, the original mousetrap was RF/microwave assembly focused on performance-driven, high quality and reliability boards and modules. SemiGen's assembly capabilities soon expanded to the analog and digital boards that are adjacent to most RF/microwave assemblies, then to testing, then to design services to supplement their customers' own capabilities. In 2012, SemiGen re-entered the world of RF diodes, now offering PIN, limiter, step recovery, point contact and Schottky diodes.

SemiGen's RF/microwave assembly capabilities are comprehensive, including epoxy and AuSn die attach, wire and ribbon bonding, welding beam lead diodes and winding and attaching coils. They have mastered the process for the eutectic, void-free attachment of GaN devices, and their ability to routinely perform this complex process attracts the leading defense companies. With PCBs, SemiGen can assemble leadless, fine pitch, VGA/BGA and micro BGA surface-mount components, as well as manual through-hole boards. They can test most RF/microwave parameters to 50 GHz, from S-parameters to noise figure and IP3. Quality assurance testing includes X-ray, bond-pull and die shear. Because SemiGen's core market is defense, their business and quality processes meet all ISO 9001 requirements and the relevant military standards, including ITAR registration.

Recognizing that customers do not always have the engineering capacity to handle their design backlogs, SemiGen partnered with the area's top RF consultants to offer module, circuit board and mechanical packaging design services. The design team can support a customer throughout the product development cycle: defining the spec, designing components and multi-function modules, writing automatic test equipment software.

To support their rapid growth, SemiGen is expanding to fully occupy their 25,000 square foot building in Manchester, N. H. The expansion includes building more clean room to support the demand for manufacturing capacity. Growth also requires a larger team. Jim believes SemiGen is defined by its people and invests in their development—training, providing opportunities to learn new skills and promoting from within. SemiGen is one of the corporate partners of a microelectronics training program at a local community college—an unusual commitment for a small company—and hired the first graduate. This approach requires a long-term view, yet it develops talent and builds loyalty in a tight labor market.

Jim's vision for SemiGen is supporting customers with a full-service microwave solution. Support means excelling in service, taking responsibility, never getting comfortable and openly working through the mistakes that can happen when addressing the challenging performance and quality demands placed on the RF/microwave industry. Jim's mother worked as a waitress for many years, and he echoes her words when he describes his business philosophy: "The customer is always right."

www.semigen.net

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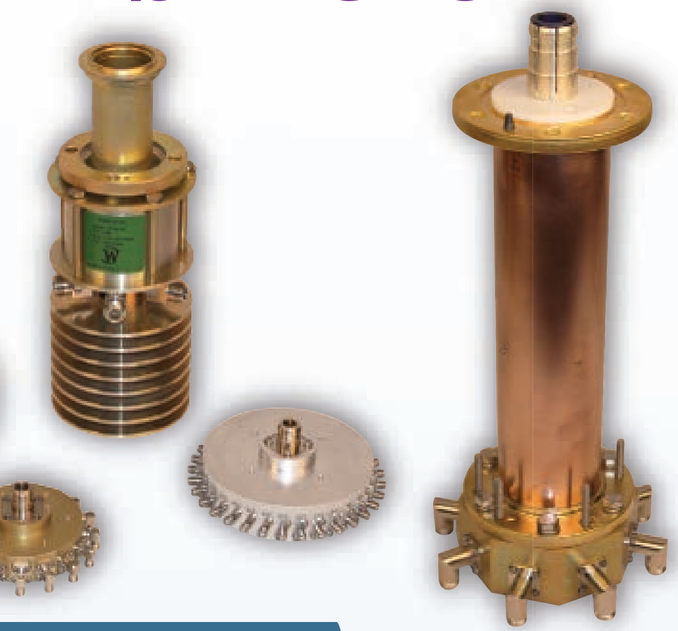

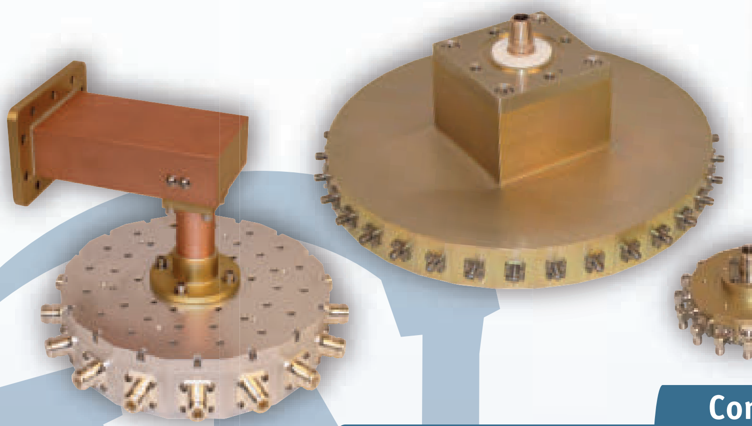

Combiners / Dividers

Model	Type	Frequency (MHz)	Power (W CW)	Insertion Loss (dB)	VSWR	Connectors (Sum Port, Inputs/Outputs)
D8182	5-Way	1175-1375	1,500	0.4	1.35:1	1 5/8″ EIA, N Female
D8454	8-Way	370-450	10,000	0.25	1.30:1	3 1/8″ EIA, N Female
D9710	8-Way	1000-2500	2,000	0.3	1.40:1	1 5/8″ EIA, N Female
D9529	8-Way	2305-2360	1,000	0.2	1.15:1	7/16 Female, N Female
D9528	8-Way	2305-2360	2,000	0.2	1.15:1	7/8″ EIA, N Female
D5320	12-Way	470-860	500	0.3	1.30:1	All N Female
D9194	16-Way	2305-2360	1,000	0.2	1.15:1	7/16 Female, SMA Female
D9527	16-Way	2305-2360	2,000	0.2	1.15:1	7/8″ EIA, N Female
D9706	16-Way	2700-3500	6,000	0.35	1.35:1	Waveguide, N Female
D6857	32-Way	1200-1400	4,000	0.5	1.35:1	1 5/8″ EIA, TNC Female

