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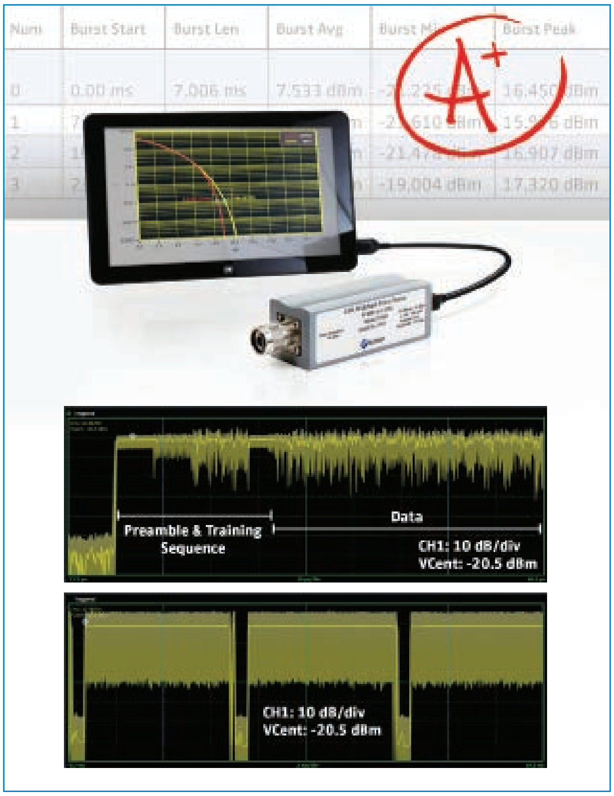

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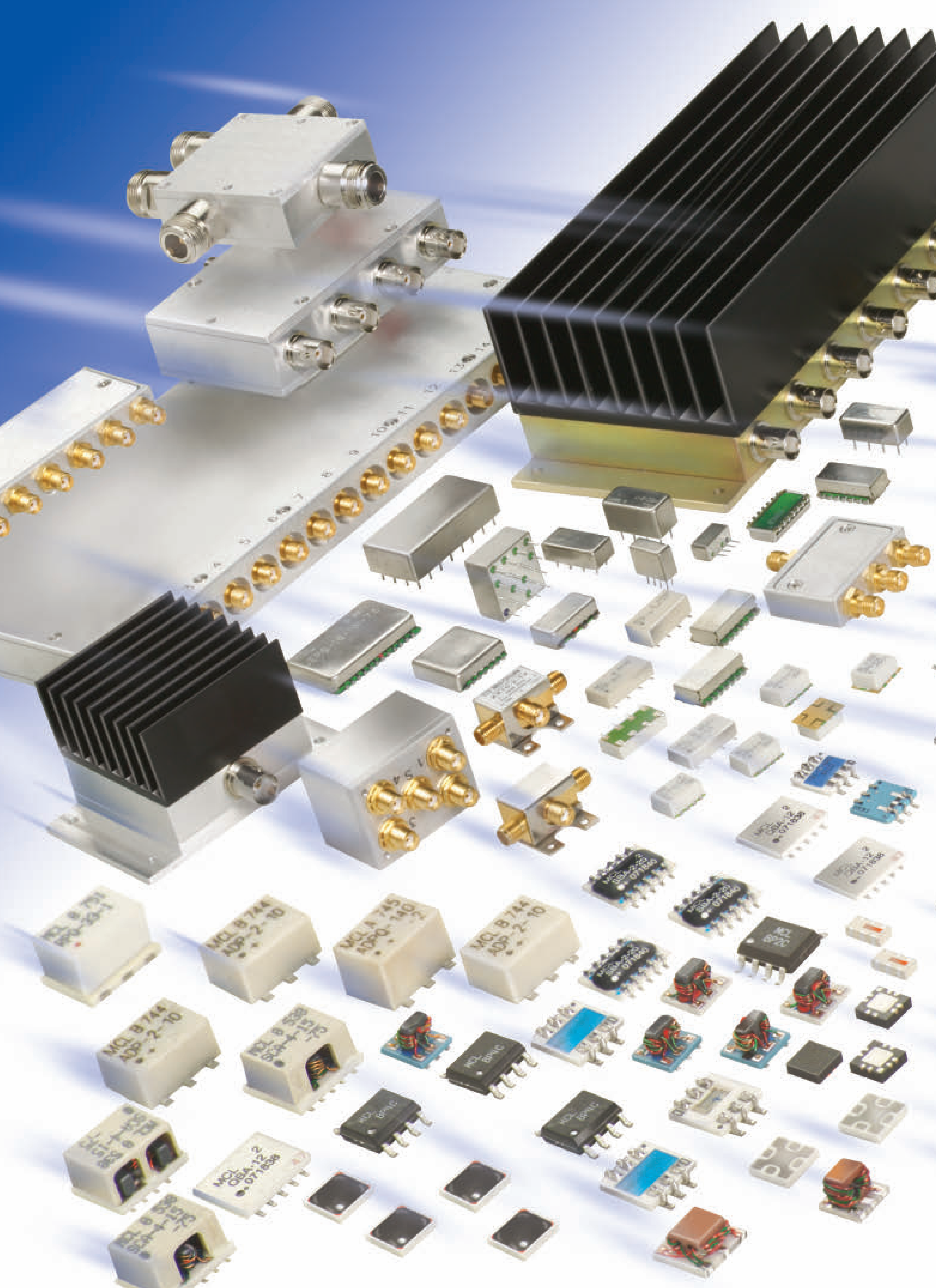
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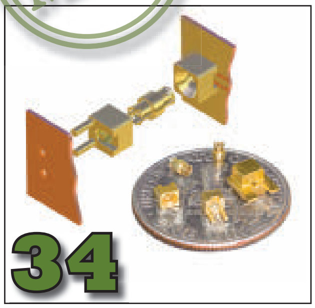

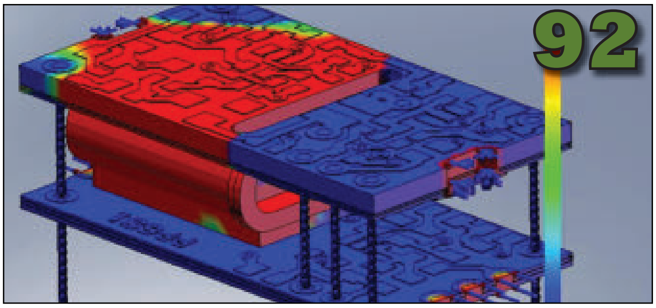

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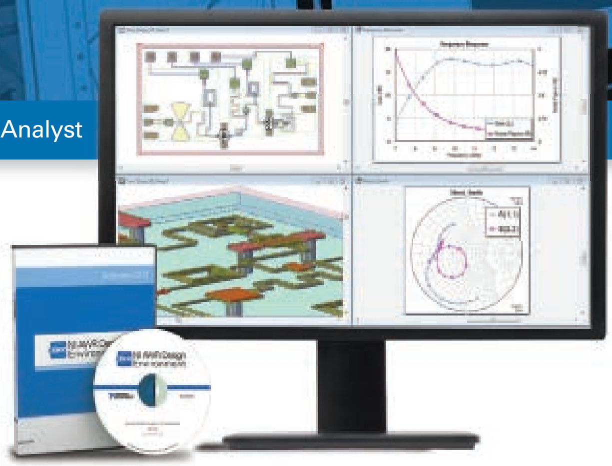

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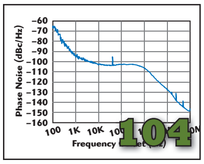

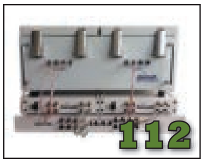

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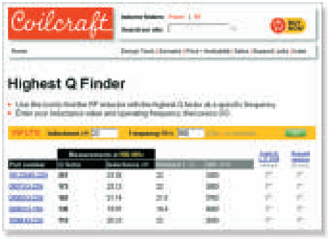

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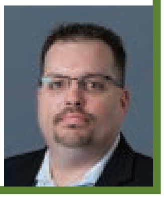
Jeff Waters, the new president and CEO of **Isola Group**, shares his view of the industry, the strengths he has found at Isola and the company's strategy.



Benjamin Culver, president of **Southwest Antennas**, discusses the company's history, what differentiates their antennas and managing rapid growth.

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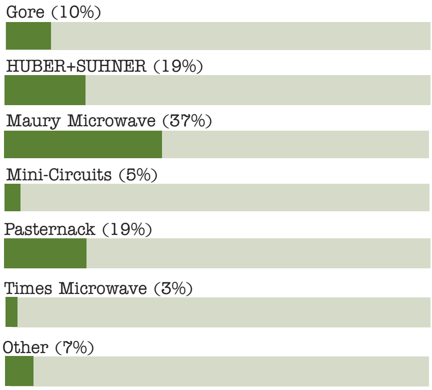

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Going Green: High Efficiency GaN Amplifiers

Patrick Hindle, *Microwave Journal* Editor

Improving amplifier efficiency is a key goal in many systems as PAs typically consume the largest amount of energy of any component. GaN has several advantages over other technologies such as high power density, high power, high gain and high efficiency.

In order to achieve maximum efficiency, manufacturers are using modulation techniques like envelope tracking or outphasing plus DPD to reduce distortion. Applying these techniques to GaN has taken high power amplifiers to the next level for many applications and promises to greatly reduce power consumption. We asked several leading GaN device manufacturers to provide examples of their highest efficiency GaN amplifier designs as we look to a greener future.

ANALOG DEVICES - BROADBAND AND HIGH POWER A&D GaN

Norwood, Mass.

GaN is changing the RF and microwave landscape across communications systems ranging from mobile wireless networks to aerospace and defense, with most future radar, military communications and electronic warfare systems investigating its benefits. By reducing device parasitic elements, using shorter gate lengths and using higher operating voltages, GaN transistors have reached higher output power densities, wider bandwidth and improved DC to RF efficiencies. As the size of modern systems become increasingly important, GaN, with its improved power density, is up to 6× better than GaAs and provides a reduced system footprint with higher reliability.

One example of the benefit of leveraging GaN is in modern phased array radar systems. With thousands of active elements, GaN technology is providing comprehensive solutions for transmit-receive modules, enabling increased power density and integration with the PA, LNA and T/R switch all developed in GaN. The high breakdown voltage also potentially eliminates the need for the limiter — traditionally used to protect the LNA — reducing component count and area, which is critical at higher frequencies with minimal antenna aperture spacing.

GaN's higher operating impedance also enables optimized solutions for electronic surveillance and countermeasures, with a single broadband power amplifier now able to cover multi-octave bandwidths. For example, ADI's HMC7149, based on a 0.25 micron process, is able to support amplification across 6 to 18 GHz with minimal variation of output power

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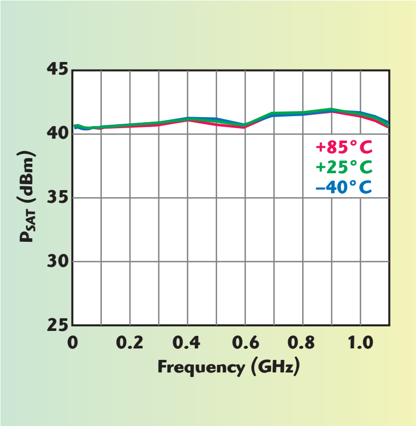
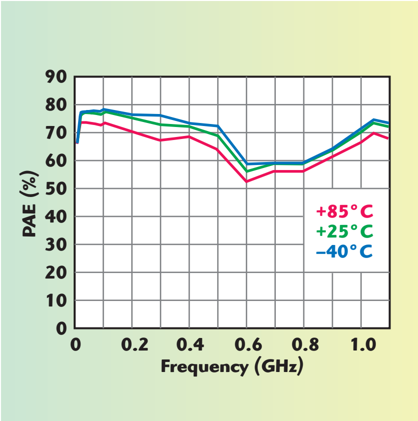


▲ *Fig. 1 HMC1099 saturated output power vs. frequency for various temperatures.*



▲ *Fig. 2 HMC1099 power-added efficiency vs. frequency for various temperatures.*

and gain. A single PA can now be used where previous PA performance necessitated band partitioning.

Advanced power combining solutions incorporated with GaN yield even stronger benefits to users. Using proprietary power combining methods and advanced bias control/monitoring circuits in core power combined modules, ADI's SSPAs provide solutions from 100 W broadband to 8 kW at X-Band, combining up to 256 MMICs. These new system-optimized solutions for radar and electronic warfare have high efficiency and RF power density and provide alternative solutions to traditional TWTs.

Another example is a 10 W GaN amplifier which operates over an instantaneous bandwidth of 0.01 to 1.1 GHz with ± 0.5 dB of gain flatness (see **Figure 1**). It offers high saturated output power with 69 percent typical power-added efficiency (PAE) and 18.5 dB of small signal gain (see **Figure 2**). The device is designed for industrial and portable applications where GaN technology is needed to meet the increasing demands on battery lifetime. The device utilizes internal prematching to realize a single external matching network to provide high PAE over the full bandwidth and is packaged in a compact, low cost 5 mm × 5 mm QFN package.

After its acquisition of Hittite, ADI is taking aim at many high performance defense and aerospace applications. The company offers a broad portfolio of experience in everything from device to subsystem products and dedicated labs, production and testing facilities.

AMPLEON – HIGH EFFICIENCY CELLULAR BASE STATION GaN

Nijmegen, The Netherlands

In cellular base stations, the need to have higher throughput forces the use of higher modulation coding schemes, which leads to higher peak-to-average signals. As a consequence, the RF PA's average efficiency is reduced. One candidate architecture suitable to minimize this issue is out-phasing, where highly efficient switched-mode PAs can be used. However, its pure version has some drawbacks, namely the nulling problem and response to DPD algorithms. A solution for these issues is to split the operation into two ranges: pure out-phasing and a linear mode in the highest and lowest input power levels, respectively. The nulling problem is solved by this method, as the zero output power is achieved when the input power is also zero and not at the expense of subtracting two high power signals with opposite phase.

Ampleon has developed an out-phasing PA prototype board that uses two IAF 0.25 mm GaN transistors. A quasi load insensitive (QLI) class-E topology is chosen for its high efficiency against load modulation. The higher harmonic impedances of the transistors were matched inside the commercial RF package, SOT1135, which eases the combiner design. Since the

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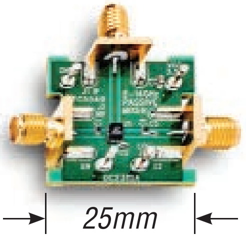

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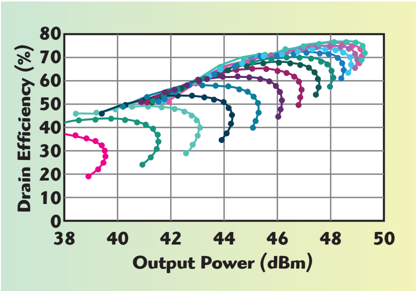
packaged devices are not very sensitive to higher harmonic load impedances, the combiner is easier to design. A standard 30 mil Rogers substrate, RO4350B, is used for the board design.

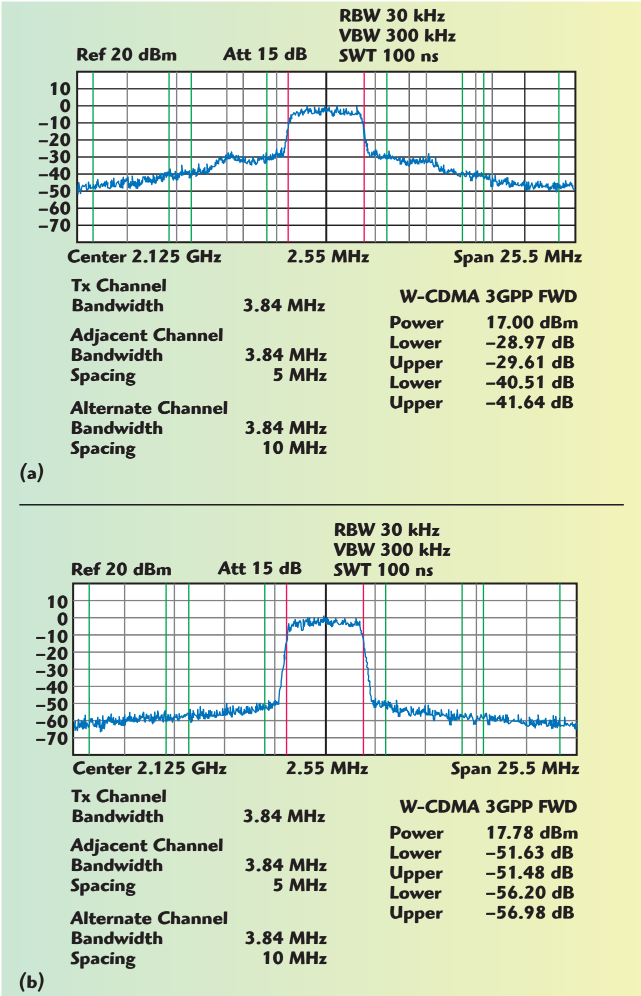
The static CW measurements for several values of input power and phase angle using a dedicated dual input measurement system are shown in ***Figure 3***. Each line corresponds to an input power level and each dot to an out-phasing angle. It is evident that in the pure out-phasing regime, at the back-off levels, the efficiency degrades considerably. Additionally, it is interesting to see that it is possible to obtain the same output power level using different values of input power and phase angle. With this unique property, the best efficiency performance can be selected (especially in back-off) using the appropriate combination of input power and phase angle using a lookup table approach. The unique amplitude and phase points corresponding to the highest efficiency are chosen and lookup tables (phase, amplitude) are formed. This method allows not only the extension of the dynamic range (nulling issue), but also efficiency optimization.



▲ *Fig. 3 Static CW measurements for various values of input power and phase angle.*

The mixed mode, out-phasing PA was tested with a single carrier W-CDMA signal seen in ***Figures 4a*** (non-linearized) and ***4b*** (linearized). Before the linearization, the starting value of ACLR is equal to -28 dBc and the EVM 9 percent. After a single pass DPD cycle, it was possible to improve these values to -51 dBc and 1.1 percent, respectively. The achieved efficiency is high (>65 percent) and the PA responded to linearization algorithms, which showed the potential of the mixed mode, out-phasing concept for future high efficiency base stations.

Ampleon is the spinoff of the NXP RF power business, as NXP acquired Freescale and kept their RF power products. Ampleon is a major player in the wireless infrastructure power market, developing many unique designs to meet the next generation of RF power: the RF energy market for applications such as microwave ovens, lighting, automobile ignition systems and food processing.



▲ *Fig. 4 W-CDMA single carrier spectrum before linearization (a) and after linearization (b).*

MACOM – BREAKING THE MOLD WITH HIGH EFFICIENCY GaN ON Si

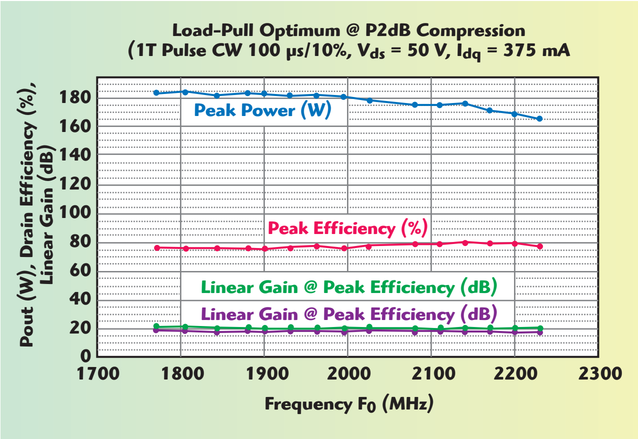
Lowell, Mass.

MACOM is the only RF GaN manufacturer that produces GaN on Si devices (the others use GaN on SiC). MACOM does produce devices on both substrates, putting significant focus on GaN on Si for low cost, high volume markets such as wireless infrastructure and RF energy. MACOM recently released a GaN wideband D-mode transistor optimized for 1.8 to 2.2 GHz modulated signal operation in cellular base station applications and housed in an over molded plastic package. Using MACOM's Gen4 GaN technology, the MAGB-101822-120B0P is one in a family of products in MACOM's MAGB series. The series enables competitive products with state-of-the-art performance for LTE base station applications at LDMOS-like cost structures (at volume). These products have been optimized to deliver high drain efficiency and linear gain and are easy to linearize using digital predistortion (DPD) according to some customers.

These products target all the cellular bands within the 1.8 to 3.8 GHz range and deliver significant power efficiency improvements, in addition to package size reduction over legacy LDMOS. The products are housed in a plastic TO-272 package, operate over 400 MHz of bandwidth, and support 30, 40 and 60 W cellular infrastructure applications. The ability of this single device to cover the cellular bands and power levels from 1.8 to 2.2 GHz would require multiple LDMOS-based products.

The device delivers 160 W of peak output power on the load-pull system (fundamental tuning only), has linear gain of 20 dB and peak efficiency of 75 percent across the full band, similar performance to the ceramic version (see ***Figure 5***). Peak efficiency can be improved to well above 80 percent when the device is presented with the proper harmonic terminations. A 2× MAGB-101822-120B0P symmetric Doherty amplifier optimized for Band 1 is capable of delivering 55 dBm of peak power. When the Doherty amplifier is measured with a two carrier 20 MHz LTE signal, a total of 40 MHz carrier, and at 7.5 dB back-off, the gain is 15.5 dB and efficiency is 55 percent. Using a commercially available DPD kit and without any special optimization, the adjacent channel power ratio (ACPR) can be easily corrected to less than -55 dBc. The Doherty amplifier achieves a video bandwidth of 200 MHz.

The device enables the implementation of a simple symmetric Doherty amplifier design without compromising RF performance, compared to less performing and complex asymmetric Doherty topologies needed when using LDMOS based transistors. The symmetric Doherty amplifier, using the MAGB-101822-120B0P, is also easy to DPD linearize, which has been a challenge for users of other GaN-based products in the market. By overcoming all the RF and thermal challenges of designing GaN-based products in a plastic molded package, this product replaces high cost ceramic air cavity packages without compromising RF and thermal performance. MACOM's improved package offering provides further system level cost savings to the customer and eliminates another barrier to full GaN adoption.



▲ *Fig. 5 Output power, gain and efficiency vs. frequency.*

The MACOM Gen4 technology is enabling wireless carriers to deploy the latest LTE releases and significantly reduce system operating expenses at highly competitive price points, with a scalable supply chain combined with experienced

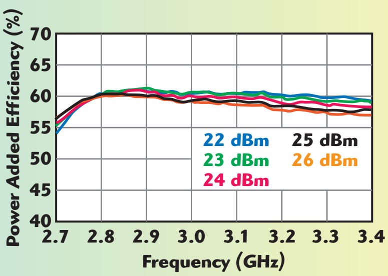
applications and design support team. MACOM is qualifying this process for widescale production and also taking aim at the RF energy market.

QORVO – HIGH PERFORMANCE GaN FOR RADAR

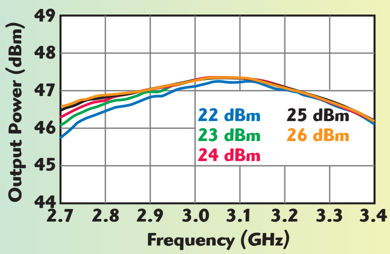
Greensboro, N.C.

Airborne, land and naval radar platforms continue to push for higher PAE for the transmit PAs. Improving the PAE of the system can result in simplified thermal management; power supply requirement relaxation and longer Tx path pulse width operation. To meet the need for higher PAE in commercial and military radar applications at S-Band, Qorvo has developed a family of GaN PAs. All Qorvo S-Band GaN PAs have > 50 percent PAE. The latest and highest efficiency member of the S-Band family is the QPA1000, well suited to meet the needs of radar applications in the 2.8 to 3.2 GHz frequency band.

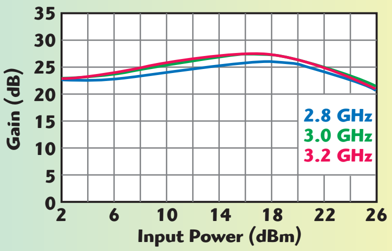
It is designed using the Qorvo QGaN25 0.25 mm GaN on SiC production process to provide >58 percent PAE and >50 W saturated power pulsed with an input power of 25 dBm (see ***Figure 6***). Measured PAE exceeds 60 percent in portions of the operating band with minimal changes to the saturated output power. The part is a two stage, near class B design with >22 dB large signal gain (see ***Figure 7***). The PA is mounted in a 7 mm × 7 mm × 0.85 mm, 48 pin molded plastic QFN surface-mount package. The PA is designed to operate at a quiescent bias point of Vd = 25 V and Idq = 200 mA. For verification testing the pulse width and duty cycle are 100 µs and 10 percent, respectively, but it is capable of supporting a variety of operating conditions and pulse applications due to the good thermal properties.



▲ *Fig. 6a PAE vs. frequency: Vd = 25 V; Idq = 200 mA; PW = 100 µs, Duty Cycle = 10%.*



▲ *Fig. 6b Output power vs. frequency: Vd = 25 V; Idq = 200 mA; PW = 100 µs, Duty Cycle = 10%.*



▲ *Fig. 7 Large signal gain vs. input power: Vd = 25 V; Idq = 200 mA; PW = 100 µs, Duty Cycle = 10%.*

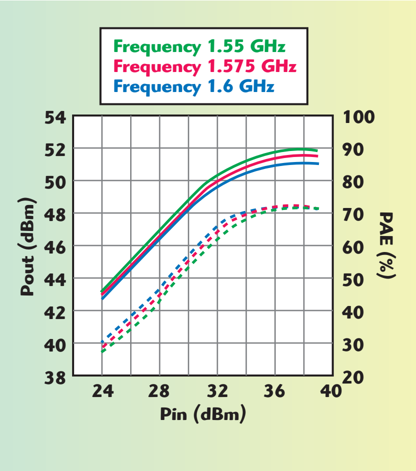
The high PAE is achieved by optimizing the load-side impedance termination for both gain stages, and the transistor layout for both electrical and thermal performance, as well as compensating for the package parasitics. Measured load-pull data, package interface models, nonlinear transistor models, electromagnetic simulation and thermal modeling are all used to optimize the circuit. Package parasitics are determined through similar design testing, modeling and calculation.

Qorvo continues to push amplifier PAE as a critical parameter for radar applications. Operating class choice, form factor, load-pull data, model accuracy and thermal considerations all play an important role in achieving optimal overall amplifier performance.

SUMITOMO ELECTRIC – HIGH EFFICIENCY GaN FOR SPACE APPLICATIONS

Osaka, Japan

Sumitomo Electric has recently qualified the SGN15H150IV GaN device at high reliability levels for space applications. This third generation GaN device is allowing an advantage over previous technologies in gain and power levels with excellent reliability. It has 150 W (51.5 dBm) typical output power and 117 W (50.7 dBm) minimum power output at 4 dB gain compression when operated at a drain voltage of 50 V. That is the highest power level of space qualified GaN device available at this frequency, covering 1.55 to 1.6 GHz according to the company. High impedance levels allow for simple external matching circuits to meet all performance goals. A high linear gain of 17.5 dB minimum, 18.8 dB typical, makes driving the device easier. It has excellent PAE of 67 percent minimum (71 percent typical has been measured in an application engineering breadboard). ***Figure 8*** shows output power and PAE vs. input power.



▲ *Fig. 8 Ouput power and PAE vs. input power: Vd = 50 V; Idq = 500 mA; frequency 1.55 to 1.6 GHz.*

The device has excellent performance over temperature with the classic HEMT two-slope gain shape. The inflection point is below -20°C, making gain constant from -40° to -10°C, and a slope of -0.012 dB/°C above that point. The same phenomenon makes the power constant from -40° to 25°C. The power has the same slope as the gain of -0.012 dB/°C from 25° to 85°C. PAE is approximately linear, with a slope of -0.068 percent per °C.

At 150 W output power, thermal considerations are very important. The thermal characteristics have been optimized in the device and housing structure, resulting in very low thermal resistance of 0.6 °C/W typical and 0.7 °C/W maximum. Each device is measured for thermal resistance individually and that data is delivered with the device. The maximum junction temperature is 250°C. This high maximum junction temperature allows for a conservative de-rating to 160°C operating junction temperature for safe and reliable operation.

The package is the same as the previous generation of GaAs high reliability designs, and the pre-match offers similar impedance levels as previous lower power devices. This eases upgrading current designs to take advantage of the higher output power.

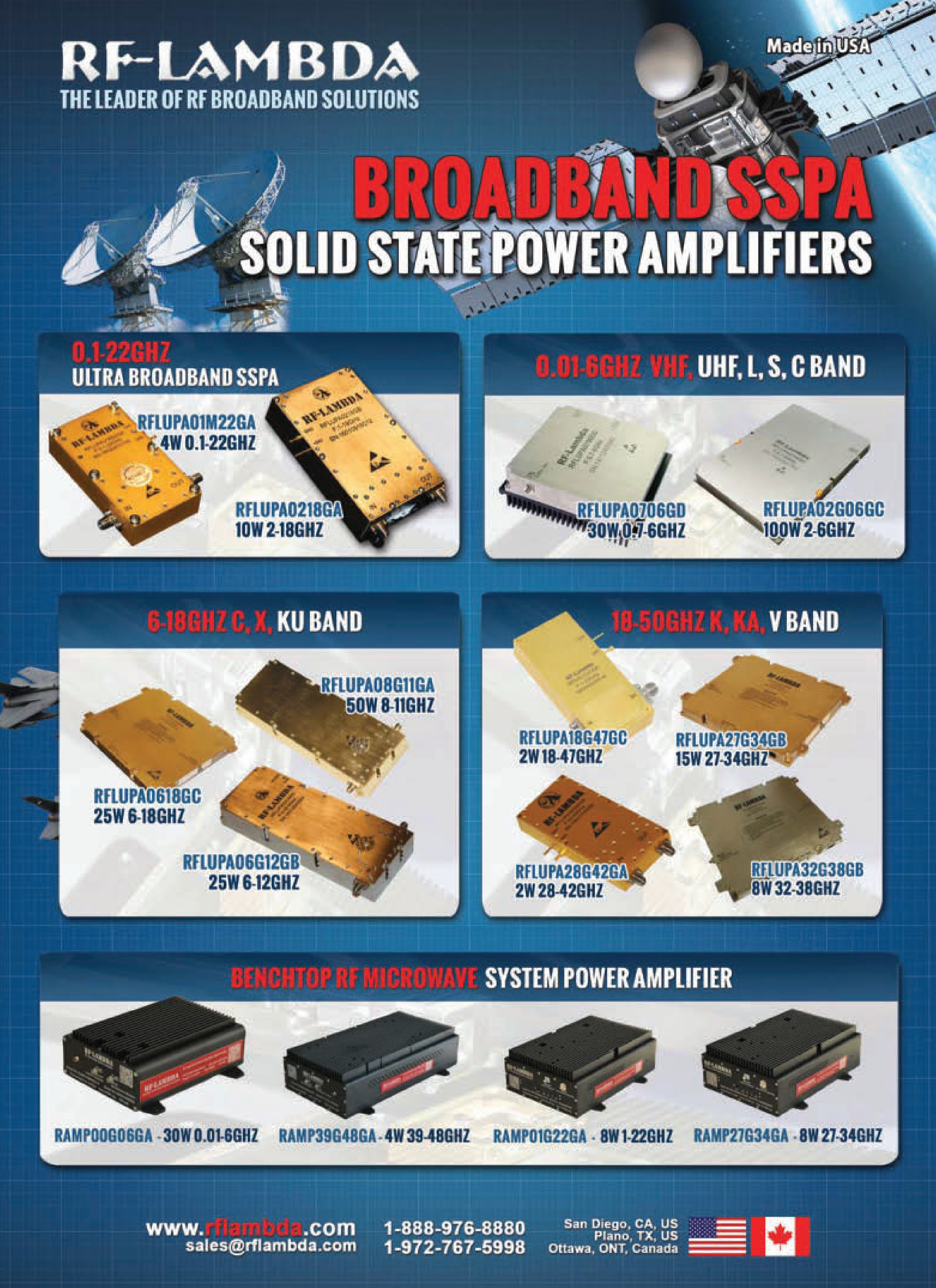
For those who are attempting even higher PAE, low Cds and excellent performance at lower voltages make this device is a good candidate for envelope tracking schemes. Low on resistance along with high reverse breakdown voltage (BVgd) also makes it attractive for switch-mode designs. Nonlinear models are available as well, for more precise first-pass design and evaluation of nonlinear behavior before building the device into a design.