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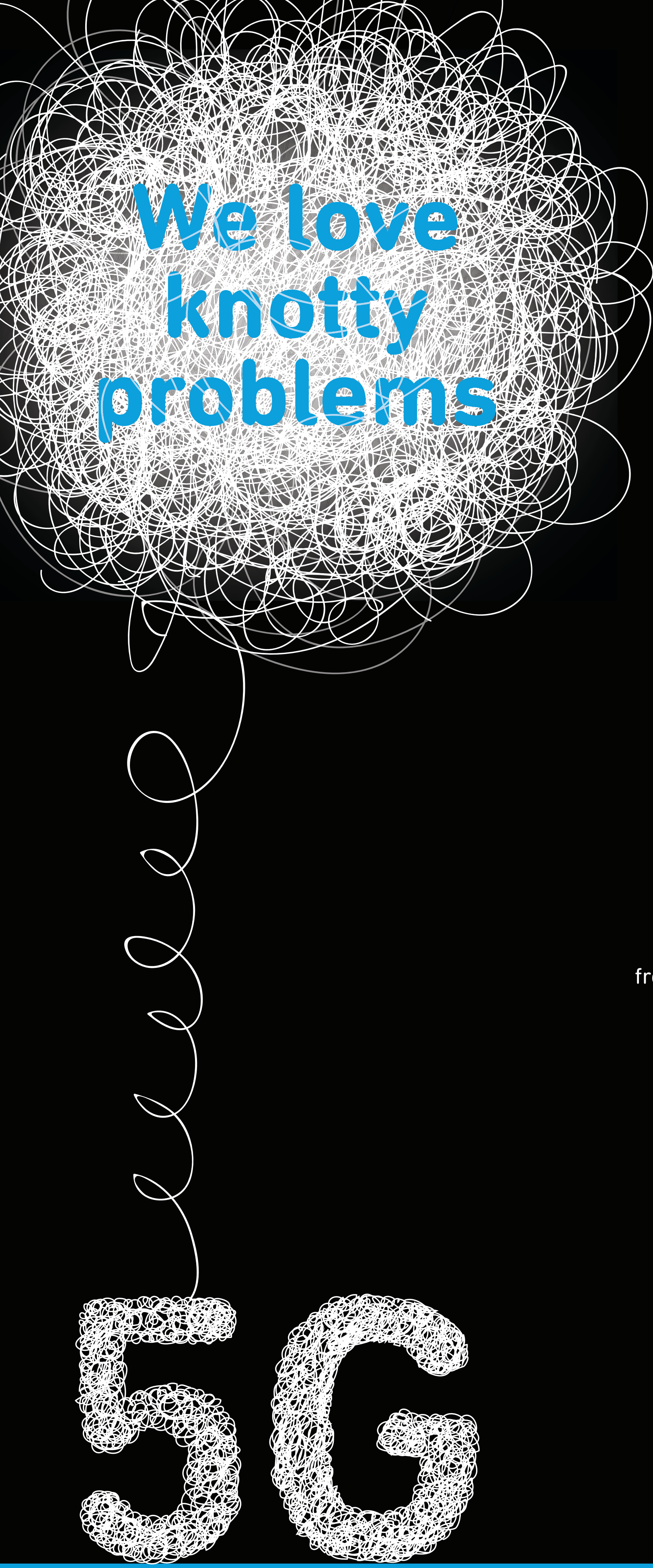
all around you

Defining What's Possible

The Path to 5G


We love knotty problems
5G

5G: The Future of RF

Beyond Smartphones to Smart Everything

At Qorvo, we aim to improve lives, solve problems and simplify. We help customers at the center of communication - building solutions that meet the growing demands of a connected world. We're helping shape the global 5G standard as a platform for a new era of connectivity. We deliver core RF technologies and innovative products that will enable 5G end to end, from wireless infrastructure to mobile devices. Partnering with customers, carriers and standards bodies, we'll bring the vision to life.

What 5G Is

5G is massively broadband reaching into frequencies never previously thought of for mobile wireless - above 3.4 GHz, and even to 30 GHz and beyond.

5G is ultra efficient for streaming data, taking full advantage of carrier aggregation and massive MIMO.

5G is fixed wireless giving more choices to get 1 Gb/s connections to your home and business.