Primary applications would be in navigation satellites, GPS L1 Band or Galileo E1 Band. Sumitomo continues to focus on high performance satellite, radar and space applications for its GaN products.

WOLFSPEED, A CREE COMPANY ENERGY EFFICIENT GaN FOR BASE STATIONS

Durham, N.C.

Wolfspeed is enabling designers to invent wireless systems for a responsible, energy-efficient future. Eta Devices, an MIT spin-out based in Cambridge, Mass., is pioneering the use of supply modulation through its technology called ET*Advanced*. ET*Advanced* enables base station transmit-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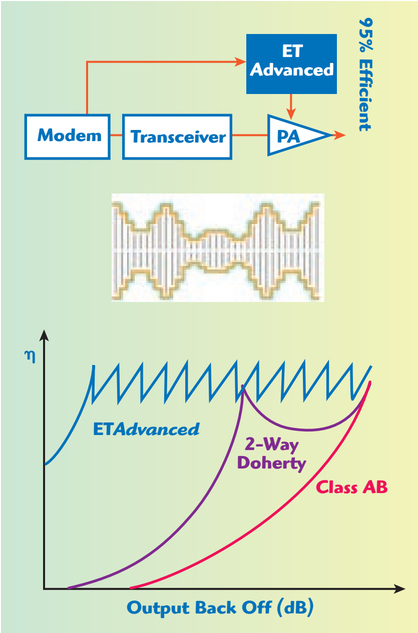


▲ *Fig. 9 ETAdvanced uses discrete supply levels to modulate the drain of a PA, making millions of transitions per second to optimize power consumption.*

ters to achieve the highest efficiency at peak power and the highest efficiency at back-off of any known technique according to the companies. And, unlike previous technologies using supply modulation, ET*Advanced* has proven to retain its advantages for both high bandwidth (multi-carrier LTE) and high linearity (MC-GSM) applications. When combined with Wolfspeed's GaN devices, the result has been reported to be the highest efficiency base station amplifiers.

ET*Advanced* solves the key power challenge facing the wireless industry today. As shown in ***Figure 9***, ET*Advanced* uses discrete supply levels to modulate the drain of a PA, making millions of transitions per second in order to optimize power consumption. At almost every place in the wireless ecosystem, the power consumption and the heat dissipation of the PA are limiting factors that increase cost and size, limit output power and range, and overtax energy supply resources.

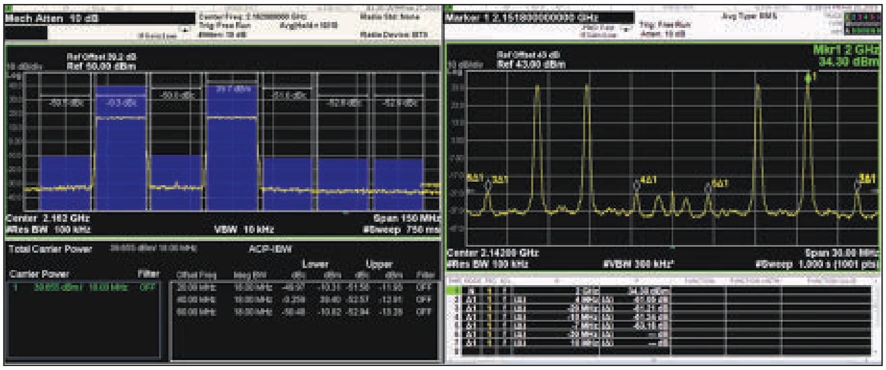
In February 2016 at Mobile World Congress, Eta Devices demonstrated what could be the highest efficiency GaN high power amplifier compliant to MC-GSM/LTE specifications. The linearity specification for MC-GSM is that distortion products must be lower than -60 dBc. According to Eta Devices, Cree GaN HEMTs can be used over a very wide range of drain bias voltages. They exploit this to achieve not only high efficiency at maximum average power, but also achieve high efficiency at back-off. Their demonstration uses Cree's high performance CGH40025F with high efficiency, high reliability and consistent performance.

Figure 10 shows measurements from Eta Devices' MWC 2016 demonstration. Eta Devices was able to demonstrate 70 percent average final stage efficiency for a fully modulated LTE carrier and >60 percent average final stage efficiency for MC-GSM transmissions. These efficiency numbers include the loss of the supply modulator.

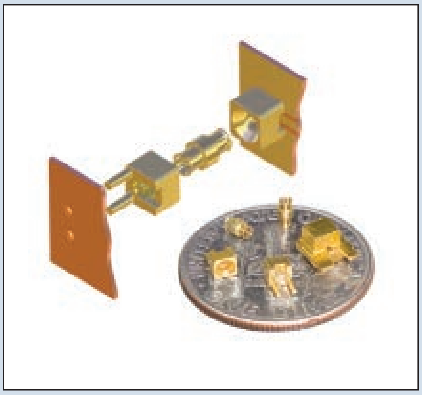
Wolfspeed and Eta Devices have teamed together to design highly efficient amplifiers for base station applications that promise to greatly reduce power consumption, saving wireless communications providers millions in Op Ex for a greener future.

CONCLUSION

It was not long ago that 50 percent efficient power amplifiers were the best in the industry, but now, many manufacturers are obtaining 65 to 70 percent efficiency. GaN and advanced modulation and matching techniques are pushing efficiencies higher every year. ■



▲ *Fig. 10 Eta Devices' demonstration of LTE and MC-GSM performance using ETAdvanced to modulate PAs built around the CGH40025F with 70% average final stage efficiency.*



Pushing Board-to-Board Interconnect Performance Boundaries

Southwest Microwave, Inc.
Tempe, Ariz.

Nearly four decades ago, the RF design community was introduced to a new push-on connector that addressed the need for increased electrical performance, quicker installation and greater density in higher frequency applications. This design, commonly known as the sub-miniature push-on (SMP) connector, was built around a blind-mate adapter, or bullet, housed between two PCB or panel-mounted receptacles. The bullet, available in different lengths, tolerated a degree of axial and radial misalignment, or float, while still maintaining transmission integrity. This new connector opened the door for looser alignment tolerances and simplified the production process. It also accommodated a higher concentration of simultaneous microwave interconnects per circuit board or panel, by eliminating the bulky mounting hardware associated with threaded connectors.

Through the years, SMP size has continued to decrease, providing corresponding improvements in frequency. The introduction of a micro sub-miniature push-on (SMPM) – 45 percent smaller than the original SMP – then a sub-micro, sub-miniature push-on (SMPS) – which achieved a further 30 percent profile reduction – moved RF capability beyond 65 GHz. These developments provided a solution for integration into tighter packaging and a reduced module footprint to support ongoing system and module miniaturization initiatives. As demand for these connectors has grown, many producers have introduced similarly engineered sub-miniature push-on products, enabling a high degree of vendor inter-mate-ability in the SMP realm, along with retrofit flexibility for the system design community.

Near industrywide commonality of design has perpetuated electrical and structural performance challenges with most SMP connectors. These include measurable VSWR degradation and insertion loss with radial or axial float, as well as pin instabil-

ity, misalignment or breakage. Premature bullet failure, due to outer contact beam flex limitations, and PCB or interconnect damage, resulting from the high de-mating force required to decouple these interconnects at higher densities, can require costly rework or replacement. Ultimately, the shortcomings of sub-miniature push-on products has left electronic system designers with a distinct need for new and better board-to-board interconnect alternatives.

ADDRESSING THE CHALLENGES

To address the performance issues of legacy SMP technology, Southwest Microwave has taken a "ground up" design approach in developing a unique suite of SuperMini Board-to-Board DC to 67 GHz connectors. These ultra-high frequency, miniaturized push-on interconnect solutions for high density PCB interface feature advanced bullet and receptacle construction that maximize product lifespan and significantly improve resilience against RF signal degradation. Ideal for defense, aerospace, communications, networking and test applications, these lightweight yet rugged blind-mate connectors enhance reliability and performance for board-to-board stacking, edge-mount to backplane or board-to-panel interconnections.

SuperMini Board-to-Board connectors employ a 0.9 mm interface to achieve the industry's smallest, widely used footprint and highest volume of interconnections per board. With horizontal and vertical mount options, they are an excellent answer where space and weight efficiencies are essential, such as radar systems, phased array antennas, amplifiers, receiver units, switch matrices, channelizers and circuit cards. Designed to optimize electrical performance of the transmission path between connector and circuit for surface and thru-hole PCB mounting applications, SuperMini Board-to-Board connectors are available in smooth bore or detent style vertical and end-launch jack configurations for stripline, microstrip and grounded co-planar circuit launch transitions. All meet MIL-PRF-39012 for resistance to corrosion, vibration, mechanical shock and thermal shock.

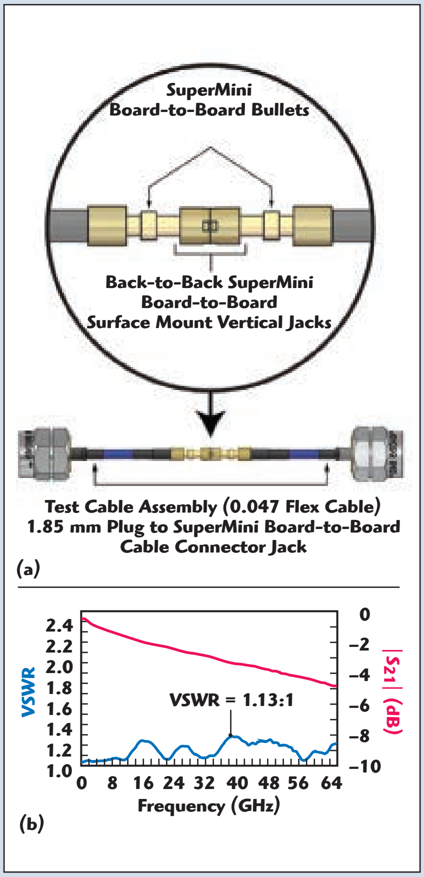
SuperMini Board-to-Board solutions feature mating and de-mating forces that are the lowest in the industry: The typical mating force is 6 oz for smooth bore and 9 oz for the detent style. The typical de-mating force is also 6 oz for the smooth bore and 12 oz for the detent style. Without the excessive mating pressure common to legacy push-on solutions, engagement of hundreds of interconnections may be achieved without risking board damage, pin misalignment or fracture. Similarly, the low total de-mating force, even in a high volume array, facilitates ease of simultaneous decoupling of interconnects without the negative effects on the connector or PCB that are seen with other designs.

The SuperMini bullet's outer contact beam (spring finger) design enables the prescribed amount of flexure without the over-stress and yield that cause premature set in standard bullets. This results in unmatched mating and de-mating cycles: more than 500 for both the smooth bore and detent styles. This positions the SuperMini as ideal for automatic circuit testing applications.

Since board-to-board stacking applications inherently have the potential for connector misalignment, the challenge with earlier push-on designs has been the

degree of axial and radial float achievable before electrical performance is sacrificed. Widespread mating plane problems with legacy technology, which alters the characteristic geometry of contact surfaces when bullet-receptacle misalignment occurs, can create an inductive path that negatively affects VSWR. Conversely, Southwest Microwave's unique bullet-receptacle interface design incurs dimensional changes on misalignment without significantly affecting the character of the transition contact surface, minimizing the effect on signals passing through the connector. This achieves superior electrical performance of the transmission path between connector and circuit, while accommodating axial float of up to 0.010" and radial float of ±10° without significantly affecting VSWR.

SuperMini Board-to-Board connectors also successfully address the physical construction limitations of standard SMP designs, which restrict PCB stacking proximity based on profile size or risk to receptacle center conductor durability at low interface clearances. Southwest Microwave's receptacle, which provides superior center conductor support and stability along with its consistent transition character, assures RF and millimeter wave transmission line dependability for tightly-stacked PCBs, with zero compromise to performance. An extensive range of bullets enable industry leading board-to-board spacing as close as 3 mm. The millimeter wave performance of the SuperMini Board-to-Board technology is superb, with VSWR of 1.13:1 (see ***Figure 1***), and highly repeatable, even with misalignment. The proven reliability of these connectors at or beyond 67 GHz now allows system designers to easily solve common, lower frequency, high-density interface challenges, while similarly achieving a long-term solution for sophisticated next-generation miniaturized high frequency applications.



▲ *Fig. 1 SuperMini Board-to-Board interconnect performance, showing test configuration (a) measured insertion loss and VSWR (b).*

Southwest Microwave Inc.
Tempe, Ariz.
www.southwestmicrowave.com

New DARPA Grand Challenge to Focus on Spectrum Collaboration

DARPA recently announced the newest of its Grand Challenges, one designed to ensure that the exponentially growing number of military and civilian wireless devices will have full access to the increasingly crowded electromagnetic spectrum. The agency's Spectrum Collaboration Challenge (SC2) will reward teams for developing smart systems that collaboratively, rather than competitively, adapt in real time to today's fast-changing, congested spectrum environment—redefining the conventional spectrum management roles of humans and machines in order to maximize the flow of RF signals.

The primary goal of SC2 is to imbue radios with advanced machine-learning capabilities so they can collectively develop strategies that optimize use of the wireless spectrum in ways not possible with today's intrinsically inefficient approach of pre-allocating exclusive access to designated frequencies. The challenge is expected to both take advantage of recent significant progress in the fields of artificial intelligence and machine learning and also spur new developments in those research domains, with potential applications in other fields where collaborative decision-making is critical.

"DARPA Challenges have traditionally rewarded teams that dominate their competitors, but when it comes to making the most of the electromagnetic spectrum, the team that shares most intelligently is going to win," said SC2 program manager Paul Tilghman of DARPA's Microsystems Technology Office (MTO). "We want to radically accelerate the development of machine-learning technologies and strategies that will allow on-the-fly sharing of spectrum at machine timescales."

The Challenge comes at a time of fast-growing need. Military operations increasingly rely on access to the wireless spectrum in order to assess the tactical environment and coordinate and execute their critical missions. But the military is not alone in this challenge: as society enters an era in which ever more products, from refrigerators to automobiles to commercial unmanned aerial vehicles, need access to the spectrum, it will take far more efficient and nimble use of finite spectrum resources to meet the demand.

To host the new Challenge, DARPA aims to construct the largest-of-its-kind wireless testbed, which will serve during and after the SC2 as a national asset for evaluating spectrum-sharing strategies, tactics and algorithms for next-generation radio systems. The "Colosseum," named after the ancient Roman amphitheater, will allow researchers to remotely conduct large-scale experiments with intelligent radio systems in realistic, user-defined RF environments, such as the wireless conditions of a busy city neighborhood or battle setting.

SC2 will unfold in three year-long phases beginning in 2017 and finish in early 2020 with a live competition of finalists and a grand prize of $2 million.

General Atomics Completes Successful Open Range Testing of Railgun Projectile GEU

VIEW VIDEO

General Atomics Electromagnetic Systems (GA-EMS) recently announced that their hypersonic projectiles with prototype components for their Guidance Electronics Unit (GEU) successfully performed programmed actions and communicated component performance to a ground station via a telemetry link in tests carried out at the U.S. Army Dugway Proving Ground in Utah. The GEU, housed in the aerodynamically stable test projectile consists of a number of components, including integrated navigation sensors and processors for guidance, navigation and control.

The five test projectiles were fired at accelerations greater than 30,000 times that of gravity (>30,000 gees) from GA-EMS' 3 mega joule Blitzer® electromagnetic railgun system. The projectiles and the critical components within them experienced, survived and operated in the multi-Tesla magnetic field within the launcher and the overall launch environment. All of the GEU components performed as expected during and after the launch event, and through multiple seconds of aero-stable flight.

Over the past year, GA-EMS has performed pioneering engineering, development and successful testing of electromagnetic railgun launched hypersonic projectiles and projectile components. GA-EMS' Blitzer railgun is a test asset designed and manufactured by GA-EMS to advance technology development toward multi-mission railgun weapon systems. Railguns launch projectiles using electromagnetic forces instead of chemical propellants and can deliver muzzle velocities greater than twice those of conventional guns. Blitzer railgun technology, when integrated into a weapon system that includes the launcher, high density capacitor driven pulsed power and weapon fire control system, can launch multi-mission projectiles with shorter time-to-target and greater effectiveness at longer range.

U.S. Navy Photo

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LM Opens Space Fence Test Facility

VIEW VIDEO

Objects in space will soon be monitored by a radar array for the U.S. Air Force's Space Fence as part of Lockheed Martin's new test site representative of the larger system under construction on the remote Kwajalein Island.

The test facility will be used for early validation of hardware, firmware and software that will enable the Space Fence to detect, track and catalog orbital objects more than 1.5 million times a day to predict and prevent space-based collisions. The test site will also provide early lessons learned on installation of the S-Band ground-based radars, support maintenance training and allow engineers to test verification procedures.

The New Jersey test site officially opened during a ceremony attended by representatives from the U.S. Air Force, local, state and federal governments, Lockheed Martin leaders and Space Fence team members.

Lockheed Martin uses the latest monolithic microwave integrated circuit technology, including gallium nitride (GaN) semiconductor materials. GaN provides significant advantages for active phased array radar systems, including higher power density, greater efficiency and improved reliability over previous technologies.

Construction continues at the 6 acre Space Fence site 2,100 miles southwest of Honolulu. Forty-five hundred cubic yards of concrete now form the foundation of the sensor site and the start of ring walls that will support the inflatable roof permeable by RF bands.

Once construction is complete, Space Fence will be tested and validated before its Initial Operating Capability occurs in late 2018.

Source: Lockheed Martin Corp.

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5G Intervehicular System Promises Improved Road Safety

The Horizon 2020-funded METIS-II project has devised and configured a new 5G Radio Access Network (RAN) system for intervehicular communication that allows cars to 'talk' to each other in real-time conditions. The system is intended to improve road safety in a future scenario where 5G technologies have become a normal aspect of everyday life.

METIS-II aims to provide an important platform for a European-led early global consensus on fundamental questions connected to the development of the future mobile and wireless communications system, and pave the way for future standardization. The main novelty of the new 5G RAN system is that it allows the continual adjustment of waveforms in such a way that vehicles can communicate with each other, thereby overcoming the hurdle of not having a set station for communication.

In terms of hardware, the system includes three programmable cards, each of which has a high-performance field-programmable gate array (FPGA) to integrate different waveforms, which are what carries data through the air, and four antennas. These cards will allow direct communication between vehicles, as well as the integration of intervehicular communications into conventional mobile communication systems.

METIS-II envisions an overall 5G RAN system to operate in a wide range of spectrum bands to address the diverse services that would be offered using the technology. Studies have shown that large contiguous spectrum bands are preferable for various reasons, in particular related to device complexity. In general, the 5G system will build upon a set of spectrum usage forms such as the use of dedicated licensed spectrum, horizontal sharing of bands with differentiation according to limited spectrum pools, mutual renting and unlicensed use, as well as vertical sharing of bands.

METIS-II received nearly €8,000,000 in European Union funding and is due to finish in July 2017. The project, although financed through the EU's Horizon 2020 programme boasts a truly global consortium, with partners located across the world from Europe, to Taiwan and the United States.

Image © Shutterstock

Sentinel-1B Will Complete Europe´s 'Radar Vision'

The Sentinel-1B satellite, carrying an Airbus Defence and Space built radar instrument has been launched from Europe's Kourou Spaceport in French Guiana. The satellite, which has Thales Alenia Space Italy as prime contractor, joined its twin, Sentinel-1A (launched in April 2014) to complete the Sentinel-1 polar orbiting constellation. Working together, the Sentinel-1 satellites will image the entire planet every six days.

Like Sentinel-1A the Sentinel-1B satellite carries the Synthetic Aperture Radar (SAR) Antenna Subsystem (SAS) which will be able to acquire an immense amount of data due to its continuous operation capability. The 12.3 m antenna is made up of five panels. Integrated on these panels are 280 dual polarized small transmitters delivering a total RF signal of just over 5 kW. These transmitters and their associated receive elements are supplied by Thales Alenia Space and are implemented as transmit/receive multichip hybrid modules integrated into Electronic Front-End (EFE) equipment.

> ...highly stable radar signals...

Controlling these 280 transmitters individually provides an electronic steering capability of the overall radar beam. By steering the beam across the observation track in a series of 80 km wide strips next to each other on the ground, a medium resolution image for wider swaths of up to 400 km can be assembled. The high transmit power presented a thermal design challenge in addition to the already complex mechanical design task of creating the required highly stable structure of the 800 kg antenna.

The antenna is driven by the SAR Electronics Sub-system which provides the signal processing, timing and system control, creating highly stable radar signals and precision beam orientation. The instrument has been designed to ensure a 2.5 m pixel positioning accuracy on a 400 km wide target nearly 1,000 km away on the ground while travelling at 7 km per second. This was achieved with a sophisticated mechanism for extremely accurate real-time orbit position prediction, and very precise timing knowledge to synchronize the SAR image acquisition.

Small Cell Forum and ETSI Stage Fourth LTE Plugfest

The Small Cell Forum, in partnership with the European Telecommunications Standards Institute (ETSI), is to stage its fourth small cell LTE Plugfest in Naples, Italy, in June. Taking place in TIM specialist labs, the Plugfest will enable key players and suppliers in the small cell marketplace to test their products and solutions for interoperability and reliability in mixed vendor environments.

For More Information

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> ...the impact of LTE-A

The Plugfest will include the opportunity for remote testing as well as collaborative work in the Labs. It will have a special focus on the Self-Organizing Network (SON) capabilities of small cells in a HetNet environment, as well as looking at other areas including traffic offloading, closed subscriber groups, and the impact of LTE-A.

"Plugfests are a critically important part of the process of building and developing the small cell ecosystem," said small cell forum chair, Alan Law. "The tests planned for Naples will help our members continue on the path of readying the small cell industry to provide all the tools needed for operators as they densify their networks, increase their coverage and capacity, and improve services for businesses and consumers both indoors and out."

As part of the Plugfest, TIM is inviting companies at the event to connect small cells to its network and to test them for interoperability and interference.

5G Service Revenue to Reach $247B in 2025

ABI Research projects that mobile broadband operators will reap 5G revenues of $247 billion in 2025 with North America, Asia-Pacific and Western Europe being the top markets. Specifically, network operators, vendors, and standards bodies will finalize technical details concerning the millimetre wave by 2020, with rollout ramping up afterward.

> ...the market faces several key challenges.

"5G will be a fast growing cellular technology, most probably faster than preceding generations including 4G," said Joe Hoffman, managing director and vice president at ABI Research. "The technology migration over the next few years will mean the continued decline of 2G. 3G and 4G will grow in many markets but 5G will generate new use cases and market revenues."

As infrastructure vendors and mobile operators prepare for the future of 5G, the market faces several key challenges. Obstacles include spectrum fragmentation, standards development, coverage range, availability of devices, and CAPEX/OPEX, and most importantly, the development of use cases that ensure profitable outcomes from the unique competitive advantages of 5G.

Unlike the case with LTE, 5G stakeholders are trying hard to achieve spectrum harmonization. As with LTE, however, 5G will also include unlicensed and shared spectrum schemes. Government organizations worldwide will need to work together to regulate the 5G spectrum and set the new standard.

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FCC Urges Further Work to Deliver Faster Broadband Services

The U.S. still trails its OECD counterparts in terms of broadband penetration, speed and affordability. Nevertheless, the market is currently witnessing significant investment activity in fiber deployments, Hybrid Fibre Co-Axial (HFC) upgrades with DOCSIS 3.1 technology, and mobile broadband networks. Much of the investment in fiber is being undertaken by a significant number of smaller players and municipalities rather than the two key telcos, AT&T and Verizon, which are concentrating on a hybrid fiber/copper network and limiting future upgrades beyond what has already been achieved. Indeed these operators have emphasized their wireless focus in recent years, which has meant that cable companies have made most of the gains in new broadband subscriber adds in recent quarters.

Broadband services in most regions still lack effective competition, with an effective duopoly operating in many areas of the country. Municipal activity, often geared at breaking this stranglehold and introducing competition and innovation, continues to be stymied by lobbying pressure from the main telcos. However, the FCC's National Broadband Plan envisages a greater role for public FttP networks in the pursuit of its goals, and in the activities of muni-networks to form a large part of the patchwork fiber deployments across the country in coming years.

> Broadband services in most regions still lack effective competition.

There is growing recognition of the importance of a trans-sectoral approach to broadband networks, including the health, education and energy sectors, in order to fully realize the benefits of the nascent digital economy. The FCC's 2016 Broadband Progress Report reveals how much still needs to be done to move the US broadband market forward.

Given the size of the U.S. market, and the growing demand for data on both fixed and mobile networks, there is continuous pressure for operators to invest in fiber backhaul networks and to push connectivity closer to consumers. In recent years the U.S. has seen increased activity from regional players such as Google, with its successful investments in a number of markets.

Growth in the U.S. mobile subscriber base remains strong despite penetration levels of above 110 percent. Declining revenue from voice services is compensated for by high growth in mobile data use, itself supported by excellent networks supporting LTE-based services and the high penetration of smartphones, which is more than 90 percent for some carriers. Mobile data use will grow more rapidly after 2018 when 5G services, due to be trialed later in 2016 by at least three network operators, become commercially viable.

Sub-6 GHz Backhaul Becomes Operators' Favorite by 2020 with Revenues Growing

The evolution toward 4.5G and 5G will be accompanied by substantial network densification and massive deployments of small cells. The trend will completely transform the backhaul market and create tremendous opportunities for wireless backhaul links. ABI Research forecasts that the market will deploy more than one million Sub-6 GHz licensed backhaul links by 2020.

As the fastest growing market segment, Sub-6 GHz will challenge microwave and millimeter waves for the largest market share of 35 percent in 2020. The combined wireless backhaul equipment revenues from Sub-6 GHz links and millimeter waves make up nearly 57 percent of the total backhaul revenue in 2020.

"Ultimately, operators' network densification plans continue to grow in order to support demands for higher capacity in metro locations and extend coverage to the rural and remote areas," says Ahmed Ali, research analyst at ABI Research. "This accelerated growth will mandate higher capacity links, lower equipment cost, and easier network installation. The development will, in turn, drive further investments in the wireless backhaul market."

Over the course of 2016, outdoor small cell rollouts will gain momentum. As Wi-Fi and distributed antenna systems (DAS) continue to advance and compete with small cells for the enterprise and in-building connectivity, their impact on the outdoor deployments is imminent.

"MNOs are also exploiting distributed network structures like Cloud-RAN (C-RAN) to cope with the explosive data traffic," concludes Ali. "Such evolution in the access network technologies and structures dictates the availability of diverse, flexible and interoperable backhaul solutions."

ABI Research suggests suppliers consider offering professional services, including high-resolution 3D mapping for backhaul link placement. They should also support multiple backhaul technologies and partner with Tangible Asset Monetization Companies (TAMCos), like advertising agencies, cable providers, and tower companies, to offer rights of way, and attach permits for small cell sites. Service providers, on the other hand, should look into leveraging network sharing schemes, unlicensed spectrum, and virtualization technologies in order to lower the cost of expanding backhaul and increase the overall ROI.

Six Stages Toward Smart, Sustainable Automotive Transportation

The automotive industry will undergo six transformative paradigms over the next 25 years to prepare for a future of smart, sustainable mobility. ABI Research defines the six stages as the software-defined car, sensors and big data, the connected car, cooperative mobility and the IoT, electrification and car sharing/driverless cars.

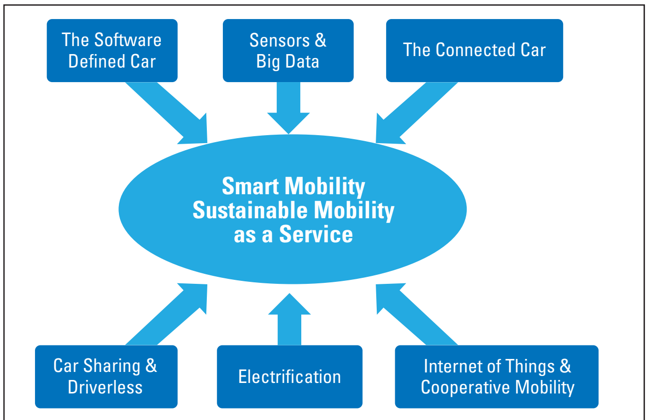
While the first three phases are already underway, the latter three will start to drive the market forward within the next 10 years.

Car manufacturers are currently revamping vehicles' electronics and networking architecture to ensure every sub-system is connected and software-defined. Moving toward the next decade, the automotive industry will achieve cooperative mobility. Cars will communicate with not only each other but also infrastructures and environments. Electrification will then change the way consumers power their vehicles. And lastly, car sharing and driverless cars will likely lead to market consolidation.

"The final three stages—cooperative mobility, electrification and car sharing leading to driverless cars—will be the most disruptive to the automotive industry," says Dominique Bonte, managing director and vice president at ABI Research. "Not all car manufacturers will survive the changing landscape. And newcomers will also emerge, ones eager to create new, software-defined, high-tech cars."