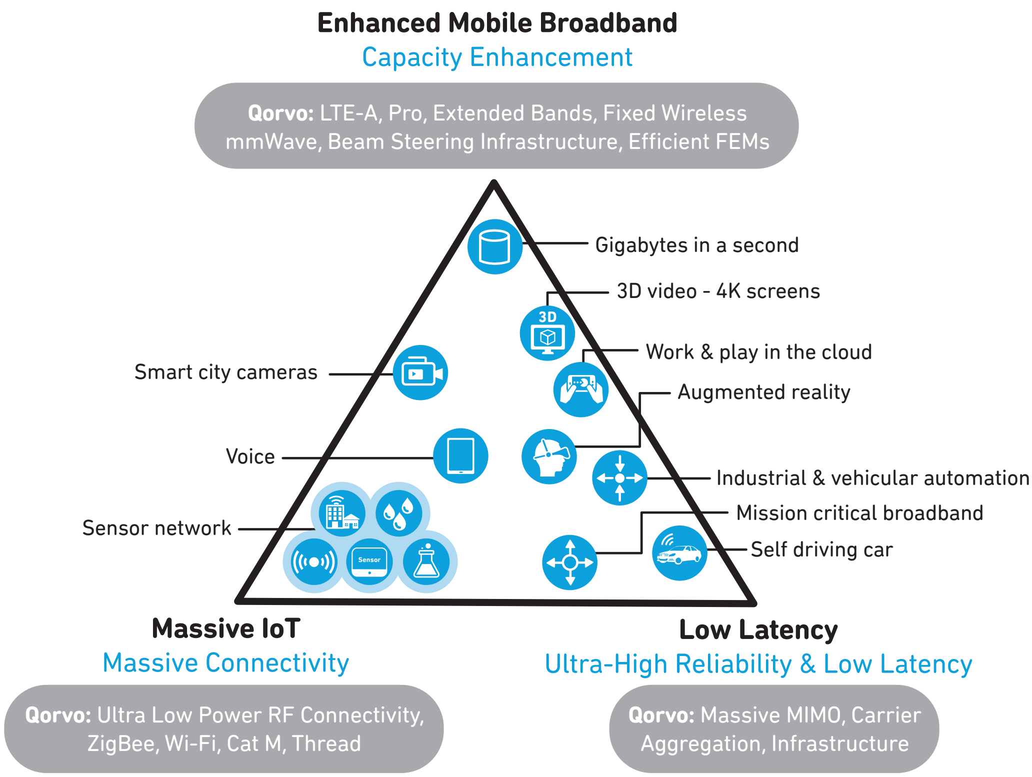
5G is wireless infrastructure using beam steering and high-power GaN, based on the technologies in phased-array antennas for defense.

5G is low-latency for real-time connections enabling autonomous vehicles and augmented/virtual reality.

5G is the backbone of the Internet of Things connecting more than a trillion devices to the internet in the next 10 years.

Connecting the Uses of 5G

Qorvo connects RF for all 5G use cases - more than just cellular and Wi-Fi.



(Source: Qorvo, Inc., from ITU-R IMT 2020 requirements)

Gallium Nitride (GaN): A Critical Technology for 5G

By David Schnaufer and Bror Peterson, Qorvo

Introduction

Carrier providers talk a lot about how their individual networks provide higher capacity, lower latency, and ubiquitous connectivity. And, while today's networks certainly are better than previous generations, providers still have much to accomplish when it comes to the promises of 5G - less than 1 ms latency, 100x network energy efficiency, 20 Gbps peak data rates, and 10 Mps/m^2 area traffic capacity. Scheduled for commercial launch in 2020, 5G is expected to offer all of these significant advantages, including a more 'green' and efficient communication network.

GaN's Superior Properties

In our last quarterly article, we discussed ways in which the telecom industry is focused on energy efficiency for 'green' communications. We explored how MIMO, beamforming, and small cells increase efficiency, making a telecom network that's more environmentally friendly overall. We also highlighted how much of the network energy consumption comes from the RF chain.

So, how do we achieve the RF chain 5G objectives and meet 'green' network goals?

Enter RF GaN - an efficient, wide-bandgap, reliable PA technology making year-over-year strides toward network efficiency. As displayed in the graph below, the introduction of GaN in the base transceiver station (BTS) ecosystem provides a sharp increase in front-end efficiency, making it a new go-to technology for both high- and low-power applications.

GaN offers superior properties of high power density, power added efficiency (PAE), gain, and ease in impedance matching, which improves overall efficiency in the RF chain. Like designers of Formula One race cars, wireless engineers meticulously tweak and tune their RF systems to extract every ounce of performance. By starting with a fundamentally better semiconductor technology, performance targets can be achieved at vastly improved energy efficiency.

Doherty Power Amp Efficiency at 8dB of Back Off

The entrance of GaN in the base station market space increases efficiency. This translates to a large savings of Watts and energy.

5G and GaN

The build-out of 4G LTE networks is maturing, but there are many upgrades that will bridge the gap to 5G. We currently are in the 5G definition and proof-of-concept phase, but companies like Verizon are accelerating the timetable for early deployments focused on fixed-wireless access.

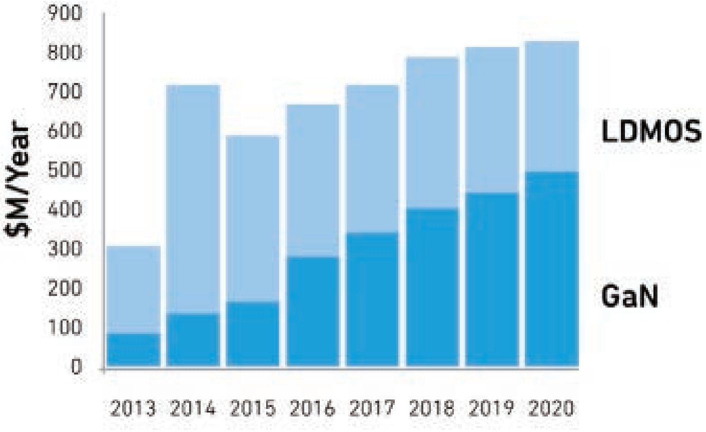
Early 5G trials began in 2013, and data from these and more recent experiments are now frequently published.

Key technologies offering promising results in millimeter wave (mmWave), massive MIMO antenna arrays, and beamforming are already in pre-commercial development. All of the base station OEMs are in the product trial mode. Companies like Qualcomm and Intel are testing 5G-enabled modems, such as the X50 modem, which works in the 28 GHz band. Qorvo and NanoSemi have published demonstration data on ultra-wide linearization of GaN devices for massive MIMO applications.

These forward-looking companies are dialing in major 5G system architectures, frequency bands, and enabling technologies to find the proper balance of cost, performance, and complexity.

To meet the diverse set of 5G requirements, GaN manufacturers need to offer several variations that span a broad range of frequencies and power levels.