Through this industry fluctuation, there will be a number of opportunities for manufacturers and vendors to reinvent themselves. Gas stations will need to rethink their market strategy and offer new services, such as electric charging stations, or risk losing their relevance completely. Taxi companies are already feeling the rising pressure, meeting stiff competition from Uber and other new car sharing services. Dealerships and insurance vendors also face potential upset. Semiconductors and software companies, on the other hand, have a huge future, as cars continue to incorporate more sensors and computing technologies into their architectures.

"Think beyond smart, sustainable mobility, and soon we may witness a new trend that links smart mobility to virtualized lifestyles," concludes Bonte. "As people start engaging in more virtual reality experiences at home, will there be as strong a need for road transportation? It's a far look into the future but a scenario that could definitely send the automotive industry into a tailspin."



Source: ABI Research

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Culminating a surprisingly prolonged auction that began last November, **II-VI** completed the acquisition of **ANADIGICS** on March 15. II-VI is paying approximately \$78.2 million in cash for ANADIGICS' 6-inch wafer fab, which it will use to produce vertical cavity surface emitting lasers (VCSEL). II-VI, self-described as a "leader in semiconductor lasers," is adding capacity to support the projected demand for VCSELs, being driven by expected growth in hyperscale data centers. Complementing the ANADIGICS purchase, II-VI also acquired **EpiWorks** for \$43 million to add capacity for 6-inch epitaxial growth.

Teledyne Technologies Inc. announced that **Teledyne LeCroy Inc.** has acquired **Frontline Test Equipment Inc.** Frontline, headquartered in Charlottesville, Va., provides electronic test & measurement instrumentation and is a market leader in wireless protocol analysis test tools. Terms of the transaction were not disclosed. Protocol analyzers are used by engineers to troubleshoot data communication systems and test device interoperability, compliance and interference. Frontline's protocol tools intercept, log traffic and analyze data that passes over digital wireless networks.

Molex, a global manufacturer of electronic solutions, announced the acquisition of **Interconnect Systems Inc.** (ISI) which specializes in the design and manufacture of high density silicon packaging with advanced interconnect technologies. Headquartered in Camarillo, Calif., ISI delivers advanced packaging and interconnect solutions to top-tier OEMs in a wide range of industries and technology markets, including aerospace & defense, industrial, data storage and networking, telecom and high performance computing. ISI uses a multi-discipline customized approach to improve solution performance, reduce package size and expedite time-to-market.

GigOptix Inc. announced the signing of a definitive agreement to acquire **Magnum Semiconductor Inc.**, a privately-held Milpitas, Calif. based provider of silicon ICs, SoCs, software and IP for the professional video broadcast and IoT camera markets, in a cash and stock transaction valued at approximately \$55 million net based upon the average closing price of GigOptix stock for the trailing 30 day period ended April 1, 2016. Upon the close, GigOptix Inc. was renamed **GigPeak Inc**.

Altair has acquired **AWE Communications GmbH** based in Gärtringen, Germany. AWE was founded in 1998 as a spin-off from the University of Stuttgart and the main focus has been the development of the WinProp Software Suite for wave propagation and radio network planning. Highly accurate and very fast empirical and deterministic propagation models are available for a wide range of scenarios including, rural and residential, urban and suburban, indoor and campus, tunnel and underground, vehicular and time-variant, GEO and LEO satellites.

Black Box Corp., a technology solutions provider, announced the acquisition of technology and intellectual property from **Cloudium Systems Ltd.**, a privately held company headquartered in Limerick, Ireland. The Cloudium development team also will join Black Box. Black Box will use these assets to strengthen its position in the high-performance KVM and KVM-over-IP market place.

COLLABORATIONS

Leti, an institute of CEA Tech, announced the continuation of its collaboration with **Qualcomm Technologies Inc.**, a subsidiary of Qualcomm Inc., to develop CoolCube™, Leti's new sequential integration technology that eliminates the need for through-silicon vias (TSV) and enables the stacking of active layers of transistors in the third dimension. The extended project's goals include building a complete CoolCube™ ecosystem that takes the technology from design to fabrication. CoolCube™ was created by Leti as a unique and innovative device scale-stacking technology that allows the design and fabrication of very high-density and high-performance circuits.

DragonWave and **Mitel** have announced a joint initiative focused on advancing the development of 5G networking. Mitel will contribute software and mobile network expertise to the project, while DragonWave will contribute all outdoor networking expertise combined with small cell-focused and high-capacity, spectrally-efficient packet wireless backhaul solutions. The relationship will initially focus on technology and research in support of compatible 5G solutions, with the option to evolve commercially as the 5G market matures and business opportunities develop.

Presto Engineering Inc., a world leader in semiconductor product engineering and supply chain management, and **Peraso Technologies**, a wireless chipset manufacturer, jointly announced their successful collaboration in developing a comprehensive test solution for Peraso's recently launched 60 GHz semiconductor products. The Peraso chipset is currently in full mass production with Presto providing test services at volumes of tens of thousands of parts per month. The announced solution is the first phase of a project that will culminate in a high-efficiency test solution – 40× faster and capable of supporting high-volume production (millions of devices per month) for the consumer electronics market — planned for later this year.

Customers of **Samsung Foundry** and **ANSYS** have the power to innovate the next generation of electronic devices for high-performance computing, mobile, automotive and IoT applications thanks to Samsung Foundry's qualification of ANSYS solutions. This qualification for the latest generation of chip technologies enables customers to bring their cutting-edge products to market even faster while reducing design costs and risk. Cutting-edge electronic products require high-performance, reliability and less power. To accomplish this, multiple subsystems of an electronic product are combined into one or more integrated circuits known as a system on a chip (SOC).

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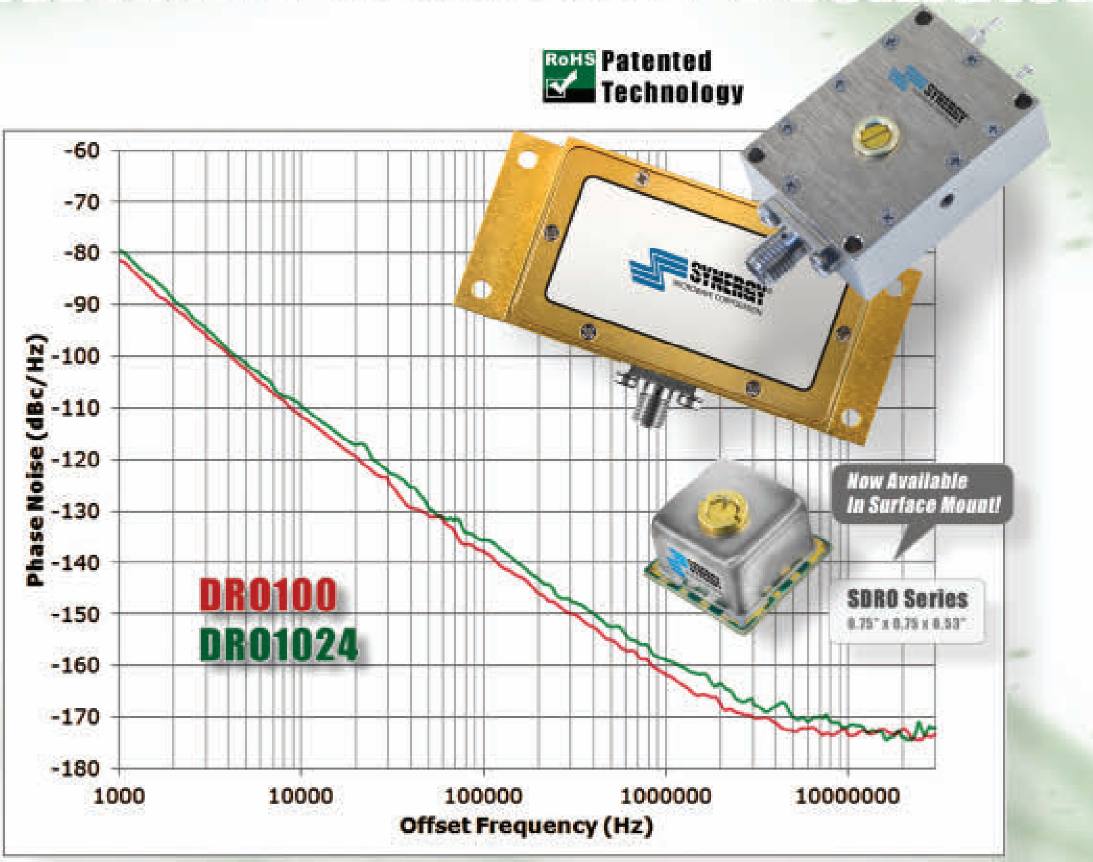

Model	Frequency (GHz)	Tuning Voltage (VDC)	DC Bias (VDC)	Typical Phase Noise @10kHz (dBc/Hz)
Surface Mount Models				
SDRO1000-8	10	1 - 15	+8 @ 25 mA	-107
SDRO1024-8	10.24	1 - 15	+8 @ 25 mA	-111
Connectorized Models				
DRO100	10	1 - 15	+7 - 10 @ 70 mA	-111
DRO1024	10	1 - 15	+7 - 10 @ 70 mA	-109

Model	Center Frequency (GHz)	Mechanical Tuning (MHz)	Supply Voltage (VDC / Current)	Typical Phase Noise @10kHz (dBc/Hz)
Mechanical Tuning Connectorized Model				
KDRO145-15-411M	14.5	±10 MHz	15 V / 130 mA (Max.)	-88

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Around the **Circuit**

NEW STARTS

SemiGen Inc., an ISO and ITAR registered RF/microwave assembly, automated PCB manufacturing and RF Supply Center, has launched a new website. The site features updated RF/microwave testing/assembly/design, PCB assembly, semiconductor upscreening, and RF/microwave module repair pages with detailed parameter and specification listings. The site also offers downloadable datasheets of all components ranging from super thin chip capacitors, spiral inductor coils and limiter diodes. If you're looking for supplies, the site now features a large selection of sizes of adhesives, bonding tools, wires and ribbon and epoxy preforms available for purchase.

ACHIEVEMENTS

Integrated Microwave has achieved AS9100 certification in accordance with the requirements of AS9104/1:2012 for the design and manufacture of precision RF and microwave filter products for the aerospace, space, defense, test equipment, scientific and communications industries. Integrated Microwave is a worldwide leader in the design and manufacture of custom ceramic and lumped element filters and diplexers. A full range of technologies is available for a wide variety of commercial and military applications.

Modelithics Inc., an industry leader in simulation models for RF, microwave, and millimeter wave devices, announced 15 successful years in business. Since 2001, Modelithics has delivered excellence and innovation in the field of RF and microwave wireless design. Modelithics' premier product, the Modelithics COMPLETE Library has grown from its initial release, containing less than 2000 components, to the latest version which now represents over 10,000 commercially available RF and microwave passive and active devices.

Globalstar Inc. announced the awarding of a Supplemental Type Certificate (STC) from the FAA for its Part 23 Light Aviation Aircraft Antenna. The issuance of the STC validates that all quality and safety requirements of the FAA for the product have been met through rigorous testing and evaluation which took place over the past year. The initial issuance was obtained on a Beechcraft Baron with an additional 700 models expected to be added to the Approved Model List (AML).

Lockheed Martin recently delivered the 150,000th Enhanced Laser Guided Training Round (ELGTR), which gives warfighters the only live-fire laser-guided bomb (LGB) training solution available worldwide. Lockheed Martin has been producing low-cost and highly effective training rounds for the U.S. Navy, Marine Corps and international customers since 1992 with the beginning of LGTR production, and continuing with ELGTR production since 2006. ELGTR accurately replicates the key performance and laser-engagement requirements of Paveway TM II laser-guided weapon systems to provide the warfighter with the employment and operational capability of the LGB, while preserving tactical weapons inventory and effectively reducing overall training cost.

Cadence Design Systems Inc. announced that **Ethertronics**, a leader in ultra-high performance smart antenna system solutions, used Cadence® Conformal® ECO Designer to completely redesign the digital interface section of a complex RF/mixed-signal design by reusing transistors in the base layers, enabling the redesign in a metal only change. This reduced the design schedule by 50 percent while also achieving more than 60 percent mask cost savings. The solution enabled Ethertronics to use automated engineering change orders (ECO) to deliver its complex product to market with the flexibility of a field-programmable gate array (FPGA) design.

SI2 Technologies, a Mass.-based RF and sensor systems company, has been recognized with an award as the first member of the latest Manufacturing Innovation Institute, NextFlex, which is focused on maturing flexible hybrid electronics (FHE) manufacturing. The award was presented by NextFlex executive director, Malcolm Thompson, at the NextFlex Founders reception held in conjunction with the 2016 FLEX Conference and Exhibition in Monterey, Calif.

CONTRACTS

Orbital ATK Inc., announced that it was selected by the **National Aeronautics and Space Administration (NASA)** as the prime contractor for the NASA Sounding Rockets Operations Contract III (NSROC III) program. The award is a one-year base contract with four one-year option periods and is valued at approximately $200 million. Orbital ATK won the new contract in an open competition and has served as the prime contractor on the program since 2010.

Construct F-35 Aircraft Engineering has been awarded a £118 million contract to build engineering and training facilities at RAF Marham in Norfolk, in readiness for the arrival of the UK's first F-35 Lightning II aircraft in 2018. The contract award coincides with the early completion of the tenth aft fuselage for the UK aircraft at BAE Systems' manufacturing site in Samlesbury, Lancashire. The contract for the new facilities has been awarded by Lockheed Martin — the prime contractor of the F-35 aircraft programme. With work beginning at RAF Marham this month, BAE Systems will construct three facilities to support the operation of the F-35 fleet; a maintenance and finish facility, a logistics operations centre and an integrated training centre. The work is scheduled to be completed in early 2018.

The National Science Foundation has awarded $8 million to **Raytheon BBN Technologies** to continue the redesign of the Internet. The foundation-funded Global Environment for Network Innovations (GENI), a collaborative community of scientists from around the world, is working to meet the performance, security, and agility demands of new and emerging technologies online. Under the new award, Raytheon BBN Technologies will oversee expansion of the GENI platform for continued advances in education, medicine, network research and public safety.

Cubic Global Defense, a business unit of Cubic Corp., announced the award of a four-year, $3.6 million contract to support the U.S. Army Europe (USAREUR) Joint Multinational Readiness Center (JMRC) situated in

Hohenfels, Germany. This new contract is an expansion of a five-year contract the Joint Multinational Simulation Center awarded to Cubic earlier this year to expand support for simulation and maneuver training efforts. JMRC is one of the seven directorates falling under the leadership of USAREUR's 7th Army Joint Multinational Training Command (JMTC) headquartered in Grafenwoehr, Germany.

Mercury Systems Inc. received a $2.2 million order from a leading systems integrator to supply high-performance digital signal processing and RF modules for a signals intelligence application. The order was booked in the company's fiscal 2016 third quarter and is expected to be shipped by the end of its fiscal 2016 fourth quarter.

Comtech Telecommunications Corp. announced that its Santa Clara, Calif.-based subsidiary, **Comtech Xicom Technology Inc.**, has received a Ka-Band high-power amplifier contract for $1.3 million from a leading satellite communications (SATCOM) direct-to-home (DTH) television service provider.

Moog Inc. announced that its Aircraft Group was selected by **Northrop Grumman Corp.** to supply the complete flight control actuation system for the Tern unmanned aircraft under development through a joint program between Defense Advanced Research Projects Agency (DARPA) and the U.S. Office of Naval Research. Under the contract, Moog has been tasked to design, qualify and manufacture the flight control actuation system for the full-scale demonstration aircraft, including flight control actuators, actuator-control electronics and accessories. The Moog flight control system includes redundant actuation for vertical take-off and landing and cruise flight.

Air Products has been awarded a long-term contract by **JCET STATS ChipPAC Korea Ltd.**, a semiconductor packaging and test services provider, to supply tonnage quantities of nitrogen to its new production facility in Incheon, South Korea. Air Products will build, own and operate a new on-site nitrogen plant—which is expected to come onstream in 2016—to produce gaseous nitrogen for JSCK's new facility located in the Yeongjongdo development area of the Incheon Free Economic Zone (IFEZ). Air Products will start supplying JSCK with liquid nitrogen from another one of its facilities beginning the middle of this year.

PEOPLE

EDI CON USA 2016, a conference that brings together engineers working on high-frequency analog and high-speed digital designs, taking place September 20-22 in Boston, Mass. at the Hynes Convention Center, announced **Dr. Eli Brookner's** participation as Honorary Chair. As previously announced, Dr. Brookner will provide a keynote speech and also teach a short course at the conference,

Around the **Circuit**

▲ *Dr. Eli Brookner*

covering advancements in phased array and MIMO radar technology. As Chair, Dr. Brookner will open the conference's plenary session on Tuesday, September 20, offering his insights on today's design challenges and setting the tone for this inaugural event in the U.S.

REP APPOINTMENTS

Richardson RFPD Inc. announced an expanded global franchise agreement with **Sierra Wireless**. The new agreement builds on the long-term collaboration between the two companies, as well as a mutual commitment to serve the emerging industrial IoT market. Under the terms of the agreement and effective immediately, and with a focus on industrial connectivity, Richardson RFPD will sell and support a comprehensive portfolio of Sierra Wireless products, including 2G, 3G and 4G embedded cellular modules and modems, for an array of IoT/ M2M applications.

Southwest Antennas Inc. announced the addition of **Wes Tech Associates** to their expanding sales representative network, with a focus on bringing Southwest Antennas' rugged lineup of antennas, RF coaxial gooseneck adapters, mounts, filters, and other RF and microwave accessories to WES Tech's sales territories in the Midwestern United States. WES Tech Associates is principled by Willie Sneller and Butch Hataway, and maintains a sales office in Cedar Rapids, Iowa. Their sales territories include Iowa, Minnesota, Missouri, Kansas, Southern Illinois, Nebraska, North Dakota and South Dakota.

PLACES

Exodus Advanced Communications Corp. announced that construction has been completed on their new facility. Their corporate headquarters located in Las Vegas, Nev., will open the door for continued excellent service featuring added design capability, system integration/manufacturing and source inspection. This facility is an extension of the company's existing engineering capability that includes a state-of-the-art-chip and wire design and manufacturing centers.

Custom MMIC recently moved their offices to Chelmsford, Mass. This move will support the company's rapid growth, providing a threefold increase in office and lab space. The address of the new location is 300 Apollo Drive, Chelmsford, MA 01824. All other contact information, including phone numbers, remains the same.

Electronic Fluorocarbons LLC, a provider to the semiconductor industry of Electronic Specialty Gases (ESG's), packaged and purified to the highest specifications, announces that construction is well underway on their state-of-the-art manufacturing and purification facility on a 15 acre greenfield site in Hatfield Township, Penn. The facility is expected to begin operations in the 3rd quarter of this year.

INVITED PAPER

EDITOR'S NOTE

This is the first of a three-part series continuing to explore the theory and application of Möbius metamaterials.

Möbius Metamaterial Inspired Next Generation Circuits and Systems

Ulrich L. Rohde
Brandenburgische Technische Universitat, Cottbus, Germany
Ajay K. Poddar
Synergy Microwave, Paterson, N.J.

From metallic alloys to plastic composites, scientists and engineers have been developing artificial materials for various applications. Metamaterial, a family of artificial composite structures made from conventional material with unconventional structures, exhibits distinct properties apart from what nature can provide easily, such as negative index characteristics for selective frequency regions.[1-8] The shape, size, geometry, orientation and arrangement of metamaterial gives it smart properties, capable of manipulating electromagnetic (EM) waves by bending, blocking, absorbing and enhancing to attain benefits that go beyond what is possible with conventional materials.

Metamaterial structures that show Möbius symmetry, where coupling strengths and size of the structure scales can be engineered, are promising candidates for next generation electronics in lower profile and energy saving electronics.[2] Distinctive contributions in the field of Möbius Metamaterial Inspired (MMI) technology allow topological exploration, yielding high Q factor, based on evanescent mode resonance.[3] The reported multi-knot Möbius Metamaterial Strip (MMS) structure enables multi-injection-nodes for multi-phase-injection-locking, facilitating concurrent signal-source solutions.[4] MMI based technology enables energy harvesting for the realization of next generation energy-saving for spintronic devices, quantum oscillators, RFID, signal retention devices and proximity sensors; as well as providing enhanced dynamic range for underground detection, detection of trapped victim heartbeats and biosensor applications.[5-6]

What makes an MMI structure unique is its topology and size. It interacts with forces at the nanoscale, so that interface dynamics can be explained by quantum mechanics. The same structure scaled much larger than its wavelength would no longer exhibit the same properties. Its characteristics can be described by conventional structural engineering and material science. At the nanoscale, an MMI structure can exhibit the repulsive Casimir force,[9-11] which has important practical applications in creating anti-gravity and levitation.[12] ***Figure 1a*** shows the Casimir force 'F' on parallel plates in a vacuum, the effective force F is proportional to A/d^4, where A is the area of plate and d is the distance between the plates.[9] It can be either an attraction or a repulsion depending on the specific arrangement of the two plates. ***Figure 1b*** shows the repulsive Casimir force 'F' on parallel plate kept in vacuum,[11] while ***Figure 1c*** shows how this can be used to balance the weight of a mirror.[12]

The Casimir force arises from the interaction of the surfaces with the surrounding elec-


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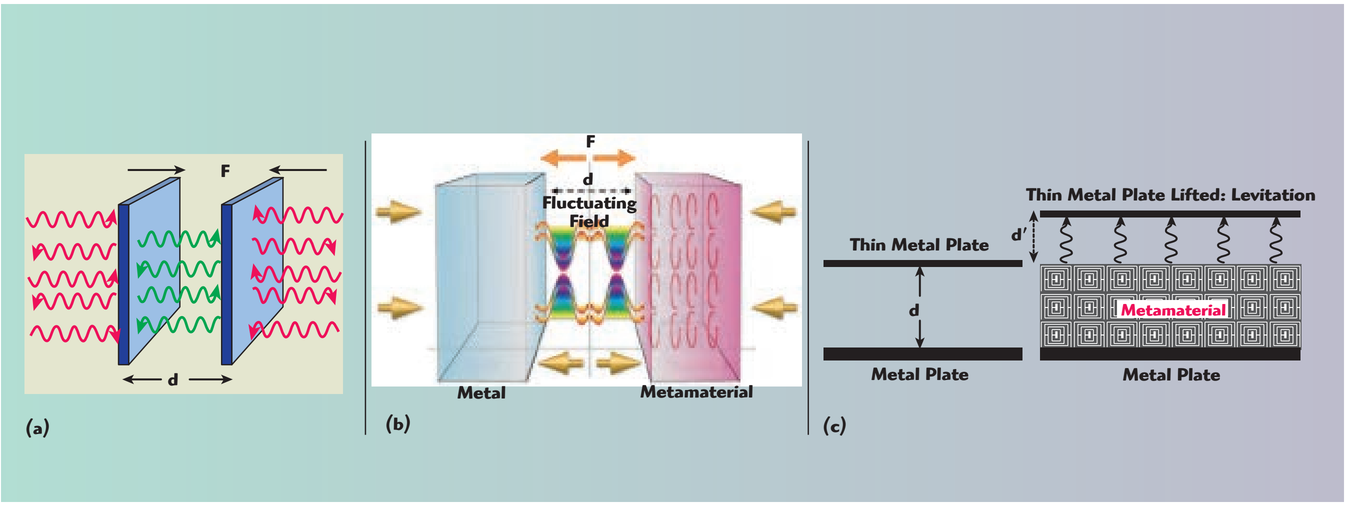

Fig. 1 The Casimir force (F) on a parallel plate kept in vacuum (a)[9] *the repulsive Casimir force (F) on parallel plate (b)*[11] *Casimir force levitating a mirror (c).*[12]

tromagnetic spectrum, and includes a complex dependence on the full dielectric function of both surfaces and the region between. The complexity of the Casimir force leads to significant possibilities for manipulation through materials, geometries and other phenomena. It potentially provides the opportunity for neutralizing or partially cancelling Van Der Waals forces. On the more theoretical side, the MMI structure can produce a powerful Casimir effect (force from nothing), which enables the transport of matter, i.e., the use of this effect to attract or repel physical matter. Some practical applications include auto focusing camera lenses, more efficient servos, silicon array propulsion systems and high speed rail systems. The implications of a repulsive Casimir force for the micro-electromechanical systems (MEMS) industry could be significant with potential applications including stiction prevention in sensors, contactless bearings and contactless power transmission.[10] MEMS based electronics offer inexpensive high performance solutions; but reliability issues arising from stiction in MEMS switching devices limits their use in high frequency applications.

The pioneering contributions relate to techniques for a stiction-free MEMS lateral switch and its application in switching networks and phase shifters in electronically scanned phase array antennas for Internet of Things (IoT) applications. In a vacuum, the force of attraction between two surfaces separated by nanometers is explained by the Casimir effect, but effective repulsive forces can be noticed when the two surfaces with materials of different permittivity are taken into consideration.[11-12] This phenomenon can also be observed if one of the surfaces possesses negative permittivity. This approach can resolve the stiction problem, leading to new material and fabrication methods in next generation MEMS.

One of the exciting properties of MMI structures is that they can bend light in a way that is mathematically equivalent to the way space-time bends light, allowing topological ex-

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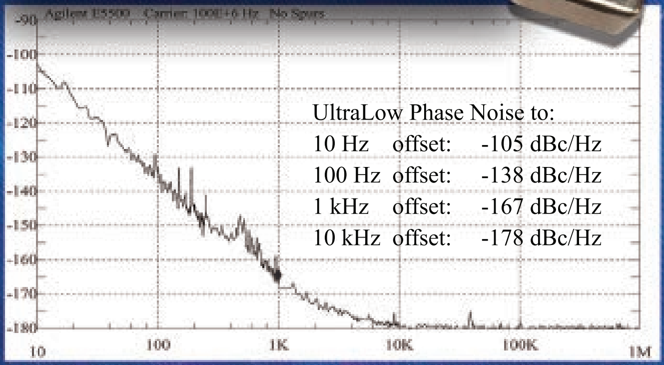
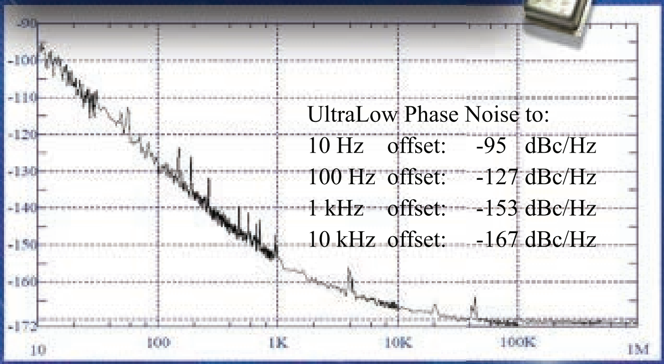


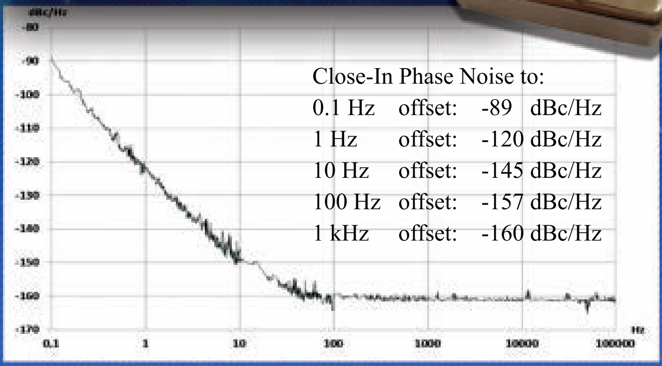
MV269 New

- Frequency range: 60-120 MHz
- Aging: ±1E-7 per Year
- Package: 20.3x12.7x9.5 mm (DIL14)



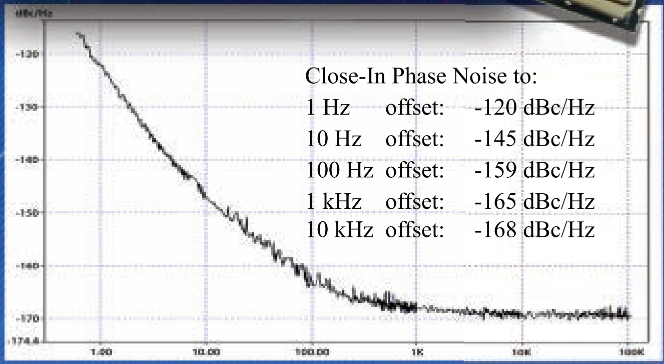
MV341

- Standard Frequency: 10 MHz
- Allan Deviation: <2E-13 per Sec.
- Package: 50.8 x 50.9 x 16.0 mm



MV272M Low G Sensitivity New

- Standard Frequency: 10 MHz
- Allan Deviation: <4E-13 per Sec.
- Package: 36.7 x 27.0 x 16.0 mm (SMD)



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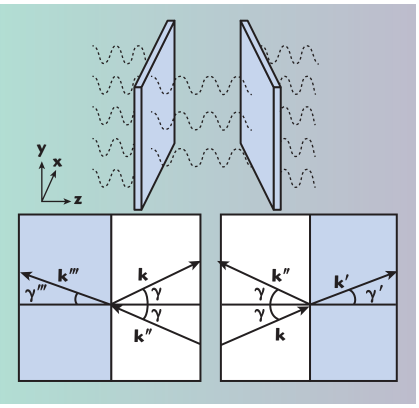


Fig. 2 The Gravitational Casimir effect.[13]

ploration for the realization of low cost gravitational wave detectors. ***Figure 2*** shows the Gravitational Casimir effect, with a two plate setup. The change in the refractive index of the plates causes the gravitational wave to refract, where k represents the wave vector of the incident, transmitted, and reflected gravitational waves, and γ is the corresponding angle with respect to the surface normal.[13]

Details of the Casimir effect and applications and use of the MMI structure for futuristic applications will be discussed in part 2 (June 2016 issue) and part 3 (July 2016 issue). This article briefly describes applications of the MMI structure for the IoT, CubeSat, and examples of the

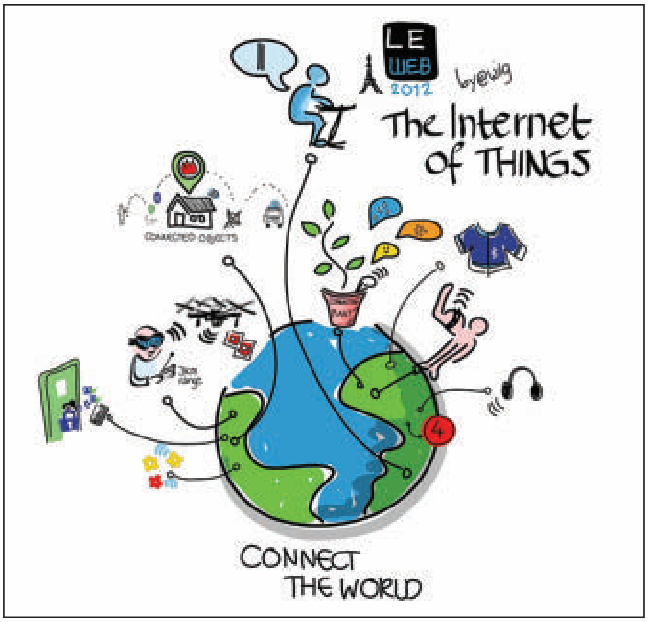


Fig. 3 The Internet of Things.[14]

Möbius transformation and metamaterial symmetry for medical telemetry, imaging and sensor applications.

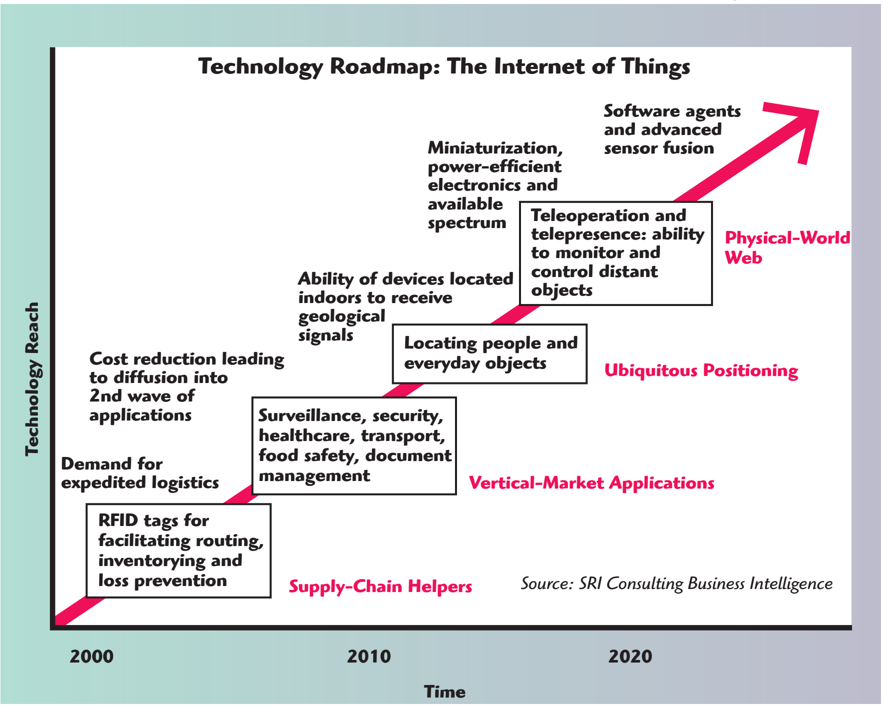
INTERNET OF THINGS (IoT)

The Internet of Things (IoT) is the network of physical objects: devices, vehicles, buildings and other items embedded with electronics, software, sensors and network connectivity that enable these objects to collect and exchange data (see ***Figure 3***).[14] The IoT allows objects to be sensed and controlled remotely across the existing network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems, resulting in improved efficiency, accuracy and economic benefit; when the Internet is augmented with sensors and actuators, it becomes an instance of the more general class of cyber-physical systems, which encompasses technologies such as smart grids, smart homes, intelligent transportation and smart cities. Each thing is uniquely identifiable through its embedded computing system but is also able to interoperate within the existing Internet infrastructure.

Figure 4 illustrates the IoT Technology Roadmap.[14] Current technology cannot yet meet the needs for faster, more reliable and more ubiquitous radio systems required by the IoT. The trend over past decades has been to place an ever increasing emphasis on digital signal processing (DSP), where spectral efficiency has been maximized via sophisticated modulation, multiplexing or MIMO schemes. However, these approaches have now reached their limits and migration to millimeter wave and terahertz frequencies has become indispensable to access broader spectral resources. Unfortunately, DSP is not applicable at such frequencies, where signals are varying too fast to be digitized. The unprecedented control of electromag-

netic properties afforded by the MMI structure opens the door to provide fast processing and low power miniaturized electronics to overcome technological challenges.

Recent publications describe the real-time analog signal processing (R-ASP) of electromagnetic waves at very high frequencies using metamaterial inspired technology in conjunction with concepts of ultrafast optics.[15-17] There is need for a special branch of metamaterial engineering concerning the manipulation of EM waves in space, time and space-time for the realization of an unlimited number of distinct types of artificial smart materials (electromagnetic band gap metamaterial, single negative metamaterial, double negative metamaterial, biisotropic and bianisotropic metamaterial and chiral metamaterial). This technology is suited for telecommunications, medical instrumentation (bio-medical, oral and oncology, ultrasound imaging and magnetic resonance imaging), optics, sensing (bio, thin film, wireless strain, aerospace and defense), energy harvesting, transportation of matter, and levitation/anti-gravity (attractive and repulsive Casimir effect).



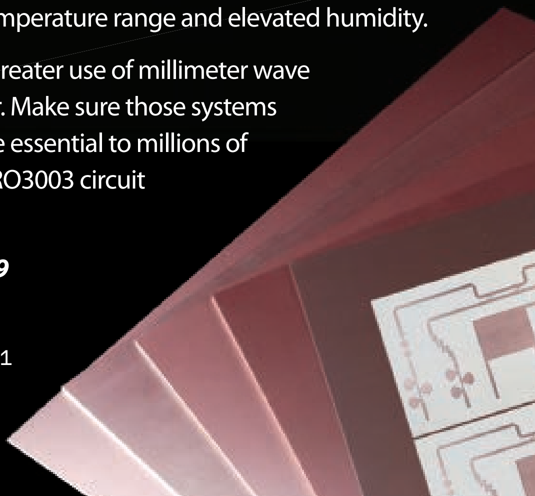
▲ *Fig. 4 IoT Technology Roadmap.*[14]

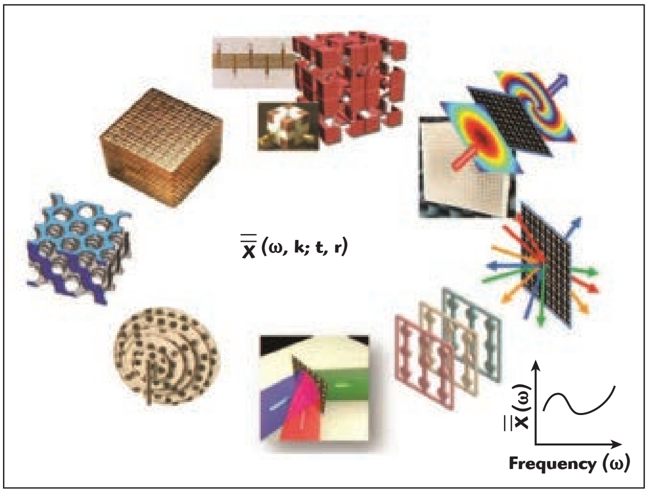
These applications are supported on the IoT technology roadmap.[14] ***Figure 5*** depicts the typical sketch of metamaterial engineering, illustrating the solutions for next generation electronic circuits and systems.[8] As shown in Figure 5, $(\bar{\bar{\chi}})\ \omega,k;\ t,r)$ is the generic notation of tensors that represents the metamaterial permittivity ($\bar{\bar{\epsilon}}$), permeability ($\bar{\bar{\mu}}$), magnetic-to-electric coupling ($\bar{\bar{\xi}}$) and electric-to-magnetic coupling ($\bar{\bar{\zeta}}$) tensors, while ω is the angular frequency (reciprocal time), k is the spatial frequency (reciprocal space), t is time (direct time) and r is space (direct space). Combining different dependencies (ω, k; t, r) and bianisotropies ($\bar{\bar{\epsilon}}$, $\bar{\bar{\mu}}$, $\bar{\bar{\xi}}$, $\bar{\bar{\zeta}}$) leads to a virtually unlimited number of distinct types of metamaterials.[8]

CUBESAT

Satellites play a decisive role for establishing communication networks; these satellites are expensive, large in size and take a number of years to build up. To keep costs low, small satellites such as the CubeSat, have yielded big rewards versus their larger counterparts. Small satellites are located in low-Earth orbit (LEO) in the range of 200 to 2,000 km altitude. The speed of small satellites in LEO (relative to Earth's surface) is around 7.5 km/s, which is an orbital period of approximately 90 minutes. The definition of CubeSat comes from its shape and weight. It belongs to the family of small satellites: Picosatellite <1 kg,


38GHz
60GHz
24GHz
79GHz



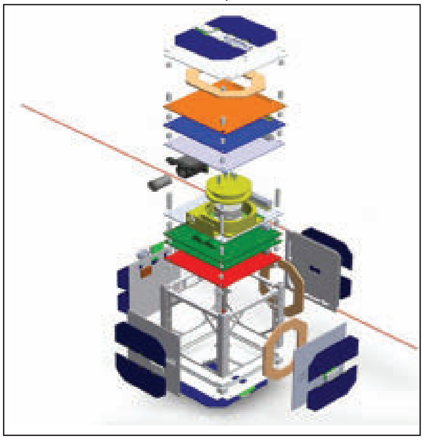


▲ *Fig. 5 Sketch of metamaterial engineering.*[8]

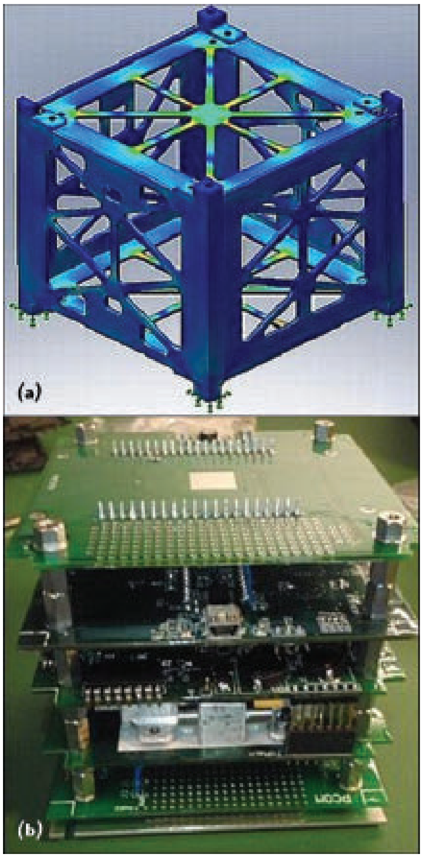
nanosatellite 1 to 10 kg, and microsatellite 10 to 100 kg). ***Figure 6*** shows a typical CAD model of a CubeSat (10 cm × 10 cm × 10 cm),[18] ***Figure 7*** shows a typical bus structure and ***Figure 8*** shows the actual CubeSat in hand as well as its position in low-Earth orbit. [20] The basic subsystems of a CubeSat are telemetry, tracking and control (TTC), power generation and distribution (PGD), data command and handling (DCH), altitude determination and control (ADC) and the payload.

Small satellites cost much less per unit; many CubeSats can be fabricated for the price of one conventional satellite. Although a CubeSat is lower in cost, it obviously does not have the individual payload capacity of a large satellite. A possible cost-effective alternative is to launch many CubeSats as depicted in ***Figure 9***, and construct a network of small satellites that can accomplish the same tasks as one large satellite. The advantage is that if one CubeSat fails, the network can be reconfigured to pick up the slack, whereas one satellite is a single point of mission failure. ***Figure 10*** illustrates the CubeSat launch operations concept,[19-22] while ***Figure 11*** shows the communication link.[23]

Antenna size for the communication link is a limitation in small satellites. The maximum gain of conventional aperture antennas (e.g., dish reflectors, horns, arrays) is determined by aperture size. The relatively large size needed for adequate performance, however, makes them unfriendly for space application. Modifications enabled by smart material



▲ *Fig. 6 Typical CubeSat layout (courtesy ESTCube-1).*[18]



▲ *Fig. 7 CubeSat bus structure (a) and photo of the interior bus configuration (b) (courtesy Colorado Space Grant Consortium).*[19]

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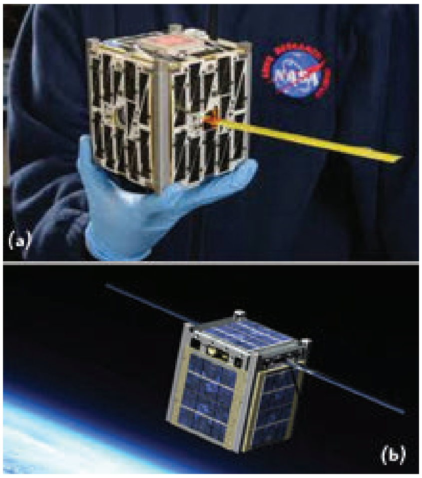
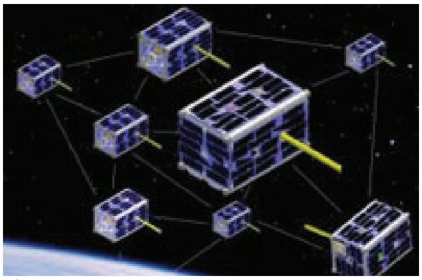
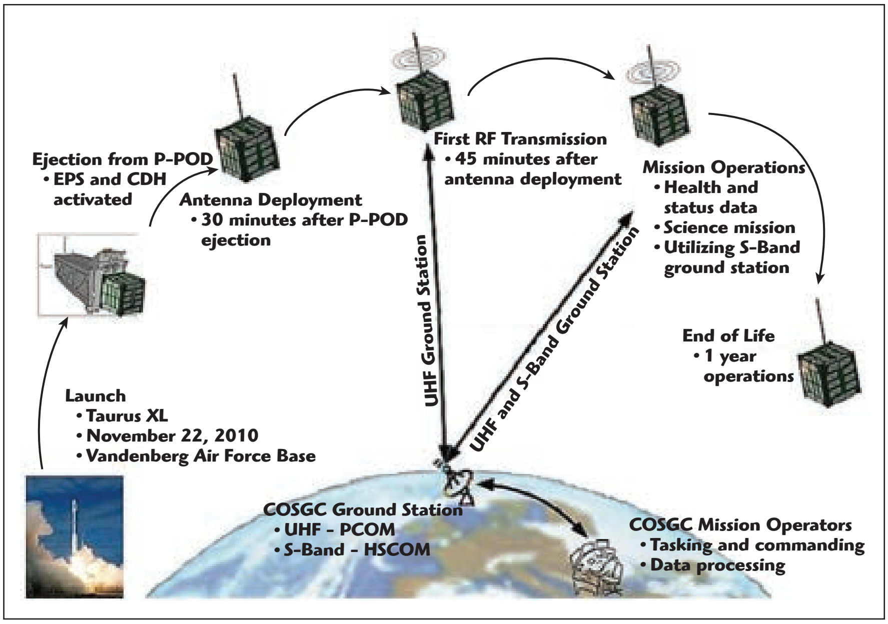


▲ *Fig. 8 CubeSat hardware (a) and CubeSat in low-Earth orbit (b) (courtesy NASA).*[20]



▲ *Fig. 9 Network of CubeSats (courtesy NASA).*[20]



▲ *Fig. 10 CubeSat launch operations concept (courtesy Colorado Space Grant Consortium).*[21]

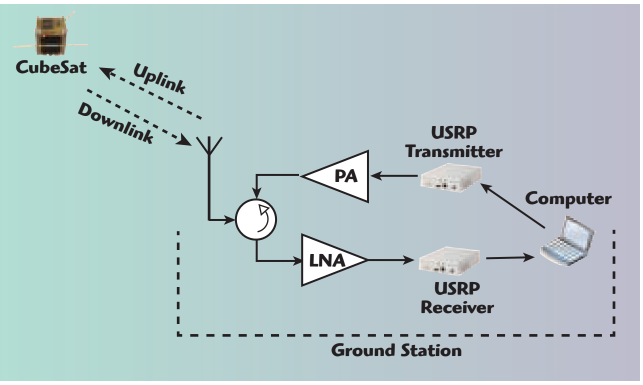
can either enhance performance or reduce mass, thus lowering the cost of putting the antenna in space. Lighter antennas reduce weight directly, while more energy efficient antennas reduce the size and weight of required storage batteries and solar cells. The metamaterial lined horn antenna with low-index electromagnetic properties shown in ***Figure 12***, for example, is relatively small in size, but not yet suitable for small satellite (CubeSat) applications.[24]

Ongoing research towards developing miniaturized low-index metamaterial lens antennas for small satellites faces challenges such as bandwidth and efficiency. Metamaterial lenses exhibit material properties that approximate the behavior of a material with low ($0<n<1$) effective index of refraction, and by using dispersion techniques a relatively wideband low-index region can be obtained. A low-index metamaterial lens can create highly collimated beams in the far field from a low directivity antenna feed by, for example, using dual-split ring resonators (DSRR) in the x-y plane for a low permeability response, and end-loaded dipole (ELD) elements in the x-z and y-z planes for a low permittivity response.

As ε or μ approaches zero, the passband narrows, improving collimation and directivity of the antenna, so that it can be integrated with software defined radio (SDR), facilitating a transformative communication system with remarkable frequency and polarization agility; this is well suited for CubeSat application where multifunctional miniature antennas is the desired goal.

Smart MMI structures support the development of miniaturized multi-

functional antennas, high efficiency solar panels for power generation and the performance of real-time analog signal processing of electromagnetic waves at very high frequencies. Tunable metamaterials using Möbius topology enable broadband tuning in a compact size with narrow instantaneous bandwidths across an entire communications band depending on the channel in use. Tuning the metamaterial and the antenna in tandem provides a dynamic operating channel with a tunable, nearly arbitrary polarization response as an added benefit. The major challenge is figuring out a way to scale these metamaterial and associated antenna structures to operate at lower frequencies while maintaining a practical physical size and weight. MMI technology enables a planar antenna with reduced size at lower frequency without degrading performance.

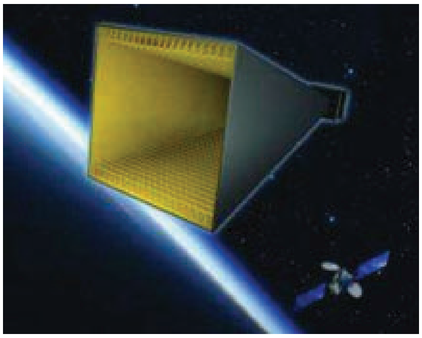


▲ *Fig. 11 Schematic of general CubeSat communication setup.*[23]

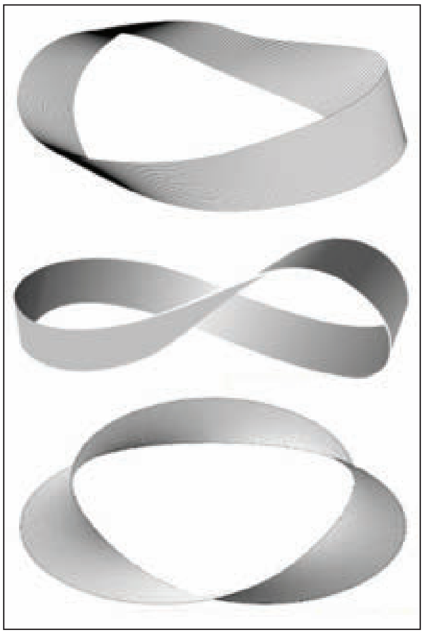
MÖBIUS TRANSFORMATION: METAMATERIAL SYMMETRY

The concept of the Möbius strip is based on the fact that one can travel without encountering obstruction around the loop. The loop behaves like a never ending point, giving rise to the concept of an infinite path in the space-time domain. The concept of infinity is not emptiness or space; rather, it is the concept of having no beginning and no end (see ***Figure 13***). As shown, the Möbius strip with one twist and pinched in the middle appears like the mathematical symbol for infinity. Since space-time is curved, it could conceivably run back on itself like the Möbius strip, and have no boundary. Our universe can be considered to be a replica of the Möbius strip with a multiple number of twists of vibrating strings in space, whirling in a warped loop as it experiences its own starting point, and recurs perpetually in space-time dynamics. These "strings" vibrate in multiple dimensions, and depending upon how they vibrate, they might be seen in 3-dimensional space as matter, light or gravity. The figure also shows a 3-twist Möbius strip (twists can be defined as knots).

For engineers, the multi-knot Möbius strip surface is a launch pad to complex geometries and topological exploration of next generation electronic circuits and systems for industrial, medical and space applications.



▲ *Fig. 12 Typical metamaterial lined feed horn antenna for satellite communications.*[24]



▲ *Fig. 13 Möbius strips with single twist (top) with single twist and pinched (center) and with three twists (bottom).*

Topology is a field of science that studies invariance of certain properties under continuous deformation, such as stretching, bending or twisting of the underlying geometry. Topological symmetry is defined as a property, conserved when the system undergoes an alteration (deformation, twisting and stretching of objects). Möbius strips deform in a way that its metrical properties barely change, and they violate the Hückel rules.[25] Some nanostructures, for example, possess identical elastic properties even after deformation.

It is interesting to note that the Möbius transformations allow complex geometries for realizing a number of distinct types of metamaterials. Metamaterials can be realized with either an array of wire/split ring structures or composite right/left-handed (CRLH) transmission line resonators. The major difference between the two is the coupling dynamics; the wire/split ring structure is loosely coupled, whereas the CRLH transmission line resonator structure is tightly coupled. Since the wire/split rings are practically uncoupled, operating bandwidth is determined by the quality factors and losses associated with individual wire/split-ring structures. The challenge is to reduce the losses and improve the quality factors. In the case of CRLH transmission line resonator-based structures, the resonators are tightly coupled, effectively increasing the operating bandwidth as compared to wire/split ring-based structures.[7]

Topological Möbius metamaterial symmetry due to Möbius transformation f(z), is given by[26]

$$f(z) = \frac{az+b}{cz+d};\quad (a,b,c,d \in \mathbb{C} \text{ and } ad-bc \neq 0) \tag{1}$$

$$z \in \mathbb{C} \rightarrow z = r\left[\cos(\theta) + i\sin(\theta)\right] \tag{2}$$

where a, b, c and d are complex numbers, and the numerator of Equation 1 is not a multiple of the denominator (i.e., ad-bc≠0).

From Equation 2, the properties of the Möbius transformation f(z) are

(i) f(z) can be expressed as a composition of affine transformations (scaling: $z \to tz$, translation: $z \to z+p$, rotation: $z \to e^{i\theta} z$, complex conjugation: $z \to \bar{z}$, inversion: $z \to \frac{1}{z}$), where t, p $\in \mathbb{C}$

(ii) f(z) maps $\mathbb{C}$ one-to-one onto itself, and is continuous

(iii) f(z) maps circles and lines to circles and lines

(iv) f(z) is conformal

From (i)-(iv), the family of functions is the composition of functions; the identity element is the identity map, and the inverse is given by inverse function. The Möbius group consists of those fractional linear transformations that map the open unit disk $\mathbb{D}=\{z\in\mathbb{C}:|z|<1\}$ to itself in a one-to-one way. These transformations and their inverses are analytic on $\mathbb{D}$ and map its boundary, the unit circle $S^1=\{z\in\mathbb{C}:|z|<1\}$ to itself. The automorphism of the disk is in the form:

$$f(z) = e^{j\varphi}\frac{\alpha - z}{1-\bar{\alpha}z} \tag{3}$$

$$z = M(w) = \frac{e^{j\psi}w + \alpha}{1-\bar{\alpha}e^{\psi}w} \tag{4}$$

$$w = M^{-1}(z) = e^{-j\psi}\frac{z-\alpha}{1-\bar{\alpha}z} + \alpha \tag{5}$$

where $\varphi\in R$, $\psi\in R$, and $\alpha\in\mathbb{D}$.

From Equations 1 through 5, the Möbius transformation can be used to achieve Möbius metamaterial symmetry, which has received widespread interest in the field of metamolecules, optical polarization, DNA sensing and high frequency components for energy saving electronics and instrumentation.[26-35]

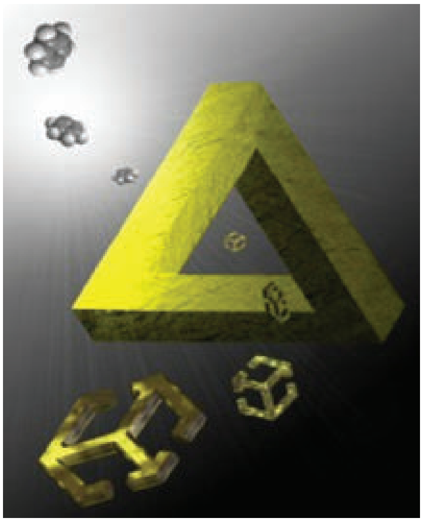


Fig. 14 Möbius strip symmetry in metamolecular trimmers.[27]

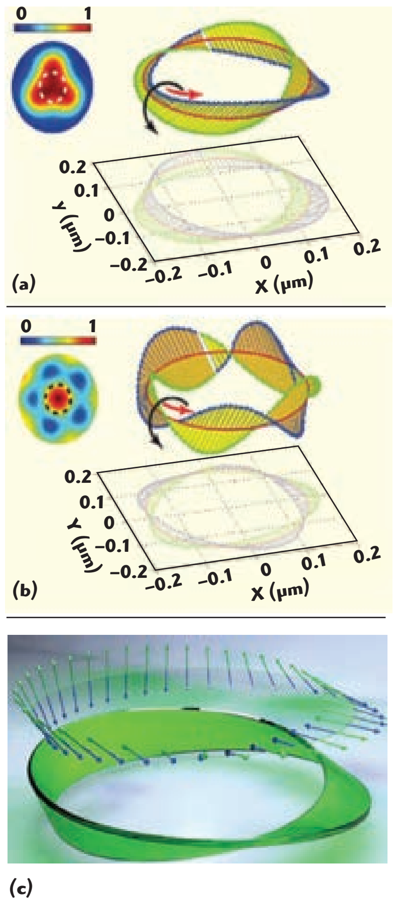


Fig. 15 Numerically calculated and experimentally observed optical polarization twist around the Möbius strip: single knot (a) multi-knot (b) and polarization twist (c).[28]

EXAMPLES: MÖBIUS METAMATERIAL SYMMETRY

Benzene Metamolecules

The EM symmetry discovered in metamaterial is equivalent to the structural symmetry of a Möbius strip, with the number of twists controlled by the sign change of the electromagnetic coupling between the meta-atoms. ***Figure 14*** illustrates metamaterial Möbius symmetry in metals and dielectrics.[27] As shown in Figure 14, the hyperspace Möbius mechanism transforms ordinary benzene molecules into metamolecules with Möbius symmetry; "the topological phenomenon that yields a half-twisted strip with two surfaces but only one side." The prototype of the metamolecular trimmer shown in Figure 14 is a 3-body system like a trimmer; metallic resonant meta-atoms configured as coupled split ring resonators (symbolized as metamolecules) exhibiting topological Möbius cyclic symmetry (C_3-symmetry) through three rota-

tions of 120 degrees. Möbius twists result from a change in the signs of the electromagnetic coupling constants between the constituent meta-atoms.[27] The interesting phenomena is that "different coupling signs exhibit resonance frequencies that depend only on the number of turns but not the locations of the twists," thus confirming its Möbius symmetry.

Polarized Light

Figure 15 illustrates the artificial Möbius strip formed by EM waves, which demonstrates that "a light-beam can be controlled so that its polarization twists follow a contour of Möbius strips."[28] The creation of EM waves around a Möbius contour is interesting for improving the fundamental understanding of optical polarization and the complex light beam engineering needed for developing optical micro- and nano-fabrication structures for sub-wavelength imaging. As shown in Figure 15, the typical Möbius strip surface consists of polarized states of a light beam, with a non-vanishing curvature, and exhibiting spatial symmetry.

DNA Strip Sensor

Figure 16 shows the nano-architectures of a Möbius DNA strip in which each colored band represents a different DNA double helix. Such nano-architectures can be used in high sensitivity biological and chemical sensing devices.[29]

MMI GRAPHENE

Graphene has received extensive attention recently due to its remarkable structural and superior electronic and optical properties.[30] A single layer of graphite exhibits mechanical properties like thin paper or plastic with large bulk modulus along the graphene plane and is easily bent or curved. This unique characteristic allows graphene to wrap into carbon nanotubes without deformation and qualifies its use as a material for the construction of Möbius strips for microwave and optical components. The bandgap and cohesive energy of Möbius graphene as depicted in ***Figure 17*** depends on the width of the strip, and is augmented by increasing the width, as described by[31]

$$E_{C0}^{r(M)} = \frac{E_{SCF}^{r(M)} - N_c \times E_{SCF}^{C} - N_H \times E_{SCF}^{H}}{\Sigma\left(N_c + N_H\right)} \qquad (6)$$

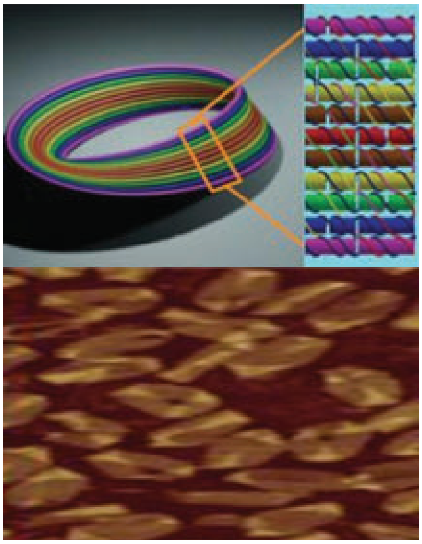


Fig. 16 Typical nano architectures of a Möbius DNA strip: colored Möbius strip (top left) strip section (top right) and DNA image (bottom).[29]

where the superscript r(M) corresponds to the graphene ribbon (Möbius strip), N_C is the number of carbon atoms, N_H is the number of hydrogen atoms, $E_{C0}^{r(M)}$ is the self-consistent field energy of the graphene ribbon, and E^C_{SCF} and E^H_{SCF} are the self-consistent field energy of the carbon and hydrogen atoms, respectively.