GaN is Heavily Used in Base Stations

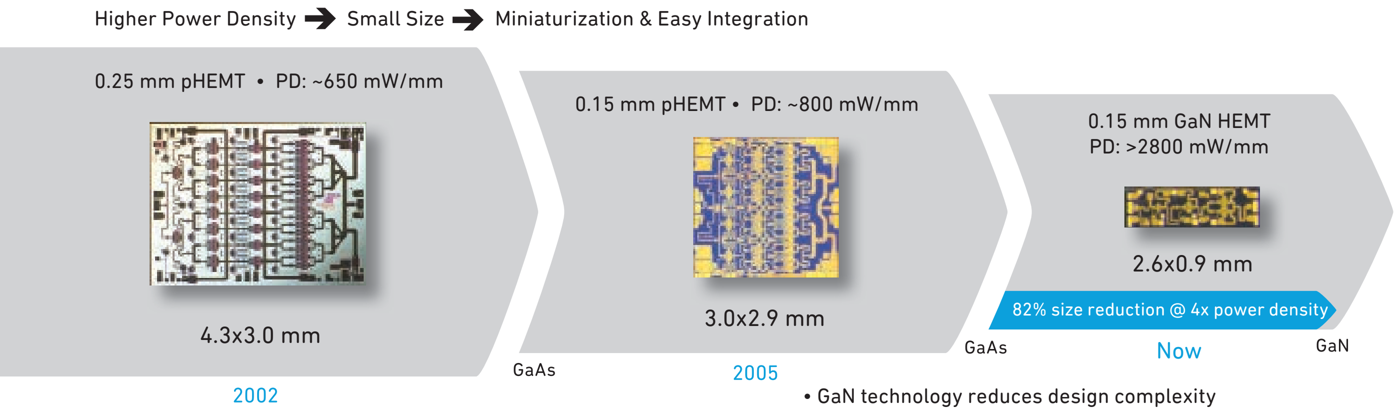


Source: Compound Semiconductor

With more than one GaN process to choose from, a designer can optimally match a GaN technology to an application. The graph below examines Qorvo's capabilities in this realm.

The incentives of untapped spectrum, high throughput, and low latency goals are enticing developers to migrate toward higher mmWave frequency bands. The mmWave spectrum bands provide 10-30 times the bandwidth of current 4G frequency bands (<4 GHz), and network capacity is directly proportional to the available bandwidth.

GaN Enabling Monolithic Front-End Solution for 5G



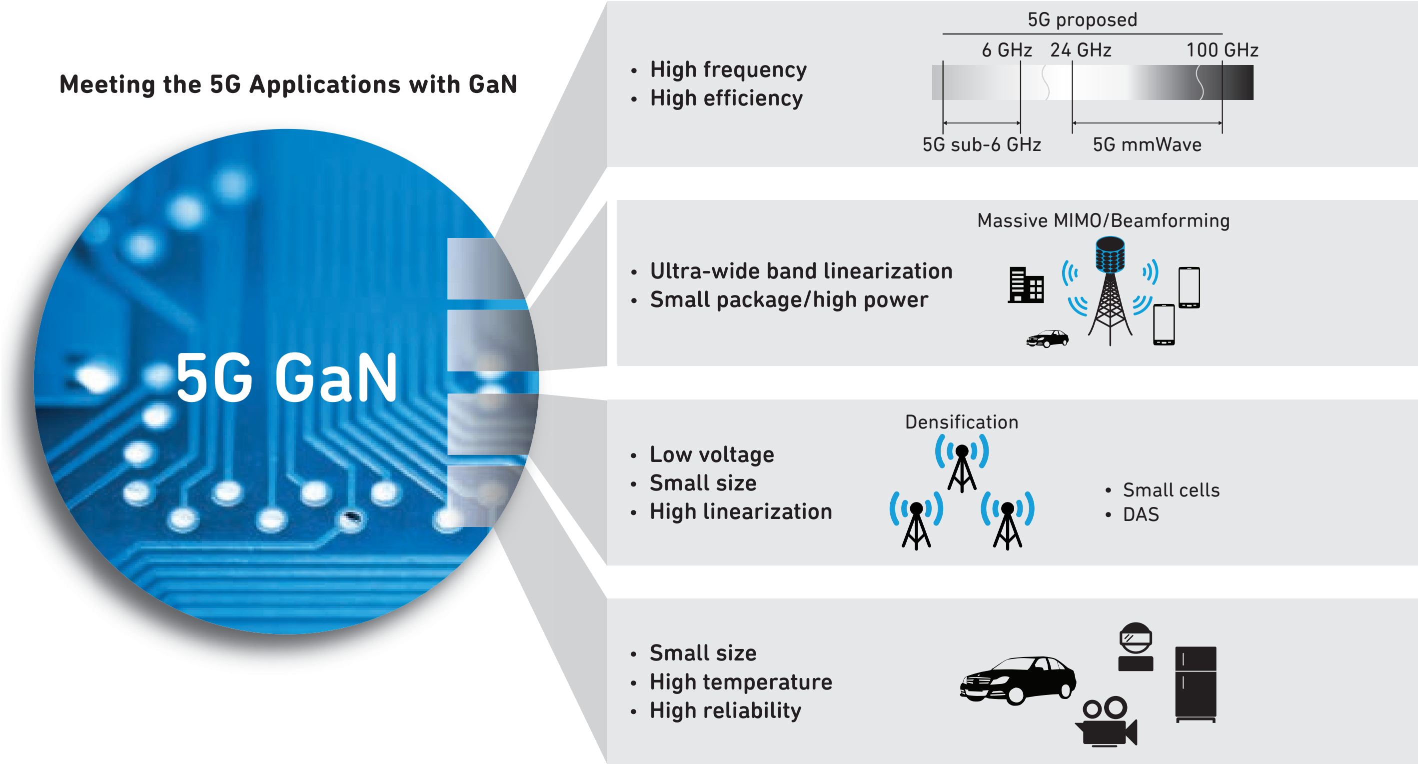
- GaN technology reduces design complexity
- Essential for success of high-frequency commercial markets

GaN is well suited for both the high frequency and the wide bandwidth required in the mmWave arena. It can fulfill the performance and small size requirements, as illustrated above. Applications using mmWave frequency bands will require highly directional beamforming technology (beamforming focuses the radio signal into a highly directive beam, which boosts power and minimizes interference at the user device). This means that the RF subsystems will require a large number of active elements driving a relatively compact aperture. GaN is ideally suited for these applications, since powerful performance in a small package size is one of its most notable traits.