The magnetic moment and spin-properties of Möbius graphene are interesting. A graphene Möbius strip maintains its metallic surface states in the presence of an external electric field. For sufficiently higher applied electric field, spin flipping can take place in the Möbius strip. In contrast with graphene nanoribbons, graphene Möbius strips show half-semiconducting properties when an external electric field is applied. ***Figure 18*** shows the typical orbital of a graphene Möbius strip and spin dependent density of states (DOS). The ferromagnetism and spin-flipping properties of Möbius graphene are attractive for spintronic devices and quantum oscillator applications.[31]

Figure 19 shows the characteristics of Möbius molecular rings that support metamaterial applications (negative permittivity ε and negative permeability).[32] Two energy bands are denoted by their different pseudo spin labels $\sigma = \uparrow$ and $\downarrow$. Detuning $\Delta\omega = \omega - \Delta_0$.[32] The difference between the Möbius molecular ring and the common annulenes lies in the boundary condition. The negative index properties offer remarkable properties such as image cloaking, sub-wavelength imaging and enhancement of evanescent fields resulting in improved Q-factor.

Figure 20 depicts the application of graphene Möbius strips for the re-

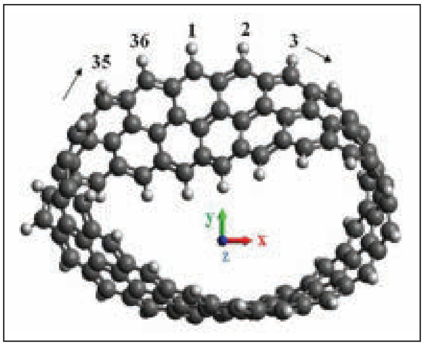


Fig. 17 Graphene Möbius structure with length L = 18 and width N = 3. Möbius axis and edge C atom index are shown.[31]

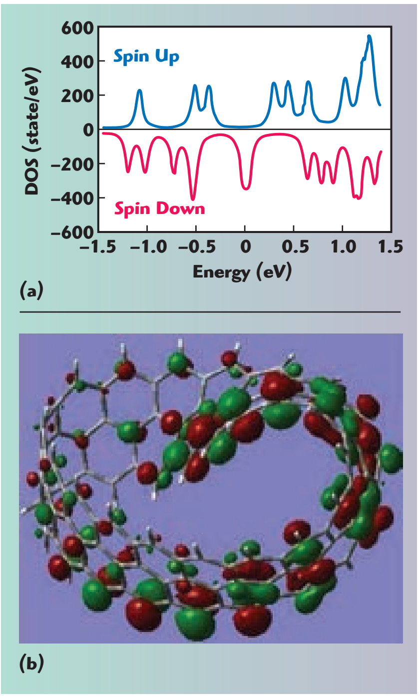


Fig. 18 Spin-dependent density of states of graphene Möbius strip as a function of electron energy (a) and molecular orbital at E=0 eV (b).[31]

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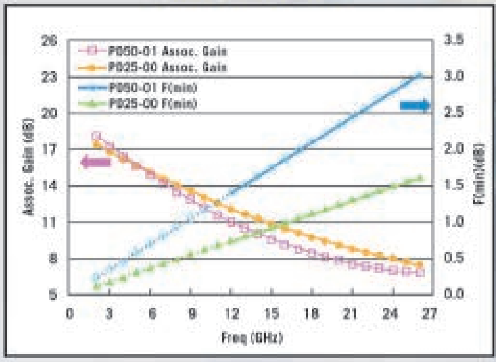
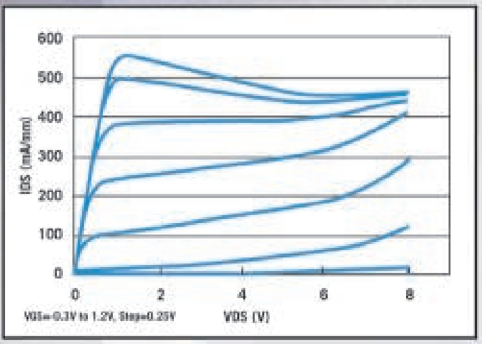
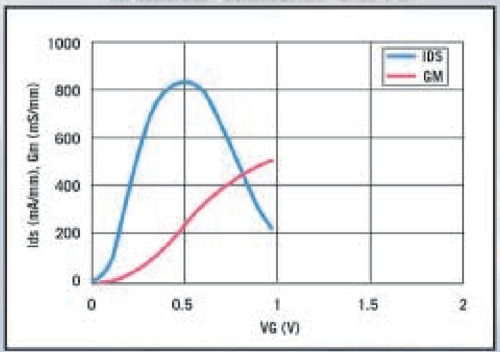


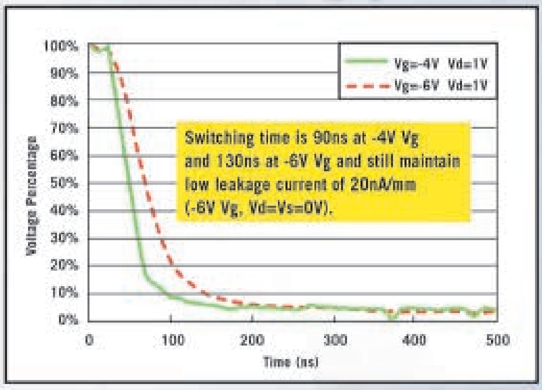
E-mode I-V Characteristics



E-mode Transfer Curve



D-mode Switching Speed



D-mode Device Performance

	PD50-01		PD25-00	
	Single	Triple	Single	Triple
Ron (ohm.mm)	1.9	3.7	1.3	2.2
Coff (fF/mm)	168	83	163	92
RonxCoff(ohm.fF)	316	310	209	198

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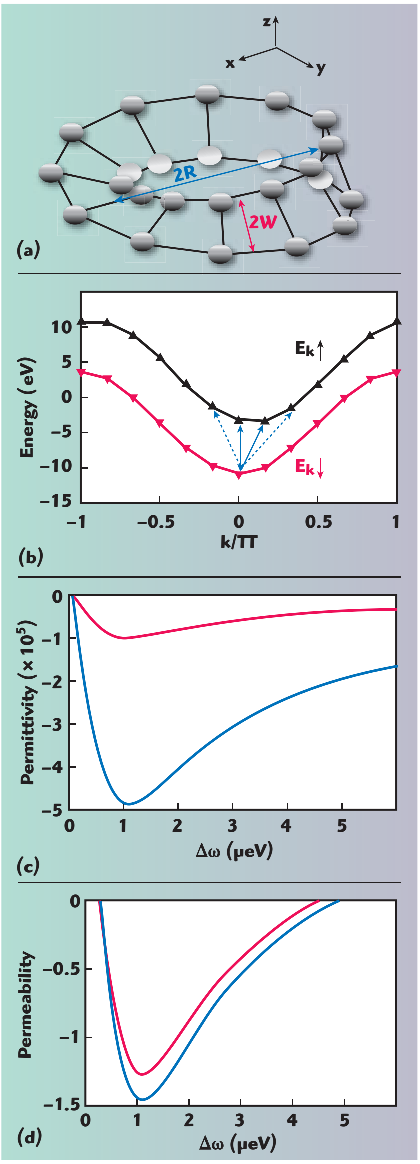
alization of microelectronic components.[30-35] It illustrates the next generation microwave components realized by Möbius metamaterial strips through the electromagnetic coupling dynamics governed by the Möbius transformation.

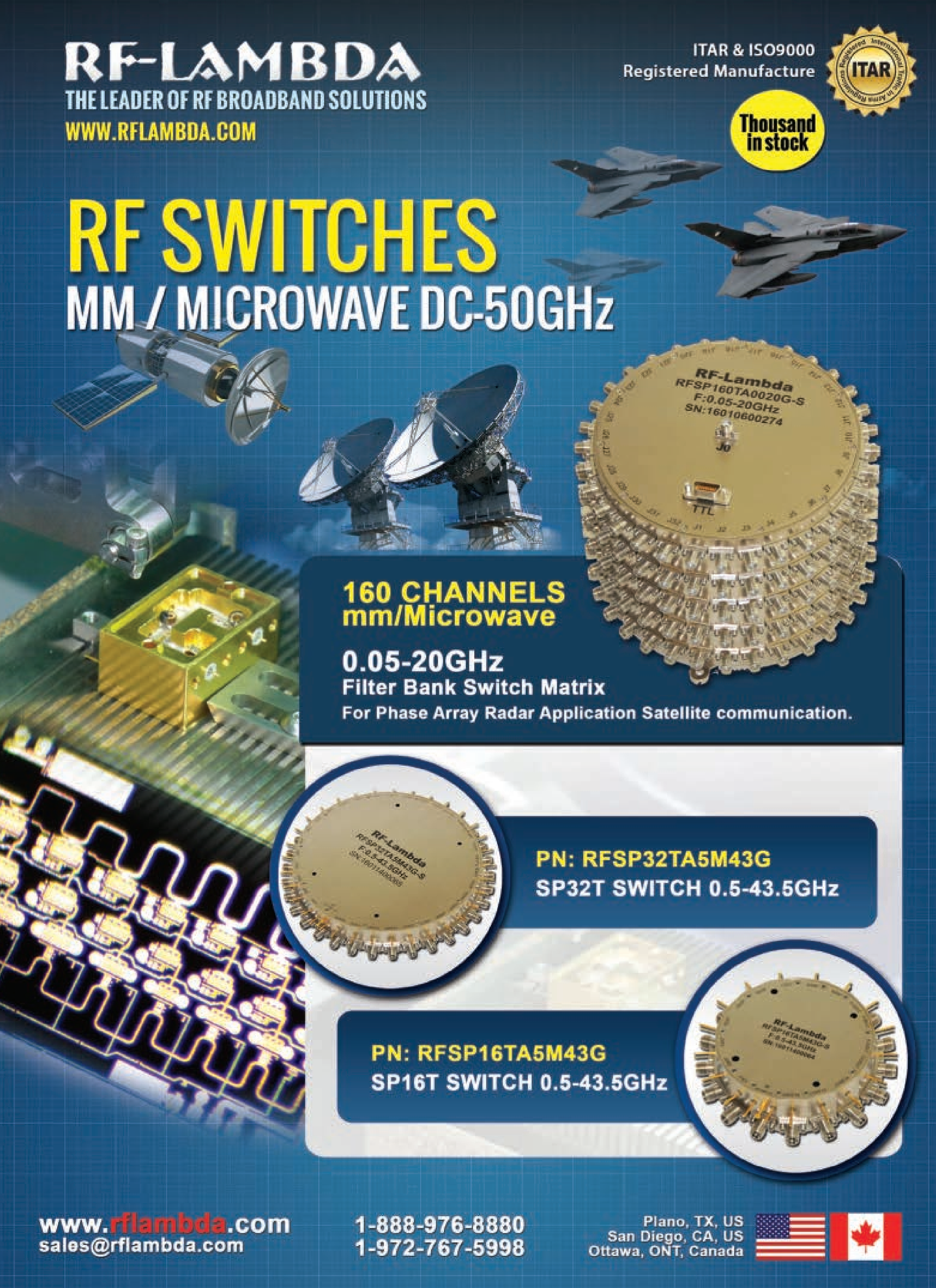
As shown in Figure 20, cylindrical closed ring structures formed by graphene nanoribbons possessing two edges exhibit anti-ferromagnetic (zero-magnetic moment), whereas Möbius closed-ring strips formed by graphene nanoribbons possessing a single-edge exhibit ferromagnetism (nonzero magnetic moment). Graphene nanoribbons with a 'zigzag' edge structure exhibit magnetism at their edges. The most stable configuration of these ribbons is anti-ferromagnetic, so that magnetic moments at opposite edges point in opposite directions, reducing the total magnetic moment of the ribbons to zero. However, a graphene Möbius strip has only one continuous edge, hence no magnetic cancellation between the opposite edges, resulting in a nonzero magnetic moment.

Medical Telemetry

Medical telemetry systems have considerably increased due to the inevitability for early diagnoses of diseases and continuous monitoring of physiological parameters. Microwave antennas and sensors are key components of these telemetry systems since they provide the communication between the patient and base station. The Industrial, Scientific and Medical (ISM) radio bands are portions of the radio spectrum reserved internationally for the use of RF energy for industrial,



▲ *Fig. 19 Möbius molecular rings made of carbon atoms (a) energy spectra $E_{k\sigma}$ of the molecular ring (b) relative permittivity as a function of Δω (c) and relative permeability as a function of Δω (d).*[32]



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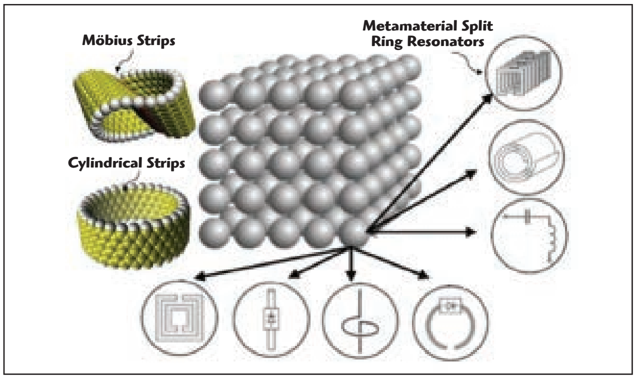

▲ *Fig. 20 Structures of Möbius metamaterial strips formed by graphene for the realization of microelectronic components.*[30]

scientific and medical purposes other than communications. Through the use of metamaterial like EBG structures in slotted microstrip antennas, increased efficiency and better return loss characteristics can be achieved.[36]

Cancer is the uncontrolled growth of abnormal (malignant) cells. Integrating microwave designs with metamaterial-inspired structures can lead to cost-effective devices that can localize abnormalities within the human body with high precision. The basic principle behind cancer detection is that small changes in the water content of biological tissues produces changes in their permittivities (ε) and conductivities (σ).[37] Malignant cells have significantly higher water content than normal tissues. Hence the permittivity and conductivity of a tumor are higher than those ones of normal tissues at microwave frequencies. A proposed biosensor consists of an array of complementary metallic metamaterial resonators. The reason for choosing split ring resonators (SRR) is their strong response to an electromagnetic field.[37] An electromagnetic source generates an electromagnetic wave impinging on a metamaterial array and a detector is placed so as to detect the signal after the array. The biosensor without any material under test has a specific resonant frequency.[37] The variation in permittivity of the material under test, acts on the capacitance of the resonators, shifting with high sensitivity the sensor resonant frequency. Thus the shift in resonant frequency and the shape of the response is extremely useful for tumor detection. ***Figure 21a*** shows a typical metamaterial-inspired coupled SRR based sensor comprising 12 SRRs. ***Figure 21b*** represents a pixel within the sensor.

If, for example, an organic tissue, interacts with the outer split of a SRR it changes its capacitance value due to a change of effective permittivity. In this way, differences in tissues, such as abnormalities, can be detected.[38] The equivalent circuit of a microstrip line loaded with a single SRR for the quasi-static case is shown in Figure 21b.[39] The SRR is magnetically coupled to the transmission line with the coupling factor S, where L_o and C_o correspond to the total SRR inductance and capacitance, respectively. The equivalent circuit yields the effective permeability with Lorentz dispersion[40]

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A-2D-001010-11-13P	0.1-1	26	1.0	1.1	2.0 / 2.0	+13	90
A-2D-001020-12-13P	0.1-2	25	1.0	1.2	2.0 / 2.0	+13	90
A-2D-001040-15-13P	0.1-4	23	1.5	1.5	2.0 / 2.0	+13	90
A-3D-001060-17-13P	0.1-6	33	1.5	1.7	2.0 / 2.0	+13	135
A-3D-001080-19-13P	0.1-8	32	1.5	1.9	2.0 / 2.0	+13	150
A-3D-001100-20-13P	0.1-10	31	1.5	2.0	2.0 / 2.0	+13	150
A-3D-001120-21-13P	0.1-12	27	1.5	2.1	2.0 / 2.0	+13	150
A-4D-001180-25-10P	0.1-18	30	2.0	2.5	2.5 / 2.0	+10	150
A-4D-001200-28-10P	0.1-20	28	2.0	2.8	2.5 / 2.5	+10	150
A-4D-001220-31-10P	0.1-22	25	2.0	3.1	2.5 / 2.5	+10	150
A-5D-001265-41-08P	0.1-26.5	24	2.5	4.1	2.5 / 2.5	+8	200
A-2D-005020-12-13P	0.5-2	26	1.0	1.2	2.0 / 2.0	+13	90
A-2D-005040-14-13P	0.5-4	24	1.5	1.4	2.0 / 2.0	+13	135
A-2D-005060-16-13P	0.5-6	23	1.5	1.6	2.0 / 2.0	+13	90
A-3D-005080-18-13P	0.5-8	33	1.5	1.8	2.0 / 2.0	+13	150
A-4D-005180-24-10P	0.5-18	30	2.0	2.4	2.2 / 2.0	+10	150
A-4D-005200-27-10P	0.5-20	28	2.0	2.7	2.3 / 2.3	+10	150
A-4D-005220-30-10P	0.5-22	25	2.0	3.0	2.3 / 2.3	+10	150
A-5D-005265-40-08P	0.5-26.5	24	2.0	4.0	2.5 / 2.5	+8	200
A-3D-020120-20-13P	2-12	27	1.5	2.0	2.0 / 2.0	+13	150
A-3D-020180-23-10P	2-18	22	1.5	2.3	2.2 / 2.0	+10	150
A-4D-020180-23-10P	2-18	30	1.5	2.3	2.2 / 2.0	+10	150
A-4D-020200-26-10P	2-20	28	1.5	2.6	2.2 / 2.2	+10	150
A-4D-020220-29-10P	2-22	26	1.5	2.9	2.2 / 2.2	+10	150
A-4D-020265-39 -08P	2-26.5	19	2.0	3.9	2.5 / 2.5	+8	150
A-4D-200265-30-08P	20-26.5	24	1.0	3.0	2.0 / 2.0	+8	150
A-4D-265330-35-10P	26.5-33	23	1.5	3.5	2.0 / 2.0	+10	180
A-4D-300330-35-08P	30-33	23	1.5	3.5	2.0 / 2.0	+8	180
A-4D-340360-35-08P	34-36	23	1.5	3.5	2.0 / 2.0	+8	180
A-4D-300400-40-08P	30-40	23	1.5	4.0	2.5 / 2.5	+8	180
A-4D-180400-40-6P	18-40	20	2.5	4.0	2.5 / 2.5	+6	180
A-5D-260400-38-10P	26-40	30	2.5	3.8	2.5 / 2.5	+10	250

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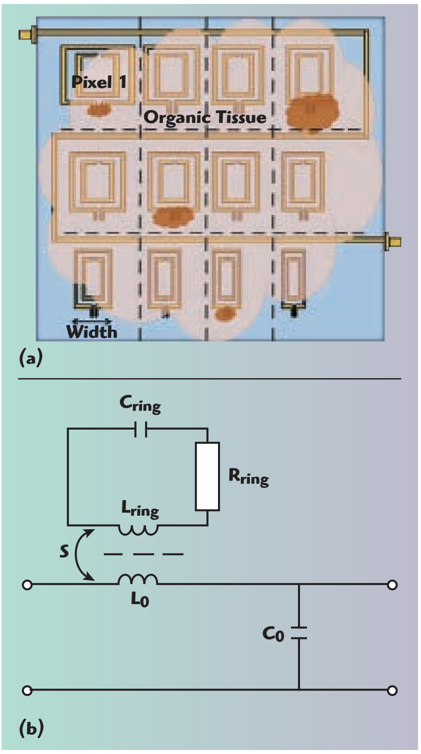
$$\mu_{eff} = -j\frac{Z_1}{\omega p} = \frac{L_O}{p}\left(1+\frac{\omega^2 S^2}{\omega_{Om}^2-\omega^2+j\omega\delta}\right) \quad (7)$$

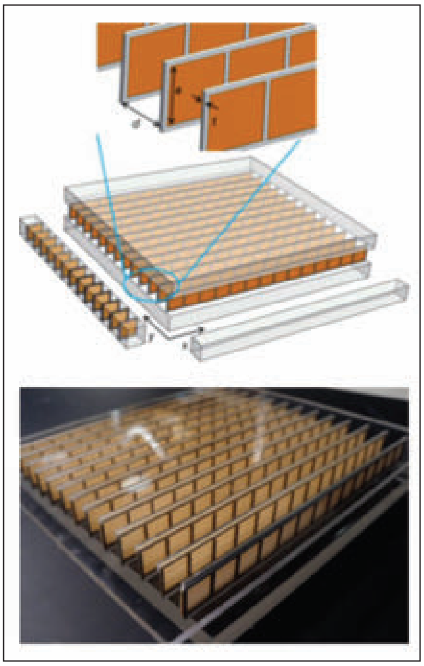
with p being the net cell length.

ACOUSTIC IMAGING

Acoustic imaging tools are used in both medical diagnostics and in testing the structural integrity of everything from airplanes to bridges. Medical personnel and structural engineers often need to focus sound for imaging or therapeutic purposes. Metamaterial gives researchers more control over the angle at which acoustic waves can pass through it. ***Figure 22*** shows a typical metamaterial inspired acoustic hyperbolic structure made of paper and aluminum for acoustic imaging application. The acoustic hyperbolic metamaterial (AHM) structure allows manipulation of acoustic waves to more than double the resolution of acoustic imaging by focusing acoustic waves and controlling the angles at which sound passes through the metamaterial.[41] It interacts with acoustic waves in two different ways. From one direction, it exhibits a positive density and interacts with acoustic waves normally, just like air. But from a perpendicular direction,



▲ *Fig. 21 Metamaterial inspired microstrip coupled SSR sensor array (a) and equivalent circuit of a SRR loaded microstrip element (b).*[27-28]



▲ *Fig. 22 Physical structure of acoustic hyperbolic metamaterial.*


IMAGING
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the metamaterial exhibits a negative density. This effectively makes acoustic waves bend at angles that are the exact opposite of what basic physics predicts. This has some very useful applications. For one, it can be used to improve acoustic imaging. Traditionally, acoustic imaging cannot achieve image resolution smaller than half of a sound's wavelength. For example, an acoustic wave of 100 kHz, traveling through air has a wavelength of 3.4 mm, limiting image resolution to 1.7 mm.

CONCLUSION

The unique features of MMI structures open the gateway to new inventions, recurring in an endless fashion; one could say that the future has the form of an MMI surface. In this article, the Casimir effect is discussed briefly. Details of the Casimir effect and applications using MMI structures for futuristic applications will be discussed in parts 2 and 3. ■

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INVITED PAPER

Ensuring Peak Oscillator Performance in Real World Systems

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Morion Inc., Saint Petersburg, Russia

All telecom, navigation, control and measurement systems require reference frequency oscillators, and the stability of this oscillator often sets the limits of system performance. Frequency stability vs. temperature and time (long- and short-term) and phase noise are the most important characteristics of reference sources.

High stability, oven-controlled, low noise crystal oscillators are particularly important, given their critical applications: 5 to 10 MHz crystal oscillators are used in the phase-locked loops of atomic frequency standards. These oscillators determine the phase noise at ≥ 0.1 Hz and the Allan deviation from 0.1 to 10 s. 50 to 100 MHz crystal oscillators are found in modern frequency synthesizers. The noise level of this crystal oscillator determines the synthesizer's noise, so the crystal oscillator phase noise is specified from 10 Hz to 1 MHz offset from the carrier. 5 to 40 MHz high stability, low noise crystal oscillators are being used in synchronization modules for time base maintenance.

The requirements for reference frequency sources are constantly tightened: smaller size, reduced power consumption, lower phase noise and improved frequency stability vs. time and temperature. To ensure the best performance, this article addresses the design of ultra-low noise oscillators and system factors that can degrade oscillator performance (see ***Table 1***), as the oscillator and system designs are both important to maximizing performance. Neglecting system considerations may cause an excellent oscillator design to underperform when it is installed in the system.

TABLE 1

FACTORS AFFECTING OSCILLATOR PERFORMANCE

Factor	Phase Noise	Allan Deviation	Frequency Stability vs. Temperature
Spurious interference to the oscillator's ground and control pins	+	+	+
Oscillator frequency digital control	+	+	–
Air flow	–	+	+
Vibration	+	+	–

HIGH STABILITY, LOW NOISE OSCILLATORS

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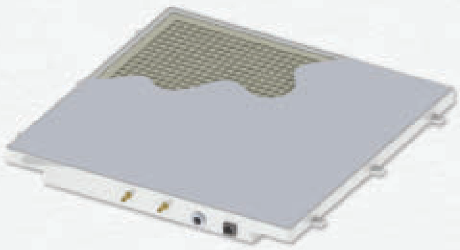

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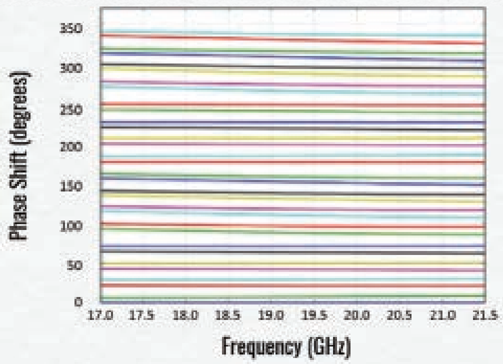

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cantly improved phase noise and Allan deviation. The size of each oscillator was reduced while maintaining high frequency stability vs. temperature. Reducing an oscillator's size makes it more difficult to maintain or improve frequency stability over temperature. Using thermal simulation (see ***Figure 1***) and optimizing the structural circuitry, the frequency stability of the single, oven-controlled crystal oscillator design was close to that of a double, oven-controlled oscillator.[1,2]

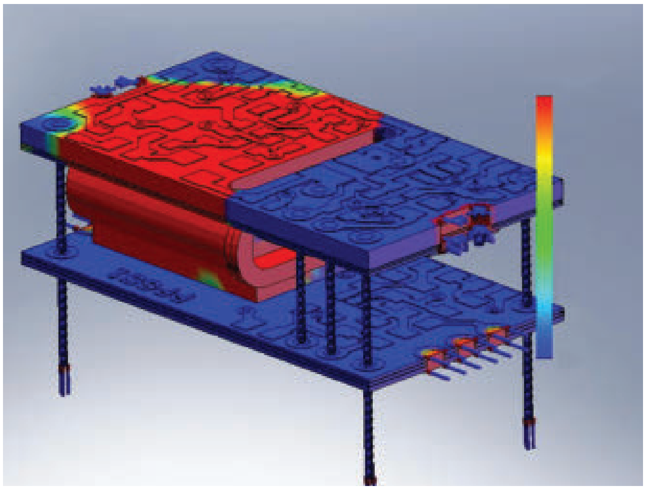

Fig. 1 Thermal model of an oven-controlled crystal oscillator.

5 to 10 MHz Oscillator Design

The design of low noise oscillators is impossible without a good crystal, and the demands for better phase noise and Allan deviation require significant improvements in crystal technology. Several approaches have been developed to increase performance and yields:

- Special technology for treating the surface of blank crystals
- A measurement system to test crystals at different power dissipations
- Studies of power dissipated in crystals vs. close-to-the carrier phase noise (see ***Table 2***).

The data in Table 2 shows that the type 1 crystal is least sensitive to dissipated power.

In addition to the crystal, the circuitry of the 5 to 10 MHz oscillator affects the phase noise and Allan deviation. To improve phase noise close to the carrier (0.1 to 10 Hz offset), the system's quality factor must be maximized. The oscillator circuit must preserve the maximum loaded Q-factor of the crystal resonator. In addition, providing "pure" voltage to the crystal oscillator and matching circuits improves phase noise close to the carrier. The oscillator's printed circuit board (PCB) layout requires careful attention. The oscillator's current may cause interference in the near and far zone phase noise and affect the Allan deviation for 1 to 10 s. The matching between the oscillator — particularly

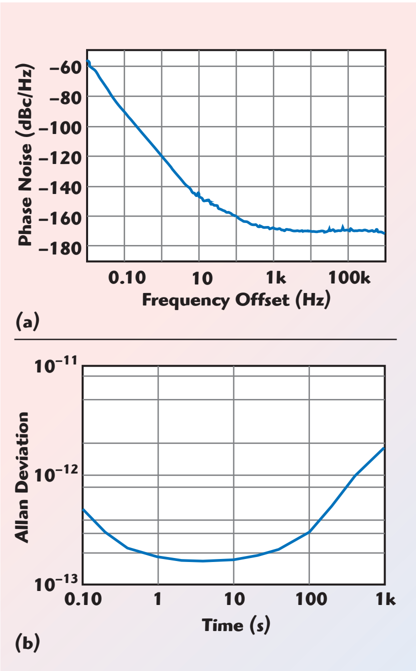

Fig. 2 Improved phase noise (a) and Allan deviation (b) of the 10 MHz OCXO.

TABLE 2

10 MHz OSCILLATOR PHASE NOISE AT 1 Hz OFFSET VS. CRYSTAL DISSIPATED POWER

Dissipated Power, μW	20	27	35	45	55
Crystal, Type 1	-119	-120	-120	-120	-119
Crystal, Type 2	-116	-118	-120	-119	-117
Crystal, Type 3	-115	-117	-118	-118	-117

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the crystal circuit — and buffer amplifier, as well as the noise figure of the amplifier, will influence the far zone noises (1 kHz to 1 MHz offset). Optimization of the circuit design and layout can yield 10 to 20 dB improvement in phase noise in the far zone.

Incorporating these crystal and circuit measures achieves considerable improvement in the phase noise and Allan deviation (see ***Figure 2***). ***Table 3*** summarizes the performance of two 10 MHz oscillators designed with these approaches.

80 to 100 MHz Oscillator Design

What is true for the 5 to 10 MHz oscillator designs applies to the 80 to 100 MHz oscillators. However, the 80 to 100 MHz oscillators have additional considerations. The linearity of the buffer amplifiers, through which the signal is fed to the output, affects the phase noise "floor" (10 kHz to 1 MHz offset), making the choice and optimization of the transistors in these amplifiers important. Feedback from unwanted loops causes self-excitation and "humps" in the phase noise curves, which affects the phase noise of a 100 MHz oscillator. So the amplifier layout should minimize unwanted capacitive and inductive couplings. A 5 V, 100 MHz oscillator incorporating these design considerations achieves the phase noise performance shown in ***Figure 3***. Its performance is summarized in Table 3.