When 5G comes to fruition in 2020, we will all find out what capabilities and advantages follow. Today, the trials, initiatives, discussions, and demonstrations continue to aid in defining the 5G standard. But tomorrow, the reality of ubiquitous, sub-1-ms latency and extremely high capacities will be in our everyday lives. Whatever the outcome, it is apparent that GaN will be a critical technology in 5G applications.

GaN: Not Just for Defense Anymore

By Scott Vasquez, Senior Market Strategy Leader, Qorvo



Introduction

Once considered a technology solely for defense programs like electronic warfare (EW) and jammers, gallium nitride's advantages are becoming increasingly cost-effective and critical for commercial applications.

This is particularly true for telecom networks and the ever-increasing demands to deliver more data, faster, and to more places.

GaN is a III/V direct bandgap semiconductor commonly used in RF amplifiers, switches, low noise amplifiers, and power electronics. GaN has become the technology of choice for high-RF power applications that require the transmission of signals over long distances such as EW, radar, base stations, satellite communications, and more.

GaN on silicon carbide (SiC) has many advantages including increased power density, efficiency, and improved thermal properties that enable higher reliability and operating temperature. But until recently, GaN was out of reach for most outside the government and defense sphere.

Plastic Packaging

Device packaging technology has been a key factor in helping bring GaN costs in line with market volumes over the last few years. Making high-power GaN MMIC power amplifiers available in small, lightweight plastic packages improves the size, weight, and power (SWaP) performance for a range of commercial applications - optimizing system performance at a competitive price point. HAST compliance of GaN die makes plastic packaging practical.

In broadband cable, GaN is already being used in DOCSIS 3.1 upgrades. Multi-system operators (MSOs) can leverage GaN packaging and integration innovations to upgrade equipment within existing product footprints, saving installation time and cost while enhancing performance.

But GaN with advanced packaging technologies is also being deployed in commercial wireless infrastructure applications, such as small cell and cellular base stations. And it appears GaN is poised to be a critical technology for 5G and next-generation mobile.

Positioned to Deliver All Elements to Fully Address 5G RF

Scheduled for commercial launch in 2020, 5G is expected to offer significant advantages, including higher capacity and efficiency, lower latency, and ubiquitous connectivity. In telecom networks, much of the network energy consumption comes from the RF chain. GaN's superior properties of high power density, power added efficiency (PAE), gain and ease in impedance-matching improve overall efficiency in the RF chain.

Must Address All Bands	Must Have Carrier Aggregation, Higher Modulation, Massive MIMO	Must Be Engaged With Standards	Must Have Infrastructure
Only Qorvo covers low, mid and high bands with complete solutions	Only Qorvo has filters, high-efficiency PAs, multiplexers and high-performance antenna switching	Qorvo is active in 3GPP and China Mobile 5G Center of Innovation defining standards	Only Qorvo combines experience in defense and mobile for GaN power and beam steering needed for wireless infrastructure

RF complexity is only increasing - Qorvo is the smart partner

Handsets

Smartphones and phablets are already the hub of our connected lives, indispensable as a means of consuming enhanced entertainment and connecting us with mobile services and managing our smart homes from afar. That means mobile devices will have to handle more RF bands in the same or smaller space with greater range, reliable connectivity, and better battery life - and without getting hot in our hands.

GaN inherently has higher efficiencies than other competing technologies, thus resulting in a reduction in system power consumption. Maximizing the reduction in power consumption decreases thermal management challenges which could ultimately lead to improved battery life and overall device performance of user equipment such as smartphones or phablets.

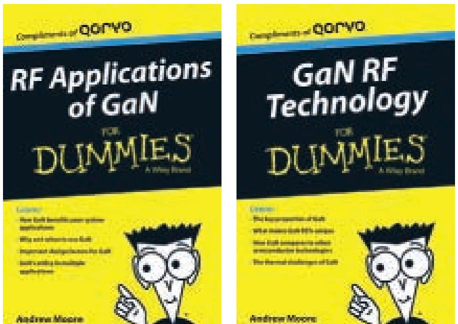
Other 5G Applications

Besides operating in high-temperature environments, GaN is well-suited for many different applications, from passively-cooled, all-outdoor tower-top base station electronics, to automobile applications, to cable boxes. Having a wide array of GaN technology choices will mean more applications being serviced throughout the world.

The superior performance of GaN is driving its adoption in base stations. Strategy Analytics currently forecasts cellular infrastructure as the largest commercial segment for GaN in the next four years. And now, 5G is poised to continue the spread of GaN into commercial communications systems.

GaN e-Books

Available for download at
www.qorvo.com/gan-for-dummies



Small Cells Help Keep 5G Connected

By Tuan Nguyen, Product Line Director of Wireless Infrastructure, Qorvo

Key to the success of small cells, which boost quality of service in wireless networks, is their high-frequency components that draw upon a number of different technologies.

As more users tap into wireless communications services, the demand on wireless network capacity intensifies in both indoor and outdoor locations. Such network density or densification further pressures wireless carriers to keep pace with the increased consumption of frequency bandwidth via voice, video, and data. It also drives those carriers to expand their cellular/wireless infrastructure with minimum increases in cost or disruption of service to wireless customers. Thus, many are turning to small cells as a solution.