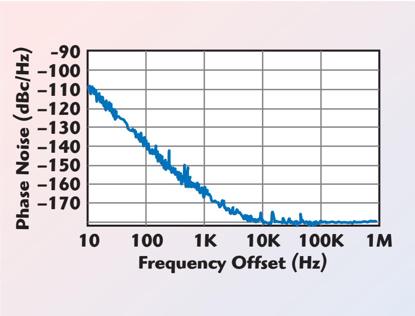
TABLE 3

10 AND 100 MHz OVEN-CONTROLLED CRYSTAL OSCILLATOR PERFORMANCE

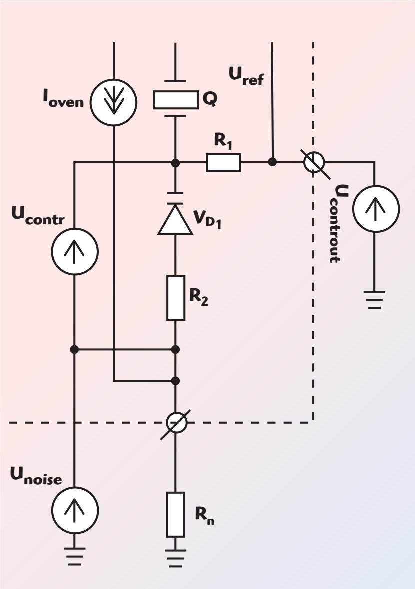
Parameter	Units	MV341	MV272M	MV317
Frequency	MHz	10	10	100
Phase Noise				
Δf = 1 Hz	dBc/Hz	-120	-120	-
Δf = 10 Hz	dBc/Hz	< -145	< -145	< -102
Δf = 100 Hz	dBc/Hz	< -157	< -159	< -135
Δf = 1 kHz	dBc/Hz	< -160	< -165	< -164
Δf = 10 kHz	dBc/Hz	< -160	< -168	< -174
Δf = 100 kHz	dBc/Hz	< -160	< -168	< -178
Allan Deviation (1 s)	10^{-13}	< 2	< 4 to 5	-
Frequency Stability vs. Temperature	10^{-9}	1	1	50
Dimensions	mm	51 × 51 × 16	30 × 40 × 16	25 × 25 × 10

SYSTEM CONSIDERATIONS

When integrated into a system, factors other than the oscillator may hurt performance. Parasitic resistance, digital control, air flow and vibration can degrade phase noise, Allan deviation and frequency stability.



▲ *Fig. 3 Improved phase noise for a 100 MHz, 5 V oscillator.*



▲ *Fig. 4 Oscillator frequency control circuit.*

Parasitic Resistance

Figure 4 shows the oscillator frequency control circuit, which has elements both inside and outside the oscillator. From the figure it follows that

$U_{controut} = U_{contr} + U_{noise,}$

where U designates voltage.

If $U_{controut}$ is fixed, and U_{noise} changes, U_{contr} will also change, directly affecting the phase noise, Allan deviation and frequency stability vs. temperature.

The ground wires of the control and reference sources, high frequency output cascade and oven ground are connected to the ground lead inside the oscillator. In precision oscillators, these grounds are separate and only connected on the board at the oscillator ground pin. This minimizes the common resistance these currents flow through (R_n in Figure 4), as the oven current varies linearly with ambient temperature and will contribute noise. This grounding concept is illustrated with the PCB layouts shown in ***Figure 5***. In ***Figure 5a***, the common ground trace creates the parasitic resistance, R_n. To remove it, separate ground tracks are created on the PCB, shown in ***Figure 5b***.

Over the operating temperature of a 5 V, oven-controlled crystal oscillator, the typical change in current is $\Delta I = 1$ A. The oscillator can be adjusted by about 1×10^{-6} as the control voltage changes over 5 V, making $K = 2 \times 10^{-10}$/mV. With a parasitic resistance $R_n = 0.01\ \Omega$, a variable capacitance diode voltage change over temperature will make

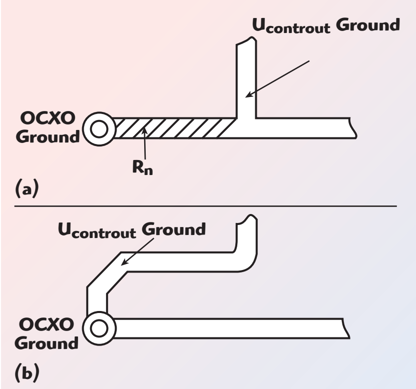


Fig. 5 Parasitic resistance created by a common ground trace on the PCB (a). Improved layout by eliminating the common trace (b).

$U_{noise} = \Delta IRn$ or 10 mV.

The frequency drift (dF/F) vs. temperature is determined by

$dF/F = KU_{noise}$ or 2×10^{-9}.

Using a 12 V oscillator — meaning a lower oscillator current change for a given temperature range — with a smaller adjustment range and lower parasitic resistance results in better frequency stability with temperature; however, dF/F will still be in the range of 10^{-10}.

Figure 6 shows how parasitic resistance can degrade frequency stability vs. temperature. Parasitic resistance

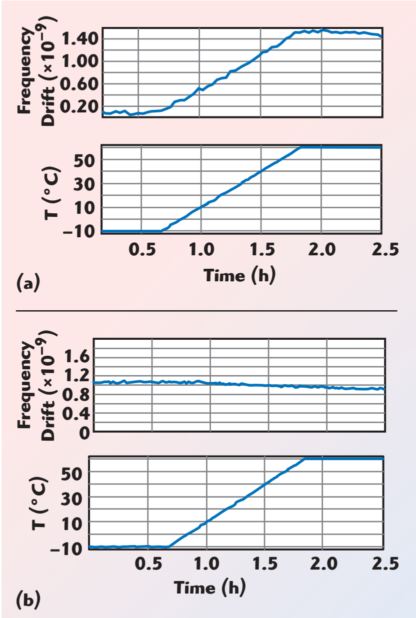


Fig. 6 Oscillator frequency stability vs. temperature with (a) and without parasitic resistance (b).

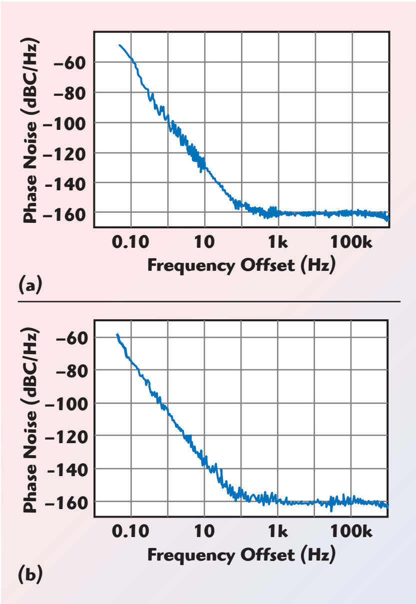


Fig. 7 Oscillator phase noise with (a) and without (b) parasitic resistance.

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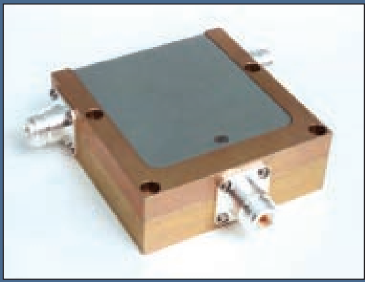

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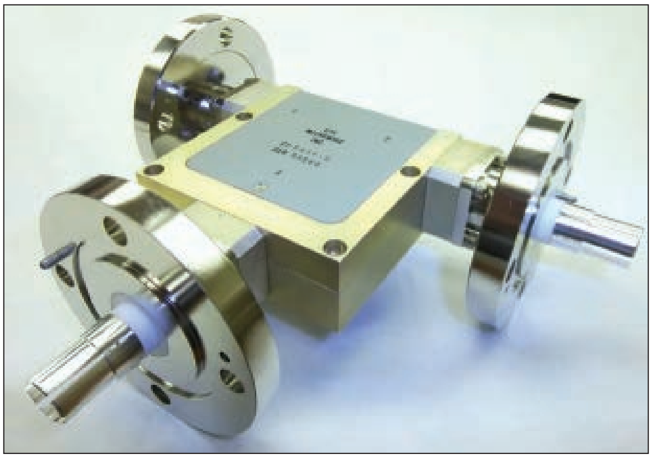

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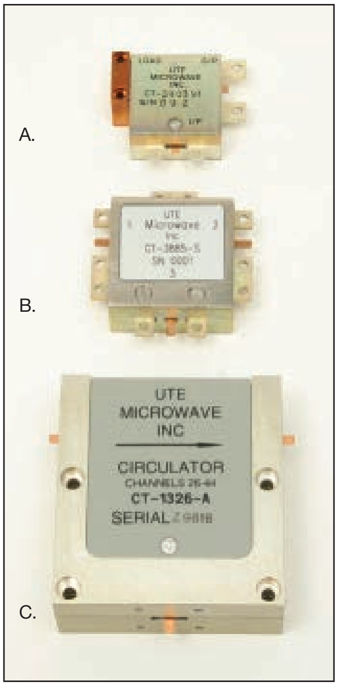

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CT-3838-N	5 Kw Pk 500 W Av	N Conn.	2.7–3.1 GHz
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Contact us for more information on our extensive product line and current catalog. We accept Visa, MC, Amex may also increase phase noise, from as low as 0.1 Hz offset (see ***Figure 7***).

Digital Control

Using a digital-to-analog converter (DAC) to control oscillator frequency can degrade the oscillator's phase noise (see ***Figure 8***) and Allan deviation. This is due to the discrete voltage steps of the DAC and interference between the oscillator frequency and DAC clock. The latter can cause interference components on the phase noise from 1 kHz to 1 MHz.

To understand the effect a DAC step has on Allan deviation, consider an oscillator with Allan deviation of 6×10^{-13} per 1 s. To avoid any effect on Allan deviation, the frequency step must not exceed $F_s = 2$ to 3×10^{-13}. If the oscillator adjustment is $\Delta F = 1 \times 10^{-6}$, then the total steps make

$S = \Delta F/F_s$, which requires a 22-bit DAC.

This example shows that controlling oscillator frequency at normal Allan deviations of 5 to 6×10^{-13} is difficult. To effectively use a DAC for frequency control, the DAC should have a high number of bits, the capability to filter the switching steps and a control algorithm with the most infrequent switching between bits. The DAC ground should be separate, as previously discussed.

To eliminate possible interference from an internal or external DAC clock, a controlled oscillator frequency shall be brought to DAC input, using a frequency divider, if needed.

Air Flow

The temperature of the oscillator body will vary with any interaction with air flows. The intensity and speed of the air will determine the heat re-

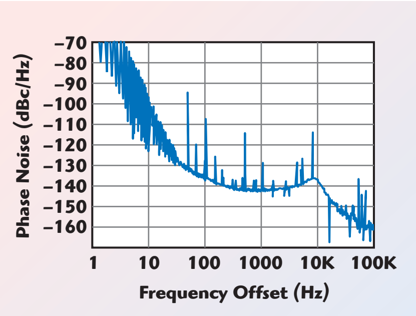

Fig. 8 Distorted phase noise from an incorrectly built DAC-controlled oscillator.

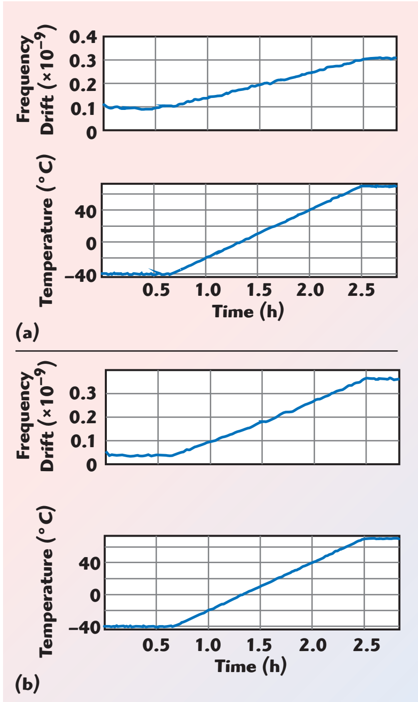

Fig. 9 Oscillator frequency stability vs. temperature in still (a) and moving air (b).

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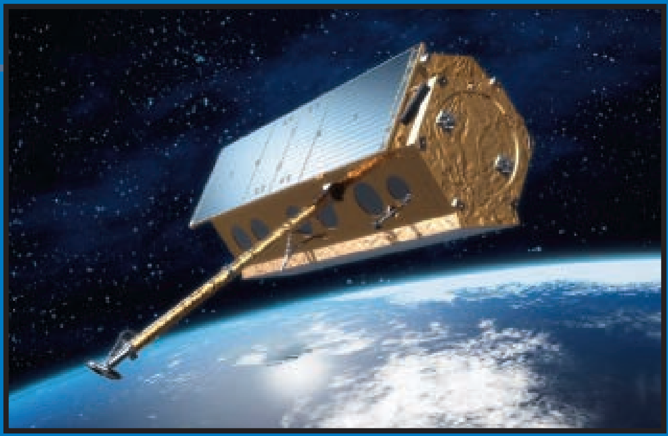

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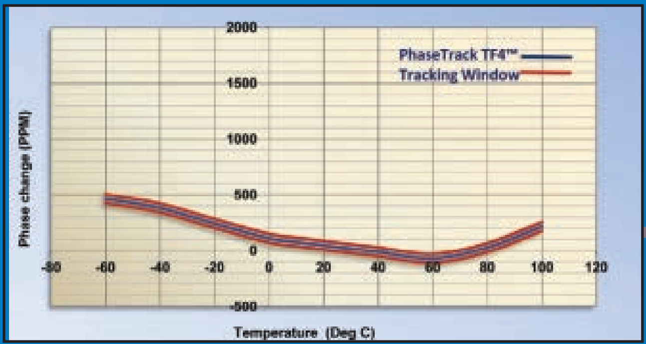

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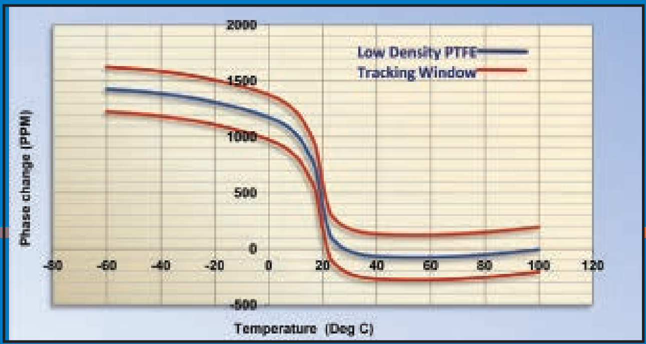

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TechnicalFeature

moved from the oscillator, which will trigger the thermostat. For precision, oven-controlled oscillators installed in equipment containing fans, the air flow should not directly hit the oscillator. Vibration from the fan may also increase the phase noise. If these factors are not well controlled, the following adverse effects can occur:

- An intensive air flow is equivalent to extending the oscillator's operating temperature range to negative values, which reduces frequency stability
- The oscillator's oven may be unable to maintain the desired operating temperature due to insufficient power
- The Allan deviation in the range of 5 to 100 seconds will deteriorate because of air flow variation and attendant temperature fluctuations at the oscillator body
- The equipment design will be more complicated to accommodate the increased power consumed by the oscillator power supply.

A comparison of the frequency drift of an oscillator in still and moving air is shown in ***Figure 9***.

Vibration

The phase noise of an oscillator will be degraded by vibration. The phase noise from random vibration may be modeled using the g-sensitivity of the oscillator.[3]

$$L(f) = 20\log[(|\Gamma||A|F_0)/(2F)]$$

where $|\Gamma|$ is the g-sensitivity of the oscillator,

$$|A| = (2PSD)^{1/2}$$

where PSD is the power spectral density, F_0 is the oscillator operating frequency and F is the frequency offset from the carrier.

Knowing the level of vibration during operation is not always possible. Nonetheless, the oscillator should be located on the PCB away from points of possible resonance or close to sources of vibration, such as fans, transformers and motors. If the direction of the vibration is known, the oscillator manufacturer can advise which oscillator axis has the minimum g-sensitivity, as it will vary among oscillator designs.

CONCLUSION

Not paying attention to the above factors may lead to a considerable degradation in the performance of precise, low noise, oven-controlled oscillators. Since the performance of the oscillator often determines system performance, degrading oscillator performance will impair the system. ■

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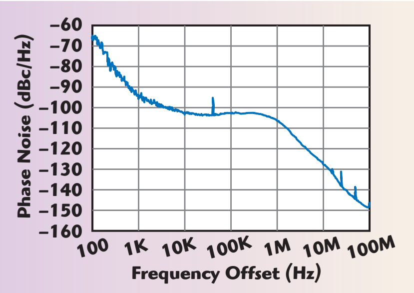
40 GHz Extension to 765 MHz Real-Time Bandwidth PXI VSA

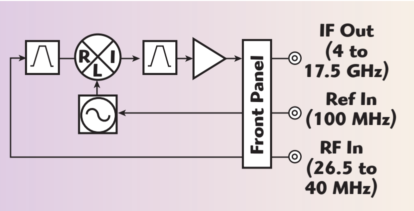
National Instruments
Austin, Texas

The use of millimeter wave frequency bands is making it possible to allocate more bandwidth to deliver faster, larger amounts of data, as well as higher quality multimedia content. Millimeter waves also have the advantage of smaller size components, particularly antennas, as well as ease of frequency reuse. The wireless and microwave world is becoming more and more millimeter wave centric.

Recent industry trends have increased the demand for signal analysis capabilities with wider instantaneous analysis bandwidth, higher frequency and lower cost. This market demand is driven by new application areas such as 5G cellular, next generation Wi-Fi, millimeter wave backhaul, Ka-Band satellite communications and the Internet of Things (IoT). In 2012, National Instruments introduced the NI PXIe-5668R, a best-in-class vector signal analyzer (VSA) with 765 MHz of instantaneous analysis bandwidth up to 26.5 GHz. To serve the demands of the market, the microwave components group of National Instruments (formerly Phase Matrix Inc.) is now offering the PXI-1421, a two-slot PXI, 26.5 to 40 GHz block down-converter module, which extends the operating frequency range of the NI PXI-5668R up to 40 GHz.

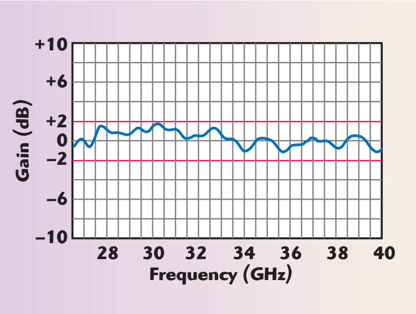


▲ *Fig. 1 Phase noise of the integrated 44 GHz LO.*

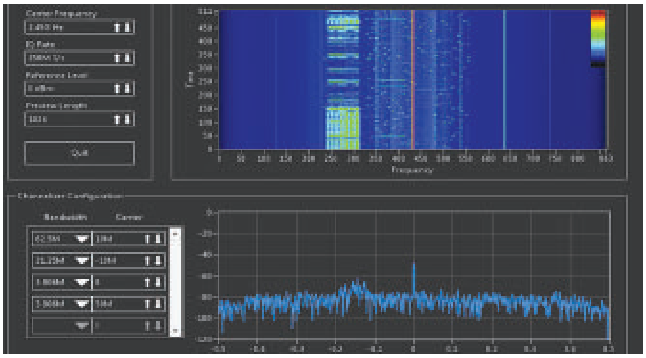


▲ *Fig. 2 Block diagram of the PXI-1421 26.5 to 40 GHz block down-converter.*

The PXI-1421 has an integrated 44 GHz low phase noise local oscillator (LO) (see ***Figure 1***) which block down-converts an RF input between 26.5 and 40 GHz to an IF of 4 to 17.5 GHz, as shown in the block diagram in ***Figure 2.*** A fundamental phased-locked oscillator (PLO) based on an 11 GHz VCO is used, with a low noise, ×4 active frequency multiplier followed by an amplifier and filter to achieve the required power output at the final frequency. The 100 MHz reference needed for the PLO is supplied by the NI PXIe-5668R. A high linearity mixer and a medium power IF amplifier are used to meet the stringent spurious requirements. The RF input noise figure of the block down-converter is less than 12 dB, and the input IP3 is better than +22 dBm. The conversion gain from RF input to IF output is typically 1 ± 2 dB (see ***Figure 3***). The IF signal feeds into the NI PXIe-5668R. The residual spur performance of the PXI-1421 is better than -80 dBm.



▲ *Fig. 3 Typical RF to IF conversion gain.*



▲ *Fig. 4 PFT-based channelizer using the PXI-7976R FlexRIO FPGA module.*

When coupled with the NI PXI-2799 DC to 40 GHz dual SPDT switch, the NI PXIe-5668R, and the PXI-1421, signal analysis can be accomplished from 20 Hz to 40 GHz, all in the PXI form factor. The PXI-1421's fixed high-side LO (which is outside the band) and the broadband mixer technology allow the preservation of the noise floor of the NI PXI-5668R at 40 GHz (-150 dBm/Hz). The low noise floor of the system allows for phase noise measurements to be made directly up to 40 GHz. In addition, the block down-converter architecture allows for 765 MHz instantaneous analysis bandwidth at 40 GHz, which is useful for measuring adjacent channel power levels of wide bandwidth signals.

The latest addition to the family of NI's software-designed instruments, the NI PXIe-5668R includes a LabVIEW programmable Xilinx Kintex-7 FPGA that allows the user to customize the instrument's behavior by adding triggering or signal processing routines. With the addition of an NI PXI-7976R FlexRIO FPGA module, the user can configure the instrument to do high performance signal processing, such as real-time spectral analysis and narrow band channelizers. ***Figure 4*** shows implementation of a pipelined frequency transform (PFT) based channelizer.

The PXI-1421 extends the NI PXIe-5668R VSA performance up to 40 GHz, which is ideal for a wide range of applications. The combination of excellent analog performance, extremely wide bandwidth and ultimate flexibility empower the user to address challenging measurement applications ranging from ACLR to radar verification to spectrum monitoring.

VENDORVIEW

National Instruments
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Dedicated Handheld E-Band Spectrum Analyzer

SAF Tehnika
Riga, Latvia

In the last few years, the deployment of 71 to 76 GHz and 81 to 86 GHz bands (E-Band) has increased significantly fueled, in part, by the growing demand for high capacity point-to-point radio links. With the increased requirement for high capacity networks and implementation of 4G or even 5G in the near future, mobile operators are moving towards small cell or picocell technology. One approach is to use E-Band radios for last mile backbone connection from telecommunication infrastructure to the mobile base station, thus reaching places that fiber optics cannot reach and satisfying network capacity demands.

Fig. 1 E-Band spectrum analyzer.

Indications are that the E-Band spectrum will evolve similarly to the unlicensed 5.8 GHz band if there are no dramatic changes in the market. That means users will require in-depth link planning to avoid interference and to identify free channels before the installation. Also, it is likely that frequency regulatory authorities will begin to regulate this market. This is not happening at present because there are no convenient tools, such as portable spectrum analyzers, operating in the E-Band frequency range or the equipment available on the market is expensive.

SAF Tehnika has addressed this issue with their Spectrum Compact J0SSAP80 spectrum analyzer, made specifically for the E-Band frequency bands ranging from 70 to 87 GHz. It is an addition to the existing Spectrum Compact product line that covers the 2 to 40 GHz range.

CHARACTERISTICS

The company claims this is the first handheld spectrum analyzer on the market covering the 70 to 87 GHz frequency bands. It does not use any external down-converter, working directly with E-Band frequencies. The J0SSAP80 has a fixed 10 MHz resolution bandwidth (RBW) and a noise floor of at least -90 dBm. It comes with a wide beam sniffer antenna attached to the waveguide flange (WR 12), which is located on the back panel of the analyzer. The scan speed of 0.5 s at 1 GHz span and the level of system gain make this spectrum analyzer suitable for interference detection, free channel investigation and tower inspections from ground level.

Spectrum Compact J0SSAP80 can be used by mobile operators and private network owners in the radio network planning stage to avoid

▲ *Fig. 2 Rear view of the E-Band spectrum analyzer.*

expenses caused by installing a non-operational link because of interference. For frequency regulatory authorities, it can be a great asset and help to start real life monitoring in E-Band, with the option to perform tower inspections from the ground level and to control the licensing and deployment.

Like the entire Spectrum Compact range, the J0SSAP80 is designed specifically for comfortable outdoor use in a variety of challenging environments. This battery powered instrument is suitable for microwave radio engineers performing equipment installation, link troubleshooting or gathering data for site planning purposes. One of its most prominent features is the form factor — dimensions of this device are similar to those of a cell phone.

FIELD OPERATION

Instead of focusing on features that would only be useful in a laboratory environment, the spectrum analyzer has the qualities and functionality needed by microwave field engineers to efficiently perform their daily tasks: radio parameter verification, antenna alignment, interference and multipath detection, power in-band measurements, link troubleshooting and saving the spectrum curves for reports and later analysis. The device is shown in ***Figure 1***.

The instrument utilizes a resistive touch screen for ease of use in the field, allowing the engineer to wear gloves when using the device. Furthermore, its high sensitivity and low noise floor enable field engineers to detect even exceptionally weak signals. This makes it possible to do multiple measurements from the ground level and do link troubleshooting without site traffic interruptions.

A standard kit includes the spectrum analyzer and a small wide angle horn antenna, as shown in ***Figure 2***. The E-Band antenna is attached to a WR 12 waveguide flange at the back of the spectrum analyzer, making it possible to detect and visualize the incoming signal just by pointing it towards the transmitting radio.

The J0SSAP80 has a 54 International Protection Marking (IP code) meaning that the analyzer is dust protected and can be used in rainy conditions. A weatherproof DC socket decreases the required charging time and a fully charged unit has up to 3 hours of battery life.

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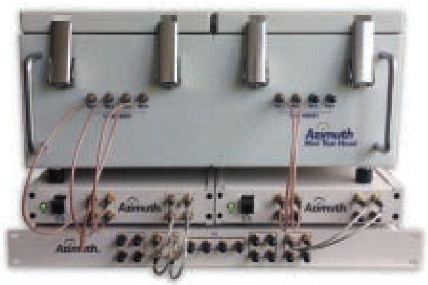


Automated, Scalable RF Platform for LTE Unlicensed, Wi-Fi and IoT

Azimuth Systems
Acton, Mass.

New technologies and applications (e.g., LTE unlicensed, IoT) have led the shift from link-level testing toward more system-level testing, from simple point-to-point topologies toward complex topologies (e.g., mesh, star) and from single to multiple radio instances. This complicates testing, so Azimuth has made it simpler, faster, more reliable and more cost effective, with a new automated RF platform called Spider™.

FIELD VS. LAB TESTING

Field testing is the ultimate trial — not the optimal place to start. It's fraught with logistical and environmental challenges that inevitably make field testing expensive and difficult to repeat. Testing should start in the lab and *then* move to the field. At a high level, there are three approaches to lab testing: conducted and two options for radiated.

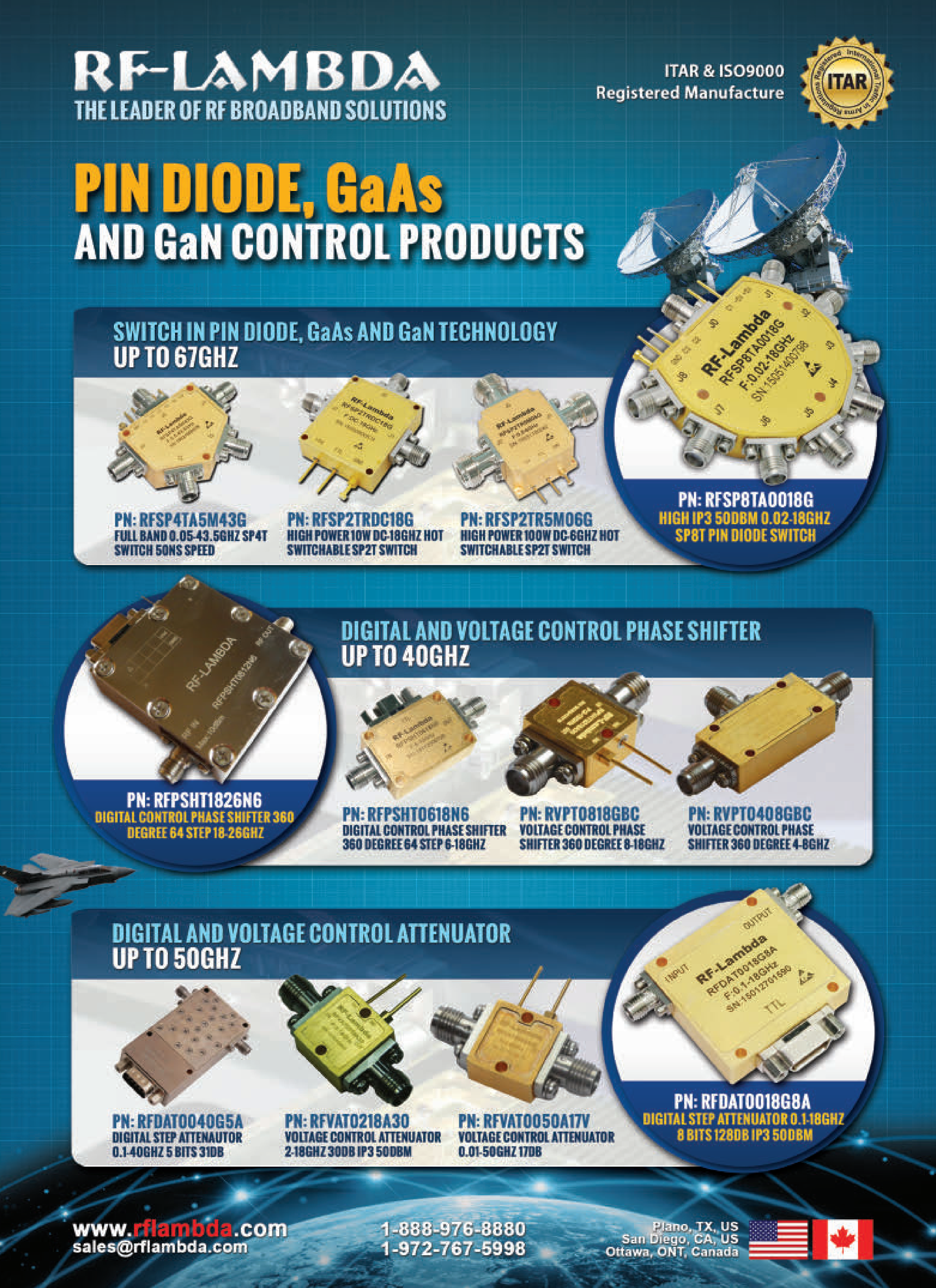
Conducted Testing: Ad hoc conducted testing is the typical go-to for its quick, relatively inexpensive startup. Users gather myriad components (e.g., programmable attenuators, combiners) to create a specific test bed, controlling it manually or with temporary code created from scratch. While this works well for proof of concept, invariably, it becomes unwieldy. Since do it yourself (DIY) setups lack platform homogeneity, the onus of test bed building, automating, expanding, maintaining and documenting falls on users. That makes test beds challenging to replicate and grow.

Radiated Testing: Users test devices in a shielded enclosure or chamber. The signal is radiated over the air (OTA) with limited or no additional conditioning. It's nearly impossible to control the RF environment and accurately recreate real world scenarios. Such setups can leave environmental dead zones, result in devices never achieving maximum performance, and require trial and error — iterative adjustments to determine the ideal combination of the devices' physical position and orientation. This frustrating, time consuming process must be repeated every time a new device is added to the test bed.

Over the Air: The traditional OTA setup with an anechoic or a reverberation chamber is typically useful for designing or characterizing antenna performance or device performance with the antenna.

In addition to field and lab testing, there's a third, more optimal option: Spider. Spider is an automated RF platform that's modular, scalable and cost effective — built to solve the challenges of the other approaches. Spider can be used stand-alone or as a platform on which turnkey solutions are built for different technologies (e.g., Wi-Fi, LTE unlicensed), applications (e.g., IoT) and use cases (e.g., MIMO, coexistence testing). Think of Spider as a model built from Lego® blocks, with fundamental hardware and software blocks that fit together quickly and easily, allowing users to build what they need, as needed:

- Controllable bidirectional multiple-input-multiple-output (MIMO) links
- Variety of topologies with complete RF isolation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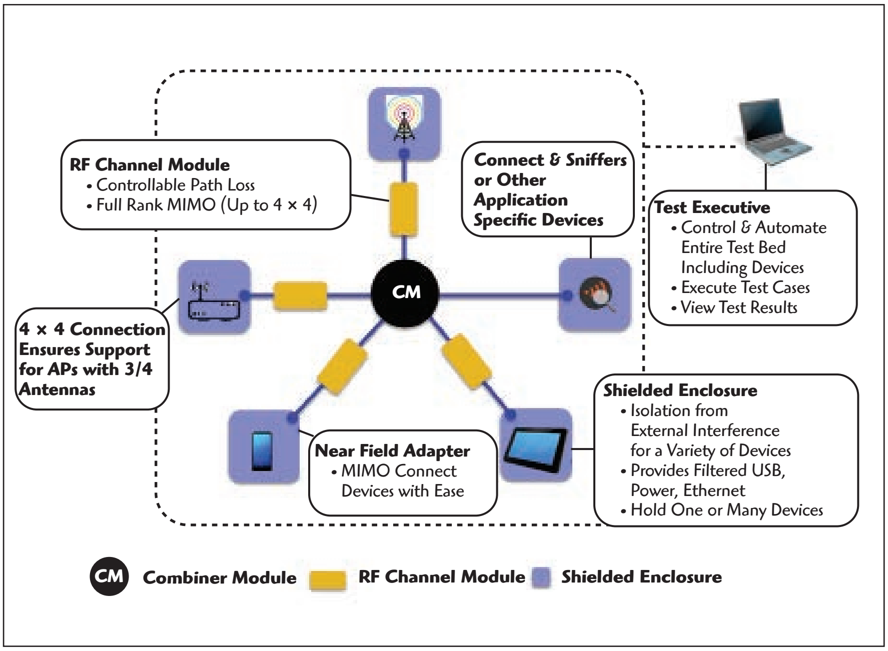


Fig. 1 *The Spider platform consists of integrated hardware and software modules.*

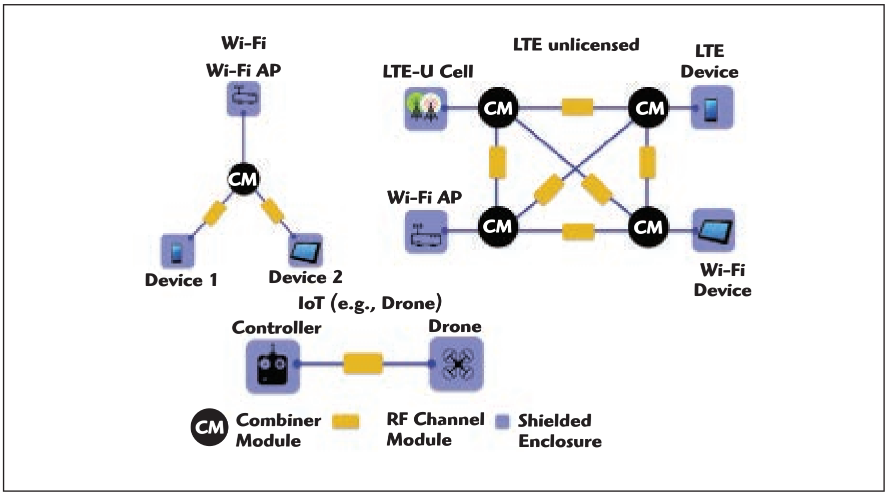


Fig. 3 *Spider's building blocks support many topologies, both standard and user defined.*

TABLE I
SPIDER PERFORMANCE SUMMARY

Parameter	Specification
Technologies	Cellular (LTE-A, LTE unlicensed, LTE, 3G/2G), Wi-Fi (802.11ac/n/a/b/g/n), Bluetooth, ZigBee
Applications/Use Cases	IoT, Handover Testing, Coexistence Testing
Control & Automation	Spider™, ACE™ Channel Emulators, Devices, Access Points, Traffic Sources, Diagnostic Monitors/Sniffers, Small Cells, Others
Automation	Test Builder (GUI-Guided Automation) or API
Topologies	Star, Mesh, Custom
Frequency Range	700 MHz to 6 GHz
Channel Bandwidth	Unlimited (within the Frequency Range)
Connections	Full Rank Channels for up to 4 Spatial Streams (4×4), Inherently Bidirectional
Device Connection	Cabled or Near Field
Isolation	90 dB Typical

Fig. 2 *Near field adapter connected to a smartphone.*

- Connectivity with real devices in their native forms
- Automation of entire test bed that includes devices, access points (AP) and traffic sources.

As with Legos, users can follow the directions for common, specific designs or can use the same blocks, with others, to build test beds for unique purposes. Pre-built Lego models may also be purchased.

THE BASIC BLOCKS

Spider consists of integrated hardware and software modules (see ***Figure 1***). The basic platform comprises the following:

RF Channel Module (RFCM): The RFCM can be used stand-alone between two nodes or part of a complex topology. Featuring controllable path loss and supporting four paths, the RFCM provides individual path or group attenuation control for both single-input-single-output (SISO) and MIMO testing. It's available with (RFCM-B) or without (RFCM-C) an integrated Butler matrix, which provides a low condition number, high rank channel for testing MIMO, beam forming and other applications that require a controlled combination of different RF signals.

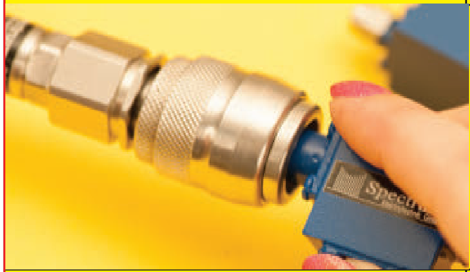
Combiner Module (CM): The CM merges multiple MIMO paths into the desired test configuration. Each CM can combine multiple groups of four paths each, enabling myriad SISO/MIMO test configurations. There are currently two versions: 1) the Mesh Combiner Module (MCM) has low loss between the master port and split ports and higher isolation among the split ports; 2) the Star Combiner Module (SCM) features identical ports. The combiner

Procedure for how to use the N, TNC and 7/16 Push-On male. Push-On Connectors mate with any standard female connector of the same connector style.

1. Convert your standard Assembly into a Push-On Assembly using the Nf to Nm Push-On Adapter.

2. Put your fingers firmly onto the knurls of the “Lock Nut”.

3. Push “Lock Nut” forward and engage the Push-On end of the Adapter with the mating female. Back nut must be released.

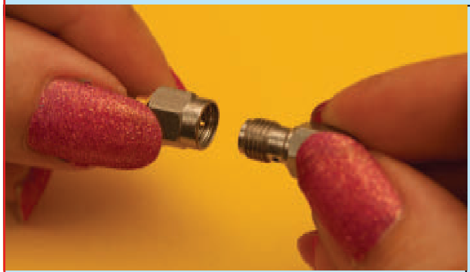


4. The Connection has been completed, easy and fast. The connector has been locked on safely.

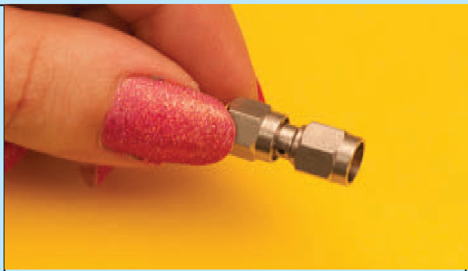
5 . To unlock (when “Back Nut” is in unlocked mode) push the “Lock Nut” forward and stop reverse movement by setting your fingers onto the “Back Nut”.

6. Keep fingers on “Back Nut” to ensure that “Lock Nut” cannot slide back and pull the connector off.

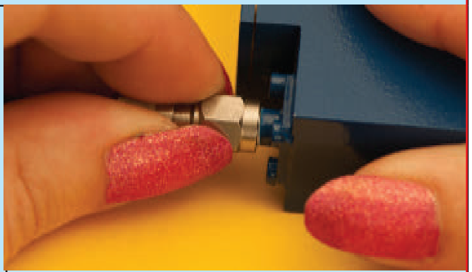
Procedure for how to use the SMA male and SMA female Push-On connectors. SMA Push-On Connectors mate with any standard connector of the same but opposite connector style.



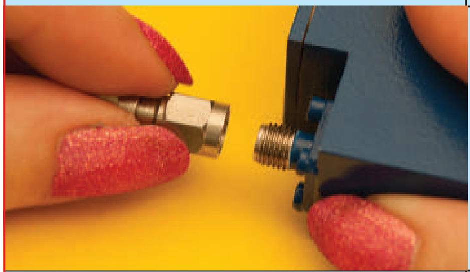
1. Convert your standard cable assembly into a Push-On Assembly by threading the standard female side of the adapter onto the male connector of the assembly.



2. Your standard SMA male cable assembly is converted into an SMA male Push-On Assembly.



3. Just slide the Push-On SMA male Connector onto any standard SMA female. The connection is securely completed in seconds.

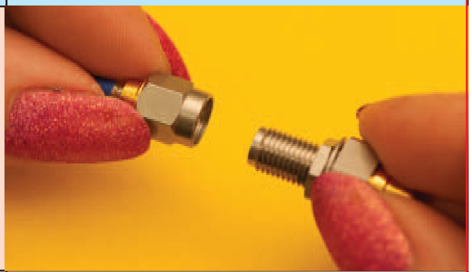


4. To disconnect, just pull the connector off.

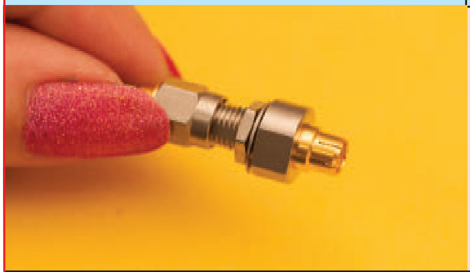
Spectrum Elektrotechnik GmbH

Please contact us at:
www.spectrum-et.com
Email: sales@spectrum-et.com
Phone: +49-89-3548-040
Fax: +49-89-3548-0490

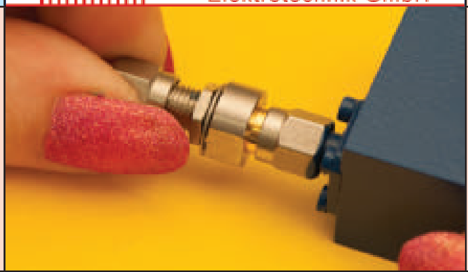
Spectrum Elektrotechnik GmbH



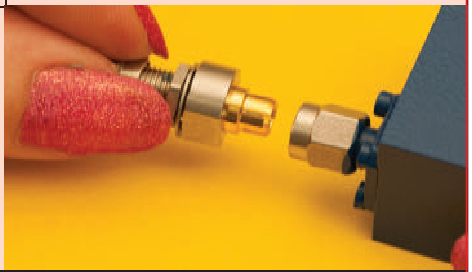
1. Convert your standard cable assembly into a Push-On Assembly by threading the standard female side of the adapter onto the male connector of the assembly.



2. Your standard SMA male cable assembly is converted to a Push-On SMA female Cable Assembly.



3. Just slide the Push-On SMA female Connector onto any standard SMA male. The connection is securely done in seconds.



4. To disconnect, just pull the connector off.

modules can combine four, five, or nine groups, each with four paths.

Shielded Enclosure: Shielded enclosures protect devices from external interference. Various enclosures can hold one or multiple devices of different forms (e.g., smartphones, tablets, laptops) or types (e.g., devices, access points, small cells), with a range of filtered connections (e.g., AC/DC power, USB, Ethernet, serial) and provisions for active cooling.

Near Field Adapter (NFA): A major challenge in conducted testing is attaching devices without exposed connectors. The NFA connects devices without having to open them (see ***Figure 2***), providing repeatability and reliability that can't be achieved through radiated testing.

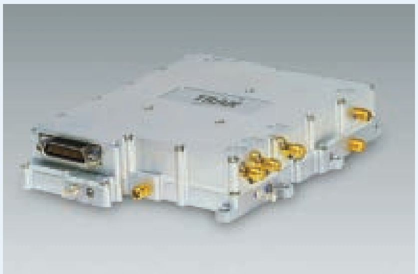
Director™ II Test Executive: A powerful test executive that controls and automates the *entire* test-bed: devices (e.g., smartphones, tablets, PCs), access points, small cells, traffic sources (e.g., Ixia Chariot, iPerf), and diagnostic monitors (e.g., Qualcomm QXDM, Wireshark). Equipped with module libraries for effortless graphing and reporting, notifications and basic programming control, Director II creates test cases through a powerful, intuitive, drag-and-drop graphical user interface test builder.

Designed with a broad operating frequency range from 700 MHz to 6 GHz, Spider has none of the bandwidth limitations of most active test equipment. Not technology specific, it can be used for a variety of technologies, including cellular (e.g., LTE-A, LTE unlicensed, LTE), Wi-Fi (802.11ac/b/g/n) and Bluetooth (see ***Figure 3***). Supporting a variety of topologies (e.g., star, mesh, custom), Spider excels at all forms of testing: conformance/certification, performance, functional validation, interoperability and coexistence. ***Table 1*** summarizes the performance capabilities of the Spider platform.

The old approaches to lab testing are not always reliable and cost effective to scale. The third option, Azimuth's new modular, scalable, automated RF platform Spider makes lab testing simpler, faster, more reliable and more cost effective, with end to end automation of the entire test bed.

Azimuth Systems
Acton, Mass.
www.azimuthsystems.com/products/spider

TechBrief



GaN SSPA Powers Ku-Band Block Up-Converter

The Model MFC147 from TRAK Microwave provides 13.75 to 14.50 GHz coverage for civilian and military Ku-Band SATCOM applications, including in-flight entertainment (IFE) and UAV communications. The unit features a ruggedized design with innovative thermal management, utilizing surface-mount construction with no open die, to withstand challenging airborne environments.

The input frequency to the block up-converter (BUC) is 950 to 1700 MHz, with the Ku-Band output from +12 to +17 dBm. An integrated, low noise, GaN solid-state power amplifier (SSPA) provides 25 W minimum output power with better than -120 dBc/Hz noise power and less than -22 dBc spectral regrowth with OQPSK modulation. The typical noise power is even better: -140 dBc/Hz.

The BUC includes 0 to +7 dB gain expansion and 30 dB digital gain control for optimum SSPA performance. Drain voltage control reduces the thermal dissipation at lower output power levels. The product includes built-in test (BIT), temperature monitoring and both forward and reverse power detectors, all monitored via standard serial commands.

The MFC147 export control classification number (ECCN) is EAR99.

VENDORVIEW

TRAK Microwave
Tampa, Fla.
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www.trak.com

HIGH PERFORMANCE
PASSIVE FREQUENCY DOUBLERS

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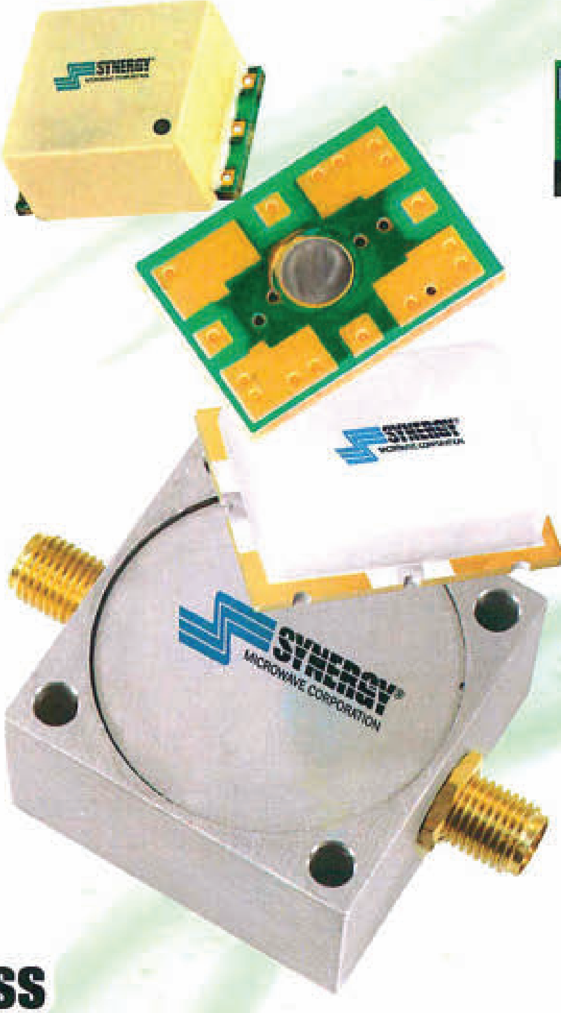

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Web: WWW.SYNERGYMWAVE.COM
Mail: 201 McLean Boulevard, Paterson, NJ 07504

Compact, Connectorized K-Band Power and Driver Amplifiers

Z-Communications released two new K-Band power and driver amplifiers. The PAC18700T and DRC23000M combine high output power and gain with superior linearity. Packaged in a module with SMA connectors and an integrated power supply that only requires a single bias, the amplifiers are quick and simple to install.

The PAC18700T provides over 30 dBm saturated output power, greater than 26 dB gain and 50 dB isolation from 17.7 to 19.7 GHz. The amplifier was designed to operate from -40° to 55°C and includes a temperature compensated power detector with 30 dB of dynamic range. The power detector can be used to control gain and ensure consistent output power. The amplifier's linearity is exceptional, with a third-order intercept point (OIP3) of 46 dBm. The PAC18700T operates from a single +5 V power supply, and the package measures 1.43" × 1.53" × 0.6".

The DRC23000M is a driver amplifier that delivers greater than 16 dBm output power and 20 dB gain from 20 to 26 GHz. OIP3 is 26 dBm, helping designers seeking a driver with minimum nonlinear effects for high gain amplifier chains. The DRC23000M also operates from -40° to +55°C and requires a single +5 V supply, typically drawing 300 mA. The DRC23000M package measures 1.2" × 1.05" × 0.6".

Both the PAC18700T and DRC23000M are well suited for satellite communications, commercial and military radar systems and point-to-point radio.

VENDORVIEW

Z-Communications Inc.
Poway, Calif.
www.zcomm.com

High Performance VCO-Based Synthesizers

SignalCore offers high performance VCO-based synthesizers covering 25 MHz to 20 GHz. The SC5510A packs the performance of large box instruments into a single slot, PXI Express module: Low phase noise of -115 dBc/Hz at 10 kHz offset from a 10 GHz carrier, a frequency range from 100 MHz to 20 GHz, tuning with 1 Hz resolution across the entire band and an amplitude step resolution of 0.01 dB from -30 to +10 dBm output set the SC5510A apart from other small modular synthesizers. Using a unique multiple phase-locked loop architecture, the phase spurs are typically below -65 dBc across the tuning range, even at 1 Hz step resolution. Using a high fundamental frequency VCO (at 20 GHz) and eliminating multipliers, subharmonics are typically less than -70 dBc, and far out spurious signals are al so below -70 dBc.

The synthesizer has a second, independent RF channel covering 100 MHz to 3 GHz with a tuning resolution of 25 MHz. This makes the module ideal for both single stage and dual stage (image suppression) up/down-converter systems. The price-to-performance of the synthesizer makes it useful as a general-purpose laboratory signal source, where demanding phase noise and signal purity are needed. It can also be used as an integrated clock source for fast DAC and ADC applications, especially those requiring variable sampling rates. Applications include RF instrumentation, wireless communications, signal intelligence, data converters and software-defined radio.

For non PXI users, SignalCore offers the SC5511A. It has the same performance and functionality as the SC5510A and is packaged as a compact, stand-alone, core module with USB, SPI or RS-232 communication interfaces.

Full implementation instructions, an easy-to-use, out-of-the-box GUI control panel, driver software and example code are provided with both synthesizers.

SignalCore, Inc.
Austin, Texas
www.signalcore.com

CatalogUpdate

Standard Products Catalog

AMI's Standard Products Catalog includes over 100 microwave components and subsystems for both commercial and military applications, featuring amplifiers, detectors, threshold detectors, detector log amplifiers and limiters with frequency ranges from DC to 40 GHz. AMI is currently focused on product system configurations to connect microwave communication to computer networking, making it possible to control or monitor the function of subsystems remotely via Ethernet I/Os. Details are described in the AMI catalog and app notes.

Advanced Microwave Inc.

www.advancedmicrowaveinc.com

Electronic Warfare Solutions

VENDORVIEW

Berkeley Nucleonics released a new eight-page Electronic Warfare Solutions Short Form catalog. The catalog features BNC's full lines of RF/microwave signal generators (up to 26 GHz), real-time spectrum analyzers (up to 27 GHz with 100 MHz real-time bandwidth), phase noise test systems (5 MHz to 26 GHz+) and wideband RF receivers (up to 27 GHz). New OEM integration provides the highest output power, lowest harmonic levels and broadest frequency range among contemporary signal generators of its size and cost.

Berkeley Nucleonics Corp.

www.berkeleynucleonics.com

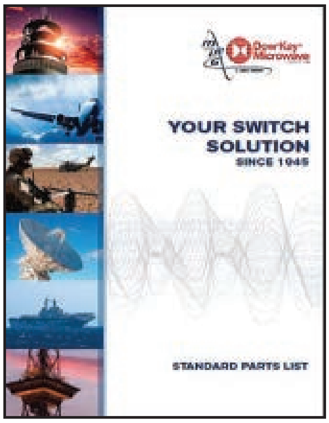
Solid-State Amplifier Solutions

CTT announced a new 48-page product catalog: Solid-State Amplifier Solutions for Military and Commercial Applications. The new catalog features over 830 amplifier products, of which over 365 are all new. Product offerings include new GaN power amplifier technology for narrowband, wideband and ultra-wideband applications. Many new GaAs-based power and low-noise amplifier designs are also listed, including new Ka-Band low-noise amplifiers. The catalog also includes application information and case outline drawings. Visit CTT's website for a free download.

CTT Inc.

www.cttinc.com

Your Switch Solution



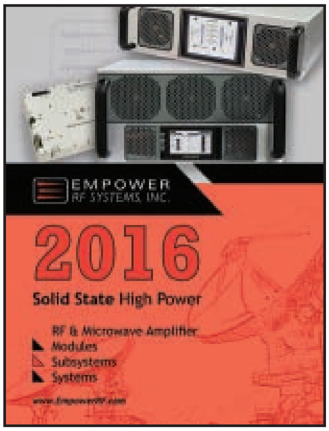
In order to provide products with the best lead times, pricing and superior performance, Dow-Key® Microwave introduces their newly released Standard Part List catalog and in-stock part list. This new product catalog will provide access to Dow-Key's most popular switch selections as well as enhanced product improvements. There are no minimum order quantities with standard or in-stock RoHS compliant parts. Dow-Key is Your Switch Solution™ since 1945.

Dow-Key® Microwave

www.dowkey.com

Solid State High Power

VENDORVIEW



Empower RF Systems is an established manufacturer of high power, solid-state, RF/microwave amplifiers offering modules, rack-mount amplifiers, and multi-function power amplifier solutions to 6 GHz, with output power combinations from tens of watts to multi-kilowatts. Applications include communications, radar, satcom and telemetry, wireless infrastructure, electronic attack, product testing and EMC. To learn more download the company's newest catalog or call (310) 412-8100 to request a copy.

Empower RF Systems Inc.

www.empowerrf.com

IoT Design Challenges

VENDORVIEW

Keysight's new application note, "IoT – With Great Power Comes Great Challenges," discusses the challenges that IoT device designers and developers face, including component, circuit and system levels, what tools and solutions are available today, as well as what test considerations may help save time and cost. Focus is on the intricacies of IoT design and test that utilize the many RF and high-speed digital technologies used in IoT.

Keysight Technologies Inc.

www.keysight.com/find/IoT-Insight

CatalogUpdate

Test Solutions Product Guide

VENDORVIEW

Mini-Circuits' Test Solutions Product Guide is an 88-page, full color publication featuring detailed information about the company's innovative line of RF test and measurement solutions including custom rack-mounted systems, user-defined modular racks and portable test devices. The guide showcases the many capabilities these products offer and applications they support. Comprising functionality ranging from signal source to amplification, routing, attenuation, distribution and power measurement, Mini-Circuits' test solutions have significantly lowered costs and improved test efficiency for customers.

Mini-Circuits

www.minicircuits.com

Filters, Multiplexers and Multi-function Assemblies

VENDORVIEW

When being first to react makes all the difference in the world, choose Reactel for your mission-critical filter requirements. You can count on Reactel to satisfy the most demanding requirements for units used in extremely harsh environments. The full-line catalog features RF and microwave filters, multiplexers and multi-function assemblies for the military, industrial and commercial industries. To request a copy visit the company's website or e-mail reactel@reactel.com.

Reactel Inc.

www.reactel.com

FeatherMate Application Note

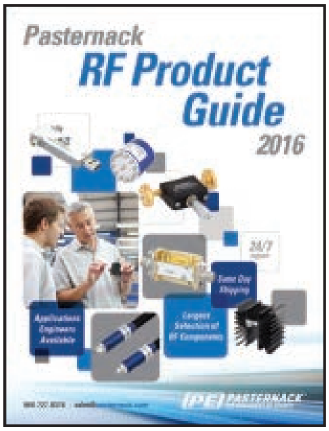
SV Microwave updated their FeatherMate application note to include additional performance graphs, more electrical specs, assembly process, pictures and more. SV's FeatherMate RF interconnect system is a high density (.085" center-to-center spacing, 2.16 mm pitch), 50+ GHz multiport connector that does not damage PCB solder joints during detachment. Direct connection to board trace, solder-free board mounts and small diameter coax cable connectors are available. Ideal for high density, low-force applications including bench-top testing, evaluation boards and automated test equipment (ATE).

SV Microwave

www.svmicrowave.com

2016 RF Product Guide

VENDORVIEW



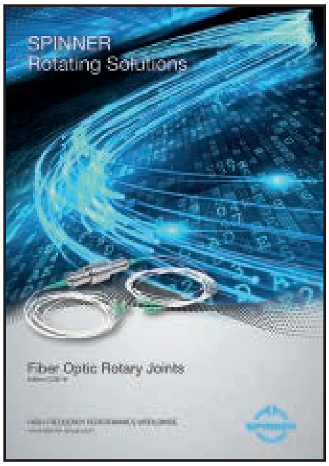
Pasternack's 264-page 2016 RF Product Guide contains thousands of in-stock products including an expanded portfolio of RF amplifiers and electromechanical switches, the industry's largest selection of RF cable assemblies, and hundreds of other passive, active and test & measurement components, all available for same-day shipping worldwide. New additions include GaN, GaAs and LDMOS amplifiers, SPDT through SP12T switches, waveguide components, VNA calibration kits, test cables and ultra-high frequency RF adapters. The catalog also features product selection guides as well as other useful charts and resources.

Pasternack Enterprises Inc.

www.pasternack.com

Rotating Solutions

VENDORVIEW



The new SPINNER Rotating Solutions Fiber Optic Rotary Joints brochure showcases major design advancements in the SPINNER single and multichannel portfolio. The new single-channel SPINNER FORJ 1.14 comes with an outer diameter of just 14 mm, specifying a < 1.0 dB insertion loss. The brochure also presents the pressure compensated single-channel SPINNER FORJ 1.17 pc for deep sea applications. Where the roughest of environments are a reality, the multichannel SPINNER FORJ x.65 accommodates up to 20 channels — and now comes in a sea water resistant IP65 design.

SPINNER GmbH

www.spinner-group.com

RF Cables, Connectors & Assemblies

Times Microwave Systems recently updated its High Power RF Cables, Connectors & Assemblies brochure covering 50 ohm flexible cables for use in demanding high power applications such as high power radar and lasers, pulse power, medical equipment (MRI), semi-conductor, flat panel & solar panel manufacturing, and particle physics. Cables are available for use at continuous operating temperatures up to 200°C. Custom high power coaxial cable assemblies are also available. The brochure includes a comprehensive connector list for the most popular high power cables.

Times Microwave Systems

www.timesmicrowave.com

eLEARNING center

Presented by: Microwave Journal

May Short Course Webinars

Technical Education Training
Proving Reliability and Efficiency with Solid State Spatial Combining Technology
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Live webcast: 5/3/16

Innovations in EDA
Advances in High Power RF Design
Presented by: Keysight Technologies
Live webcast: 5/5/16

Technical Education Training
Designing Next-Gen Cellular and Wi-Fi Switches Using RF SOI Technology
Sponsored by: GlobalFoundries
Live webcast: 5/12/16

RF/Microwave Training
Mixers and Frequency Conversion
Sponsored by: Mini-Circuits
Live webcast: 5/17/16

Past Webinars On Demand

Technical Education Training Series
- Introduction to Radar
- Effect of Conductor Profile Structure on Propagation in Transmission Lines
- Minimize Your Y-Factor Noise Figure Measurement Uncertainty
- Doherty at Eighty
- Millimeter Wave and E-Band Vector Network Analyzer Solutions
- Making Noise Work for You
- RF and Microwave Heating Simulation and Application Design
- Critical Aspects of Dielectric Constant Properties for High Frequency Circuit Design
- Demystifying MIMO Radar and Conventional Equivalents
- Passive Intermodulation (PIM) in Printed Circuit Boards: Mechanisms and Mitigation
- Port Tuning — EM Accuracy and Circuit Theory Speed
- Antenna Simulation with COMSOL

RF/Microwave Training Series
Presented by: Besser Associates
- RF and Microwave Filters
- Passive Components: Dividers, Couplers, Combiners

CST Webinar Series
- Hybrid Simulation for Electrically Large Aerospace Platforms
- Simulation of Implanted Medical Devices
- Advanced PCB Rule Checking for Signal Integrity and EMC
- Graphene-Enhanced Devices: Simulation-based Design from Microwave to Optical Frequencies

Innovations in EDA
Presented by: Keysight Technologies
- 5G Physical Layer Modeling: A Communication System Architect's Guide
- Designing X-Band PAs Using SMT Plastic Packaged GaN Transistors

Keysight Technologies Webcast
- LTE in the Unlicensed Spectrum
- Using a Multi-Touch UI to Streamline Signal Analyzer Measurements
- Testing Voice Over LTE on Your Device

Keysight RF and Microwave Basics Education Series
- Simulating, Generating and Analyzing Custom-modulated Satellite Signals

Keysight FieldFox Series
- Wireless Site Survey, Spectrum Monitoring and Interference Analysis

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COMPONENTS

PIN Diode Miniature Switch

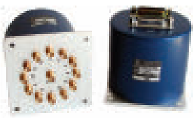
VENDORVIEW

20 to 40 GHz single pole 4 throw PIN diode miniature switch. The insertion loss can be 1.5 dB with 75 dB isolation.