The rollout of 5G wireless networks will address demands for increased capacity and data, but these networks are still some years away. So, a more practical answer that's in keeping with today's 4G wireless networks is to use small cells, which function as miniature base stations that are added to an existing wireless network. They operate at relatively low power levels to fill any 'holes' that exist in wireless coverage, in both indoor and outdoor locations.

As an example of the magnitude of growing wireless user demands, fans attending the National Football League's (NFL) 2016 Super Bowl championship game in Santa Clara, Calif., used more than 7 TB of data on the Verizon Wireless network alone - nearly three times as much data used at the 2015 Super Bowl game. Fans connected to the network via smartphones and many other unique wireless devices. They benefited from the generous capacity provided by 4G Long Term Evolution (LTE) technology bolstered by the use of small cells, macrocells, and mobile cell sites (as reported by Verizon Wireless in a press release dated February 8, 2016).

Small Cells + DAS Solutions

Small cells and distributed antenna systems (DAS) are being employed (Fig. 1) to achieve increased data capacity in 5G wireless networks while enhancing quality of service (QoS) in those networks. But with densification comes interference and mobility handover challenges between small cells and the macro network, requiring careful network design and management.

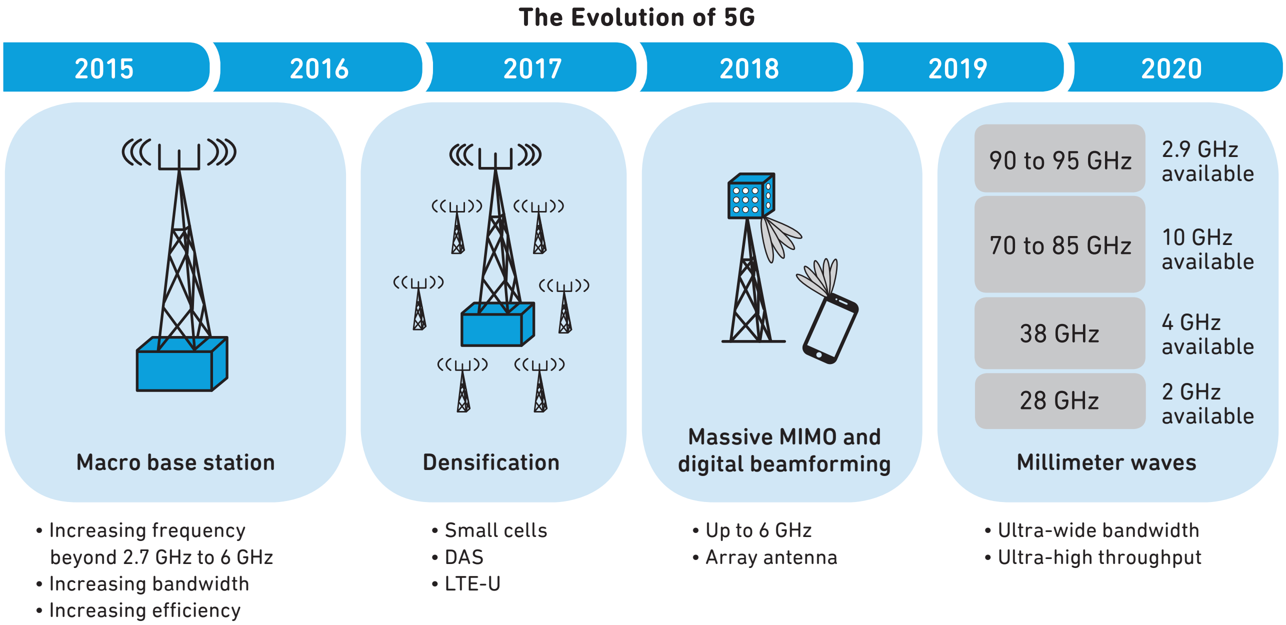


Figure 1. A number of technologies will be required to optimize performance in 5G wireless networks, including distributed antenna systems (DAS), millimeter-wave technology, and small cell base stations.

As mobile communications devices move from a macrocell environment to a small cell coverage area, the network will instantaneously switch profiles. The relatively low power levels of small cells allow mobile devices to be in close proximity to those small cells. They are able to gain network access while conserving battery life, and they needn't establish radio communications links with more distant larger cell sites at transmission levels diminished by distance. Mobile-device users will benefit from increased data speeds, mobility, and flexibility, too, since small cells and DAS solutions support multiple standards, such as third-generation (3G) and 4G cellular, and implement carrier aggregation with LTE Advanced (LTE-A) systems.

Antenna technologies such as multiple-user multiple-input, multiple-output (MIMO) approaches, beam steering, and phased-array techniques help provide additional wireless coverage and interoperability of multiple-band 3G and 4G systems. With massive MIMO methods, wireless network operators can increase data rates and network capacity by transmitting multiple, spatially separated data streams over the same frequency band, using multiple antennas on the base station and the user's device.

Massive MIMO base stations seek to provide from 16 to 256 channels, challenging designers of those base stations to target smaller component sizes with high energy efficiency and effective thermal management. Therefore, highly power-efficient semiconductor technologies become attractive for such base stations.

Table 1: Sizing up Small Cells

Cell Type	Output Power (W)	Cell Radius (km)	Users	Locations
Femtocell	0.001 to 0.25	0.010 to 0.1	1 to 30	Indoor
Picocell	0.25 to 1	0.1 to 0.2	30 to 100	Indoor/Outdoor
Microcell	1 to 10	0.2 to 2.0	100 to 2000	Indoor/Outdoor
Macrocell	10 to >50	8 to 30	>2000	Outdoor

High levels of semiconductor integration are also instrumental in achieving the high channel counts in these relatively small-sized base stations. Squeezing as many as 256 transmit channels into a single base station requires subsystems that package power amplifiers (PAs), low-noise amplifiers (LNAs), and switches into compact modules, and employing small-form-factor filter solutions.

Technology Potpourri

As Table 1 shows, small cells differ in output power levels, coverage areas, and number of users served. For the best performance and power efficiency, the subsystems used in small cell base stations must combine components based on different process technologies. For example, PAs may provide suitable output power and power efficiency.

Filters could require yet a third technology, especially for operating conditions that may experience extremes of temperature and humidity. Temperature-stable bulk-acoustic-wave (BAW) LowDrift™ filters from Qorvo provide a solution for filtering high-power signals while also avoiding interference from adjacent frequency bands.

Table 2: PAs for Small Cell Base Stations

PA Model	Frequency Range (MHz)	Average Output Power (dBm)
TQP9218	1805 to 1880	+24
TQP9418	1805 to 1880	+27
QPA9219	1930 to 2000	+24
QPA9419	1930 to 2000	+27
TQP9221	2010 to 2170	+24
TQP9421	2010 to 2170	+27
TQP9224	2300 to 2400	+24
TQP9424	2300 to 2400	+27

In addition to the various components required for wireless infrastructure designs, including filters, switches, and LNAs, Qorvo developed a line of highly integrated PAs for small cell base stations. The PAs do not require linearization, and feature on-chip bias control and temperature-compensation circuitry to further simplify the design of a small cell base station. They are available with +24 or +27 dBm average linear output power when driving a 20 MHz wide LTE signal (Table 2). The PAs also incorporate two stages of amplifier gain in low-cost surface mount technology (SMT) packages.

For example, model TQP9218 is a 0.25 W (+24 dBm) PA designed for small cell base stations operating from 1805 to 1880 MHz. It offers 31 dB small signal gain across its frequency range with internal impedance matching, on-chip bias control circuitry, and temperature-compensation circuitry - all packed into a 7×7 mm RoHS-compliant SMT housing. The PA achieves 16% power-added efficiency (PAE) and draws just 240 mA quiescent current from a +4.5 V dc supply.

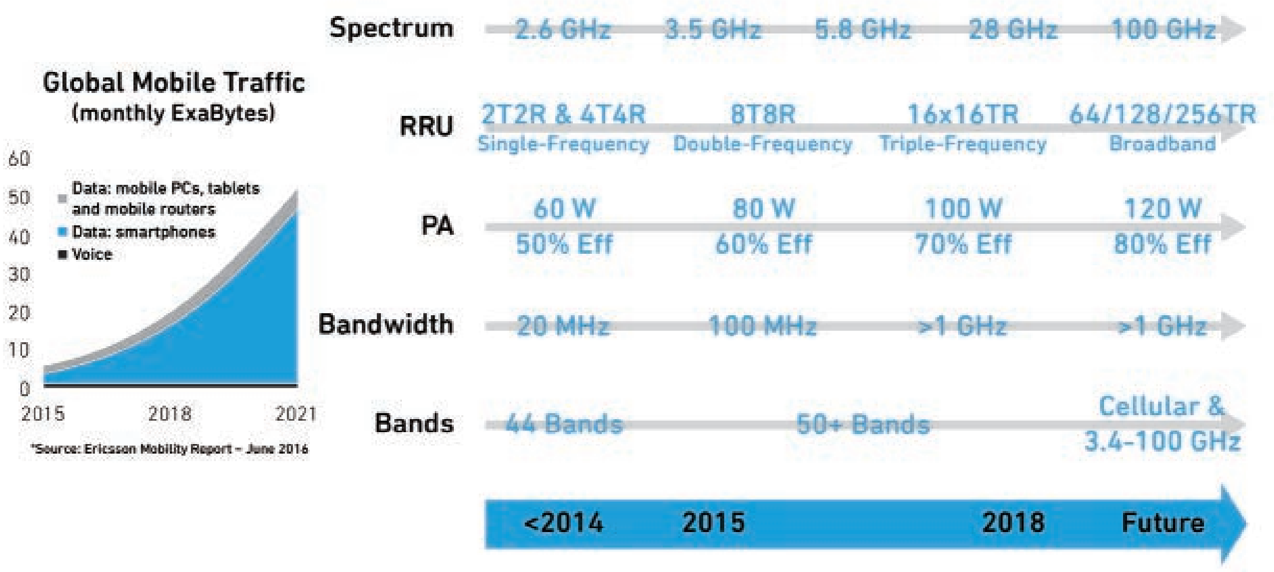
Enabling 5G with GaN Technology: Setting the Table for Success

By Dr. Doug Reep, Retired Senior Director of Research, Qorvo

At Qorvo, we're closely tracking the emerging 5G standard. One thing that's particularly exciting is the likelihood that 5G includes mmWave functionality for high data-bandwidth connections. As PC board space becomes more limited and as frequencies increase in the 5G environment, GaN technology becomes even more appealing for RF applications.

The Path Toward 5G

Compared to GaAs, silicon or other traditional semiconductor materials, GaN will really start to shine in 5G network applications, such as high-frequency and size-constrained small cells. As shown in the figure below, wireless network enhancements will drive many technology advancements as the standard evolves toward 5G.



Ultimately, when we get to the emerging mmWave standards, GaN will have a clear advantage over today's technologies. GaN offers higher power density, which brings several benefits:

- Size reduction
- Lower current consumption
- Higher system efficiencies

We already see the benefits of GaN in the 4G base station arena, where GaN has begun displacing silicon LDMOS. For 5G, GaN's ability to work in the high-frequency range allows it to evolve from base stations to small cell applications and, ultimately, into mobile devices.

Going Beyond Infrastructure: Moving GaN into Mobile Handsets

The first GaN applications were developed for high-power military use such as radar or counter-IED jammers, eventually moving into commercial base stations and cable TV repeaters. Typical operating voltages for these applications range between 28 and 48 volts.

In handheld devices, however, the average voltage range is 2.7 to 5 volts. To operate GaN at these low voltage levels, we will need to work on a different class of device. We've already started to look at GaN devices in alternative materials, in order to operate efficiently at low voltage.

GaN Developments for 5G at Qorvo

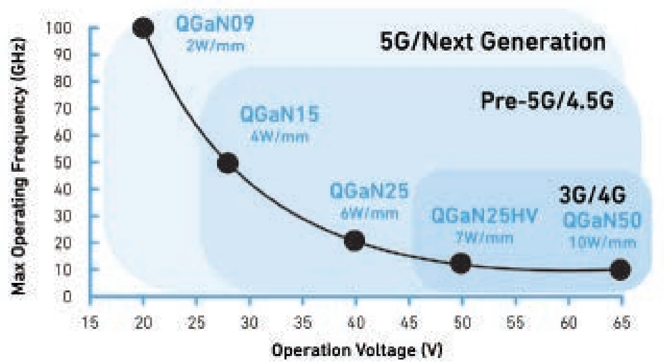
As shown in the figure below, Qorvo currently has a broad range of production-released GaN foundry processes used to enable products for 5G applications:

- Higher voltages, lower frequencies: As we move lower in frequency, we bring into play our 0.25 µm high voltage technology, or QGaN25HV. This QGaN25HV allows us to move to 48 volts with a 0.25 µm device, with high gain and power efficiency. QGaN25HV is well suited for 5G base stations as they move toward 6 GHz. At the lower 4G frequencies, between L- and S-band, our highest power density 0.5 µm technology works up to 10 watts per millimeter.

- High-frequency applications: Our current GaN process portfolio includes 0.15 µm, or 150 nanometer, technology for higher frequencies. Our 0.25 µm technology is well suited for applications ranging from X- through Ku-band. This 0.25 µm technology also offers highly efficient power amplifier functions.

But what about GaN processes for mobile 5G handsets? As we see the higher frequency standards emerge (Ka-band or mmWave), low-voltage GaN processes will require further development.

Qorvo GaN Technology Roadmap



Addressing Packaging and Thermal Challenges of GaN and 5G

One last piece of the puzzle to enable GaN for 5G involves advanced packaging techniques and thermal management. GaN devices for highly reliable military applications have traditionally been available in ceramic or metallic packages; however, commercial 5G network infrastructure and mobile handsets will require smaller, lower-cost, plastic overmold packaging to compete with incumbent silicon LDMOS or GaAs devices in plastic packages. Similarly, mobile handsets will focus on low-cost modules that include GaN mixed with other technologies, analogous to today's products - but they'll also need highly compact, highly efficient mmWave materials and devices.

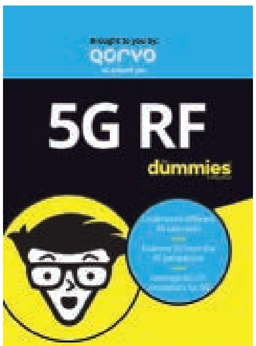
The challenge for infrastructure will be developing packages that maintain RF performance while addressing thermal management. GaN's higher power densities - from 3 to 5 and as much as 10 times higher than GaAs - present a very tough thermal and mechanical problem to the subsystem package designer.

Our engineers always balance three requirements: RF performance, thermal management, and low cost. Qorvo has plastic overmold packages with enhanced thermal management capabilities for GaN, including thermal spreaders built into the bases of the package.

Our products in plastic packages also meet stringent environmental standards, such as JEDEC standards for temperature, humidity and bias compliance. This gives our customers assurance that our products will have long-term reliability for their 5G applications - whether high frequency, high power or low voltage.

Looking to the Future

Although 5G is still several years away, Qorvo is already working to develop the process technology and packaging techniques to enable our customers' 5G applications. GaN is sure to play a key, exciting role in the 5G landscape.



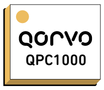
5G: A Future Technology Standard Qorvo is Enabling

Just as we did for 2G, 3G and 4G, Qorvo is collaborating with industry leaders and partnering on research efforts that will create the new 5G standard. Check out the below press releases at **qorvo.com/news** that show how we're building a new connected world through integration, technology and partnerships.

03/01/2017	Qorvo Delivers Highly Integrated Solution for Pre-5G Massive MIMO Networks
02/27/2017	Qorvo Accelerates Race to 5G with Industry's First 5G Front End
01/26/2017	Qorvo Joins China Mobile 5G Innovation Center
07/19/2016	Qorvo Powers 5G Field Trials with Industry-Leading Infrastructure Solutions
02/22/2016	Qorvo Joins 3GPP to Promote Development of 5G Standard

Qorvo 5G Product Highlights

QPF4005
Integrates 2 Multi-Function GaN MMICs
- Frequency range: 38.6-40 GHz
- Package dimensions: 6x6 mm



QPC1000
5-Bit Digital Phase Shifter & SPDT
- Frequency Range: 29-31 GHz
- Package Dimensions: 6x5 mm

TGA4030-SM
Medium Power Amplifier & Multiplier
- Frequency Range: 17-37 GHz
- Package Dimensions: 3x3 mm

TGA2594-HM
Packaged Power Amplifier
- Frequency Range: 27-31 GHz
- Package Dimensions: 7x7 mm

QPB9318
Highly Integrated Front-End Module
- Frequency Range: 2.3-2.7 GHz
- Package Dimensions: 5x5 mm

QPB9319
Highly Integrated Front-End Module
- Frequency Range: 1.8-4.2 GHz
- Package Dimensions: 7x7 mm

QPL9503
Flat-Gain, High-Linearity, Ultra-Low Noise Amplifier
- Frequency range: 0.6-6 GHz
- Package dimensions: 2x2 mm

Visit **www.qorvo.com/5G** for our latest products.

At Qorvo, what we do matters. Developing solutions today, for a better, more connected tomorrow.

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