Cernex Inc.
www.cernex.com

SP12T Terminated RF Switch with Ultra Low Intermodulation

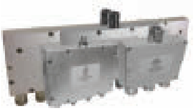
CEI model T12P-941518 is a SP12T internally terminated latching switch with indicator circuitry operating from DC to 15 GHz. The ultra low PIM switch features a -160 dBc minimum 3rd order IM. The T12 series is also offered as a failsafe or normally open switch along with various actuator and mounting options. CEI offers a complete line of coaxial RF switches for ATE, matrix and critical switching systems. The low PIM specifications are available with all CEI switches.



Charter Engineering Inc.
www.ceiswitches.com

V-Line Power Divider/Combiners

VENDORVIEW



2-way through 16-way, 40 W power divider/combiners are optimized for excellent performance across all wireless bands from 698 MHz to 2.7 GHz. Their rugged construction makes them ideal for both base stations and in-building wireless systems. Always in N, SMA, BNC, TNC, QMA and RP TNC connector configurations for your 4G/LTE – WiMAX applications. Made in the U.S. and 36-month warranty.

MECA Electronics Inc.
www.e-MECA.com

Power Splitter/Combiner

VENDORVIEW

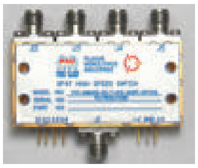
Mini-Circuits' ZX10-2-183+ is a coaxial, ultra-wideband 2-way 0° splitter combiner providing RF input power handling up to 30 W as a splitter (from 1500 to 8000 MHz) and 0.8 dB insertion loss for an extremely wide range of applications from 1500 to 18000 MHz. Its outstanding combination of high power handling and low loss make this model an excellent choice for distributing signals in systems where efficient transmission of signal power is needed. The splitter/combiner comes housed in a rugged, compact case (1.90" × 0.96" × 0.46") with SMA connectors.

Mini-Circuits
www.minicircuits.com

Absorptive Switch

VENDORVIEW

PMI Model No. P4T-50M40G-55-T-515-292FF-OPT27G is a 50 MHz to 27 GHz, single pole four throw, absorptive switch. This switch offers 55 dB of port-to-port isolation and a maximum insertion loss of 8 dB. It has a switching speed of 100 ns and is independently TTL controlled. The operating power is +20 dBm CW and the typical VSWR is 2.0:1 max.



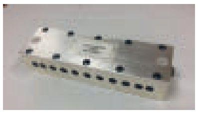
Planar Monolithics Industries Inc.
www.pmi-rf.com

6 to 40 GHz Directional Coupler

Pulsar CS20-51-435/4 is a broadband directional coupler covering 6 to 40 GHz. Coupling is 20 ±1 dB, with ± 1 dB coupling flatness and loss of 1.2 dB. VSWR is 1.70:1 and directivity is 10 dB. The unit can accept an input power level of 20 W. Connectors are 2.92 mm female. Outline dimensions are 1.06" × 0.625" × 0.40".

Pulsar Microwave Corp.
www.pulsarmicrowave.com

GPO Filters



RLC Electronics introduced a new line of GPO and Miniature-GPO connectorized filters. These filters are available in all filter topologies, including tubular, cavity/comb and lumped element, in frequencies up to 26.5 GHz (GPO), 40 GHz (GPPO) and 65 GHz (G3PO). One main benefit of the GPO connector is the ease of mating on the customer board or in the overall system, which potentially eliminates the need for cables.

RLC Electronics Inc.
www.rlcelectronics.com

Wideband 90° Hybrid

The DQP-15-150, hermetically sealed-plug-in, is a wideband 90 degree hybrid, ideally suited for applications in HF and VHF bands. This product is an essential building block for wideband amplifiers, phase shifters, SSB modulators, image rejection mixers and vector modulators. This model covers a phenomenal 10:1 bandwidth between 15 MHz and 150 MHz and handles (1 W) of input power. The typical insertion loss across the specified band is 1.2 dB with a typical amplitude unbalance of 0.9 dB.

Synergy Microwave Corp.
www.synergymwave.com

610 to 970 MHz Wideband Coaxial Circulator

Model F2548-0079-46S is a wideband SMA connectorized circulator covering 610 to 970 MHz. It features 0.5 dB maximum insertion loss, 15 dB minimum reverse isolation, 1.40:1 maximum VSWR and can handle 50 W of CW power. The package size of the circulator is 2.362" × 2.472" × 1.180".

Wenteq Microwave Corp.
www.wenteq.com

CABLES & CONNECTORS

Flexible Precision VNA Test Cables

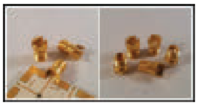
VENDORVIEW

Designed for use as VNA test port extenders, these highly durable and flexible test cables are able to withstand the rigors of test lab use where these cables are constantly flexed during common testing situations. Pasternack's newest lines of highly flexible VNA test cables have excellent electrical properties including low VSWR of 1.3:1 at 50 GHz and 1.4:1 at 67 GHz as well as superb phase stability with flexure of ± 6° at 50 GHz with the 2.4 mm connectors and ± 8° at 67 GHz using 1.85 mm connectors.

Pasternack
www.pasternack.com

NewProducts

Microwave Edge Launch Connectors



SGMC's microwave edge launch connectors feature 1.85 mm, 2.4 mm, 2.92 mm, 3.5 mm and SMA series readily available for 0.062" thick PCB's. Electrical: 50 ohm, low VSWR, low insertion loss, mode free through 65 GHz. Materials: beryllium copper gold plated components. Dielectrics are PCTFE (PolyChloroTriFluoroEthylene) (SMA Fluorocarbon (PTFE)).They are available for immediate delivery – same day shipping for all stock items.

SGMC Microwave
www.sgmcmicrowave.com

AMPLIFIERS

300 W, 0.7 to 6 GHz Solid-State Amplifier

VENDORVIEW

Model 300S1G6AB is a solid-state; 300 W Class AB amplifier that instantaneously covers 0.7 to 6 GHz in one unit with an input power level of 0 dBm. This wideband output power amplifier is approximately half the size of a traditional Class A design, more efficient and offers a more economical price. Typical uses include wireless and EW applications.

AR RF/Microwave Instrumentation
www.arworld.us/post/300S1G6AB.pdf

X-Band SSPA Module

VENDORVIEW

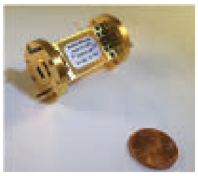
Exodus Advanced Communications' introduced the new AMP3085, an 8 to 12 GHz, 100 W Min/120 W Typical GaN module. It features instantaneous bandwidth from 8000 to 12000 MHz with 100 W Minimum Saturated CW Power, 4 dB peak-to-peak flatness and 22A max

consumption. Suitable for any application requiring high power and wideband coverage such as TWTA replacement, EW and EMI/RFI susceptibility testing.

Exodus Advanced Communications
www.aspen-electronics.com/exodus.html

In-line Amplifier

VENDORVIEW



Norden Millimeter introduced a new waveguide package with in-line waveguide transitions. This WR-22 amplifier has 35 dB typical gain, ±2.5 dB gain flatness, 1.5:1 VSWR, +10 dBm P1dB and noise figure <6 dB. The unit typically draws 220 mA from 12 V.

Norden Millimeter Inc.
www.nordengroup.com

800 W GaN HEMT

Wolfspeed, a Cree Company and a leading global supplier of gallium nitride on silicon carbide (GaN-on-SiC) high-electron-mobility transistors (HEMTs) and monolithic microwave integrated circuits (MMIC), introduced a new 50 V, 800 W GaN HEMT device that provides high output power for L-Band radar applications. The CGHV14800 provides 70 percent efficiency at pulsed PSAT, with a 3 μs pulse width and 3 percent duty cycle.

Wolfspeed
www.wolfspeed.com

SYSTEMS & SUBSYSTEMS

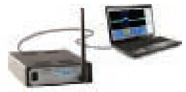
Up/Down-Converter 3 to 40 GHz

A complete remote converter system using a computer network control including I/OS, USB, RS232 and Ethernet (RG45). This product can be an up-converter, down-converter or both, built per customer application using computer controlling the gain up to 30 dB with 0.5 dB LSB. The gain and frequency can be changed by operator using any computer by typing gain or frequency. This product comes with instructions and hardware/software needed to operate converter.

Advanced Microwave Inc.
www.advmiv.com

Wideband Receivers

VENDORVIEW



With BNC's wideband receivers, a solution is now available for any user with the goal of operating across multiple frequency bands, and without spending large amounts of money on down-converters and time on integration. In keeping with the mantra of deployment flexibility, the RTSA7500 series devices only weigh 6 lbs. (2.7 kg), have footprint smaller than a standard sheet of paper, and come with a GUI that lets the RTSA7500 become a real-time spectrum analyzer as well.

Berkeley Nucleonics
www.berkeleynucleonics.com

Receivers

VENDORVIEW

Richardson RFPD Inc. announced the availability and full design support capabilities for a new receiver from M/A-COM Technology Solutions. The XR1020-QH is a 31 to 36 GHz receiver with a noise figure of 3 dB and 14 dB conversion gain. It integrates a low noise amplifier, image reject mixer and LO buffer amplifier within a fully-molded, lead-free, 4 mm, 24-lead PQFN package. The image reject mixer eliminates the need for a bandpass filter after the LNA to remove thermal noise at the image frequency.

Richardson RFPD
www.richardsonrfpd.com

NewProducts

SOURCES

Dielectric Resonator Oscillator

VENDORVIEW

The EDRO-1000 series Dielectric Resonator Oscillator (DRO) utilizes advanced MIC and MMIC technology to generate precise, reliable and ultra-low noise frequency at microwave and mmWave bands up to 40 GHz. The uni-package is designed to mechanically withstand harsh environmental conditions due to shock/vibration, temperature and humidity. The EDRO-1000 series oscillator is designed using an ultra-low noise amplifier with series feedback at source and dielectric resonator at the gate. High gain, low-noise devices are biased and matched precisely to ensure minimum phase noise. The devices are carefully matched for maximum power, minimum phase-noise and voltage standing wave ratio (VSWR).

Exodus Dynamics
www.exodusdynamics.com

Micro-Size SMD Clock Crystal

Measuring only 1.25 mm x 1.05 mm, the tiny SMD Clock Crystal KX-327VT designed by Geyer Quartz Technology has numerous applications including real-time clocks, mobile medical devices and wireless LAN among others. Manufactured with special, fully automatic production processing, this unique product offers accurate time measurements over extended periods of time.

Geyer Electronics America Inc.
www.geyer-usa.com

Oven Controlled Oscillator

Greenray Industries announced the availability of the YH1485 OCXO. The new, high performance YH1485 oven controlled oscillator, available from 10 to 120 MHz with +10 dBm sinewave output, features low phase noise down to -180 dBc/Hz. The YH1485 is also available with low acceleration sensitivity dow to < 3×10^{-10}/g for better performance during shock and vibration. Packaged in a compact, one inch square, low profile package, the YH1485 uses +15 Vdc or +12 Vdc supply. EFC (electronic frequency control) is provided for precise tuning or phase locking applications.

Greenray Industries Inc.
www.greenrayindustries.com

500 MHz to 6 GHz Synthesizer

The GFS-500M6G synthesizer supplies two separate RF output frequencies which are independently programmed and can be arbitrarily stepped, swept, or hopped over the entire 500 MHz to 6 GHz band or over any chosen portion of its frequency range. Phase noise is specified down to 1 Hz offset frequency and at 1 Hz is -84 dBc/Hz at an RF output of 500 MHz. The 1 Hz offset phase noise at a 6 GHz output is -55 dBc/Hz.

GeoSync Microwave Inc.
www.geosyncmicrowave.com

Voltage Controlled Oscillator

VENDORVIEW

Z-Communications Inc. announced a RoHS compliant voltage controlled oscillator (VCO) model USSP1570-LF in the L-Band. The USSP1570-LF operates from 1540 to 1600 MHz with the narrow tuning voltage range of 0.5 to 2.5 Vdc. This miniaturized VCO features phase noise of -90 dBc/Hz at 10 kHz offset while operating off a 2.7 Vdc supply and drawing a mere 6 mA of current.

Z-Communications Inc.
www.zcomm.com

ANTENNAS

Dipole Omni Antenna

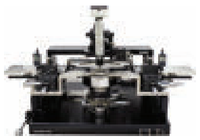
VENDORVIEW

Southwest Antennas Part # 1001-060 is a dual band, half wave dipole omni antenna with a low band frequency range of 2.1 to 2.5 GHz and a peak gain of 2.1 dBi; and a high band frequency of 4.4 to 5.9 GHz and a peak gain of 2.5 dBi. The antenna features an integrated 3" RF gooseneck with black chrome non-rotating SMA(m) RF connector, which contributes to the improvement of RF link margin and overall antenna performance.

Southwest Antennas
www.southwestantennas.com

TEST EQUIPMENT

Probe System for mmWave Applications



MPI TS150-THZ is the worldwide first probe station designed explicitly for precise measurements on wafer and/or substrates in sub-THz range. The system incorporates unique designs allowing unsurpassed 1 μm fine XYZ positioning accuracy and seamless integration of Rohde & Schwarz and other state-of-the-art frequency extenders for easy resetting of different banded mmWave solutions.

MPI Corp.
www.mpi-corporation.com

MICRO-ADS

New**Products**

Compact Calibration Kit

Using 50 Ω, 3.5 mm connectors from DC to 9 GHz the compact 3.5 mm calibration kits are designed specifically for fine-tuning and production environments and quality testing facilities. This kit includes all the required calibration standards (open, short, load) in one unit, which enables it to comfortably handle the calibration of VNAs, especially in the field. The standard kit includes a 3.5 mm (female) open-short-load. Features include a return loss: load < -38 dB and phase deviation (open, short) < 1.5 degrees.

Withwave
www.with-wave.com

MATERIALS

Next-Generation Circuit Board Plotters

PCB prototyping is an essential step in electronics development. With the ProtoMat E34 and the ProtoMat E44, LPKF offers multifunctional machines for structuring, drilling and milling of circuit boards. The plotter mechanically etches through the copper of the base material at up to 40,000 RPM. LPKF's E series ProtoMats are the low-cost entry-level solutions for professional PCB prototyping without the need for etching chemicals. They are also extremely user-friendly and compact, with a footprint barely larger than a U.S. letter sheet.

LPKF Laser & Electronics
www.lpkfusa.com

Dielectric Resonators

VENDOR**VIEW**

MCV Dielectric Resonators are offered in TE, TM and TEM mode, providing a wide range of dielectric constant from Er=6 to Er=190 having very high Q factor to ultra-high Q factor, up to Qxf>300,000 measured at 10 GHz. MCV high K substrates are made of high dielectric constant materials from K=6 to 190. Standard sizes are 1" and 2" square with thickness from 10 mils and up. Custom size and thickness available upon request.

MCV Microwave
www.mcv-microwave.com

Basic Radar Analysis

Mervin C. Budge, Jr.
and
Shawn R. German

With the migration of radar from traditional defense systems to commercial markets, you may wish to develop or refresh your knowledge of radar theory. Your career could intersect the radar range equation – and you surely want to avoid a collision.

Although the classic radar texts by Barton and Skolnik are well known, they don't address the most recent developments in the field. "Basic Radar Analysis" does, while building a solid foundation of radar theory. Mervin Budge and Shawn German developed this book from three courses taught at the University of Alabama in Huntsville, home of the U.S. Army's Aviation and Missile Command and NASA's Marshall Space Flight Center. The courses draw practicing engineers who are pursuing graduate degrees and, given the community, the courses must be relevant and practical.

"Basic Radar Analysis" begins with the fundamentals: the radar range equation, radar cross section (RCS), noise, losses, radar receivers, detection theory, matched filters and the ambiguity function. Going more deeply, the book covers waveform coding, stretch processing, phased arrays, sidelobe cancellation, signal processing, synthetic aperture radar and new system approaches (e.g., MIMO and cognitive radar). The authors consolidate discussions of receiver design and analysis and treat areas of digital receivers that are not typically found in other treatments. The book includes a CD with MATLAB scripts to supplement the chapters. "Basic Radar Analysis" is quite comprehensive and makes a good reference.

To order Basic Radar Analysis, contact:

Artech House
www.artechhouse.com
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FABS and LABS

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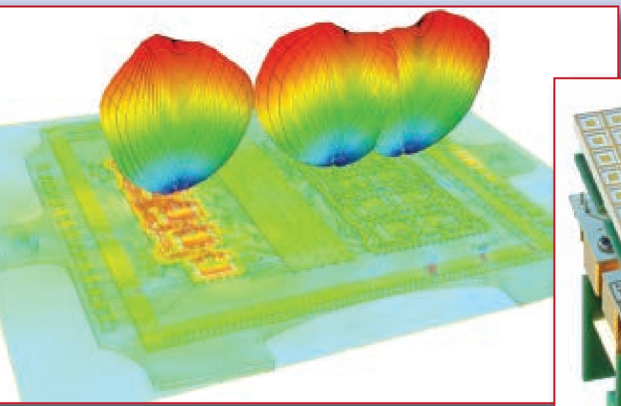

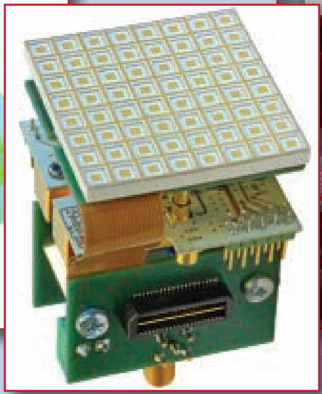

In 1992, with the financial backing of the state government of North Rhine-Westphalia, Germany, IMST was established, with the primary aim of delivering leading-edge science and technology to industry. Since then the company has become a real innovator in cutting edge telecommunication solutions.

As a leader in researching and developing new products for mobile communications systems, radar, integrated circuits, RF circuits and advancing modern antenna technology, the company specializes in creating tailor-made system solutions for industrial customers. Significantly, IMST's R&D chain supports the whole design process, starting with the creation of ideas for new products and continuing through to implementation, product qualification and manufacturing support.

The headquarters in Kamp-Lintfort, in the Düsseldorf area of Germany offers 4,500 m^2 of laboratories and offices. The company currently has about 170 employees, mostly scientists and engineers, as well as several visiting researchers. IMST is active in a number of R&D and industrial projects focusing on a wide range of antenna and RF applications such as mobile devices, 5G, automotive, medical devices, radar, RFID and satellite components. In particular, array antennas (phased array technology) have become a key area of expertise.

IMST has also leveraged its research and commercial experience into valuable software and hardware products for emerging markets. The Empire XPU™ software tool is claimed to be one of the fastest and most efficient 3D-EM-field solvers worldwide. Hardware products include 24 GHz radar systems and different wireless modules including LoRa™ solutions.

The company boasts more than two decades of experience in the design of active RF front-ends, including antenna and beam forming networks, as well as search and track algorithms, the required DSP hardware/software, baseband and the design of active and passive RF components. Also, RF simulations/benchmarking of complete front-ends and fast prototyping capabilities with full conceptual functionality are part of the company's portfolio.

Testing and qualification are key to IMST's operation. A complete range of testing and measuring services are offered. Resources include a DC to 110 GHz microwave measurement facility, a 300 m^2 clean room for hybrid technology (class 100 to 1000), equipped with photo lithography, bonding, laser trimming devices and LTCC fabrication facilities, a 110 m outdoor far field range and EMC test chambers. Testing procedures are carried out in accordance with national, European, and International directives and standards. A wide range of measurement services for verifying the performance of RF materials, antennas, circuits, and entire systems (e.g., ISM, GSM/UMTS) are available.

IMST is not only capable of offering advice to customers on test and certifications but also performs the accredited certification (acc. to DIN EN ISO 17025) regarding CE, EMC, EMF, R&TTE, SAR, OTA and high-frequency equipment, all according to the appropriate regulations such as DIN, EN, ISO, FCC, DGUV, BImSchV and ICNIRP. Its test center is also a notified laboratory to perform measurements for UN ECE-R10 by the German Federal Motor Transport Authority and there are even dedicated test cars. IMST is FCC listed and as an independent testing laboratory, it is qualified to test mobile terminal devices for network operators and handset manufacturers.

With such capabilities, above all, IMST stands for innovative advancement.

www.IMST.com

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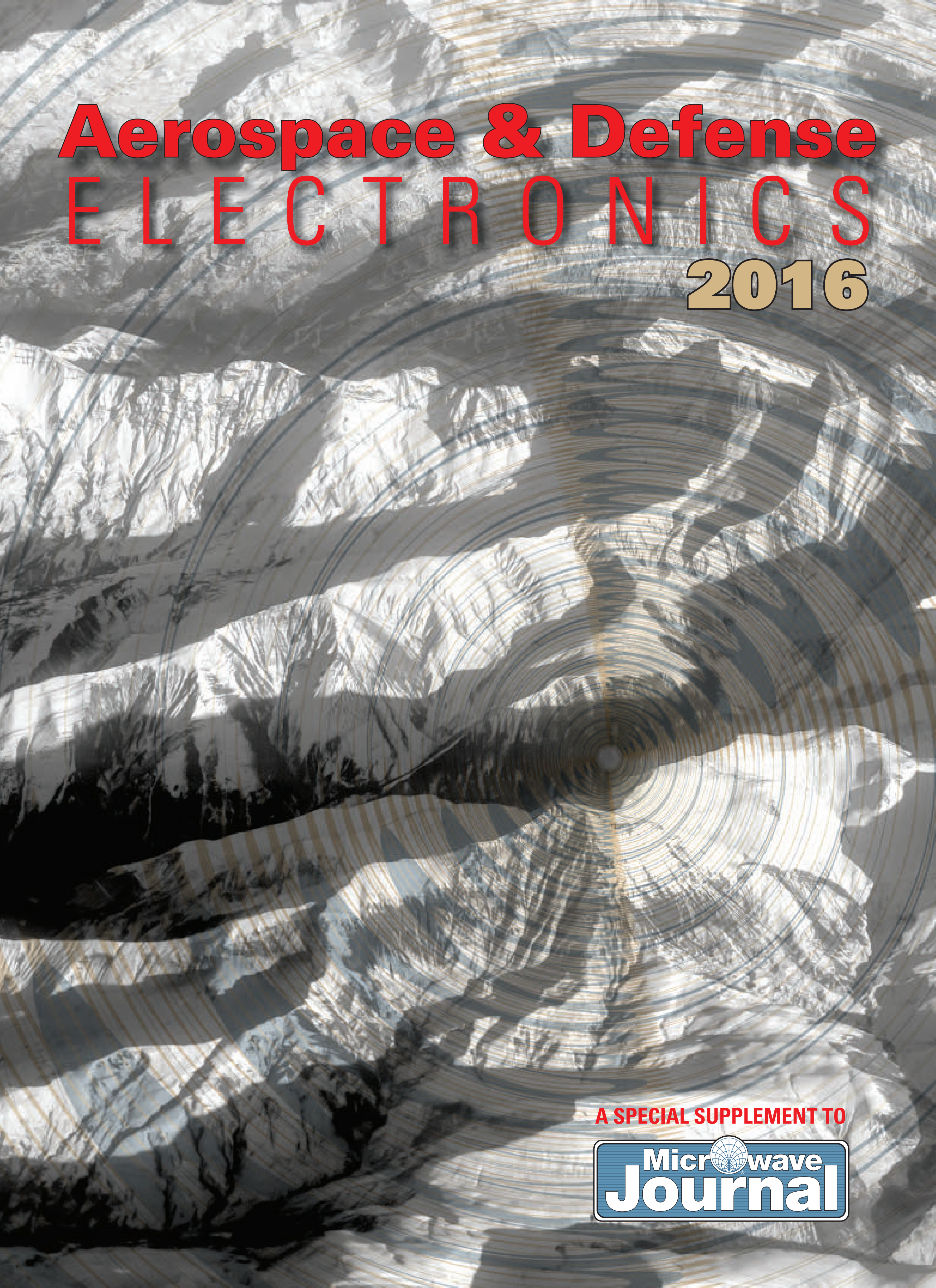

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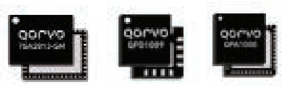

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BPA WORLDWIDE

MWJ REVIEW BOARD APPROVED

T/R Switches and Modules for Ice Sounding/Imaging Radar

F. Rodriguez-Morales, S. Gogineni, F. Ahmed, C. Carabajal, A. Paden, C. Leuschen, J. Paden and J. Li
University of Kansas, Lawrence, Kan.

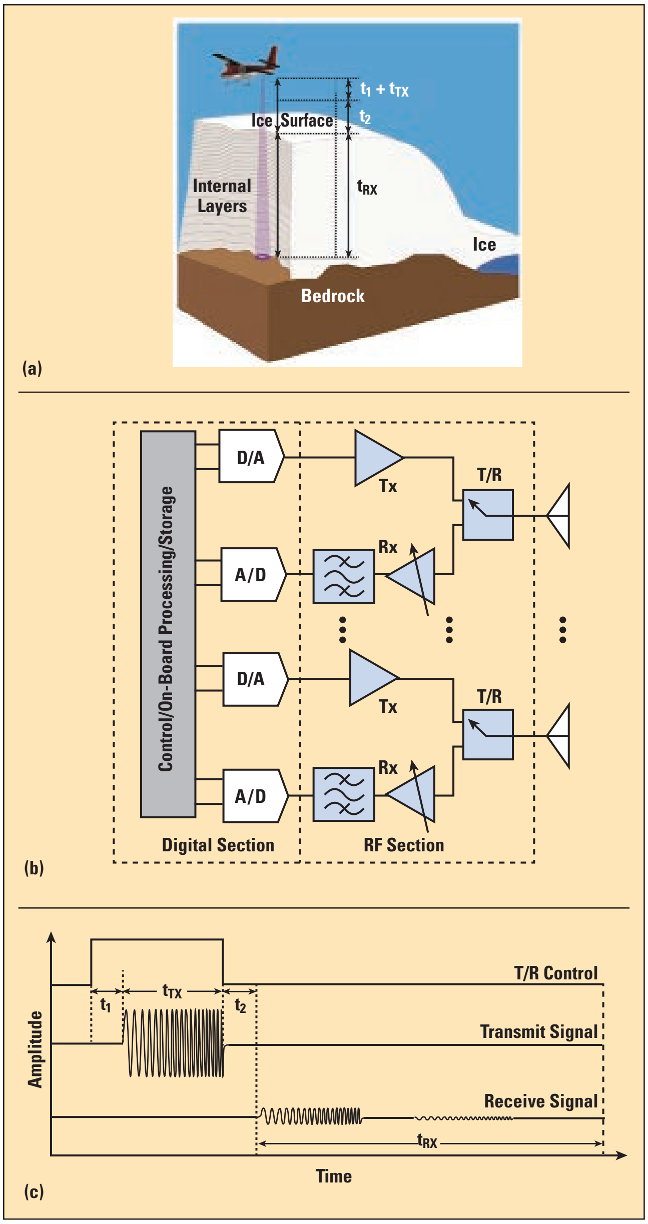
W. Fields
Cobham/Aeroflex Metelics, Sunnyvale, Calif.

J. Vaughan
Los Alamos National Laboratory, Albuquerque, New Mexico

High-power transmit/receive (T/R) switches for use in multi-channel ice-penetrating imaging radars are capable of sustaining peak power levels exceeding 1000 W. They are based on a balanced topology and built using quadrature hybrids and actively biased PIN diodes. Insertion loss is lower than 1.3 dB from 100 to 350 MHz and lower than 1.6 dB from 150 to 600 MHz. Isolation in transmit mode is higher than 85 dB across both bands with turn-on and turn-off times shorter than 1300 ns and 200 ns, respectively. Both designs were successfully used in multi-channel radars for measurements in the Arctic and Antarctic.

Airborne ice penetrating radars are widely used for measuring ice thickness and mapping the internal structure of glacial ice.[1] Recent advances in RF and high-speed digital technologies have contributed to the development of multi-channel radars for imaging the ice-bedrock interface and sounding the most challenging areas of ice sheets, such as fast-flowing glaciers and ice sheet margins.[1-3]

The configuration of a multi-channel airborne coherent radar with transmit/receive (T/R) capabilities is illustrated in ***Figure 1***. The radar RF section is composed of multiple, identical channels interfaced to a digital back-end as shown in ***Figure 1a***. Alternating between T and R modes is accomplished using a high-power T/R switch. During transmission the switch connects the antenna to the transmitter with minimal power loss and isolates the receiver. During reception, the switch connects the antenna to the receiver and isolates the transmitter. The radar timing diagram is shown in ***Figure 1c.*** The switch is toggled using a digital signal (denoted T/R control). Switching speed requirements for this application are driven by the nominal aircraft flight altitude of 500 m above the surface. This corresponds to a round-trip travel time of 3.3 μs. To maximize receiver dynamic range, the radar is operated with a combination of short (1 μs) pulses and long (3 to 20 μs) pulses. The short pulses sound the ice surface and map shallow internal layers, and the longer pulses sound the ice-bedrock interface and map deep internal layers. For 500 m altitude and 1 μs pulses, the T/R switch must be capable of fully transitioning between "on" and "off" states in less than 2.3 μs while preserving adequate power handling, isolation and insertion loss.



▲ *Fig. 1 Airborne coherent multichannel ice sounding radar operation (a) simplified block diagram (b) and timing diagram (c).*

Recent implementations of ice sounding radars with T/R capabilities employ narrow bandwidth systems with relatively low average power. These include, for example, the single-channel 60 MHz system with 4 MHz bandwidth and 1.5 W average power (600 W of peak power at 0.25 percent duty cycle) demonstrated by Christensen et al.,[4] and the 2-channel 60 MHz radar with 15 MHz bandwidth and 22.4 W of average power per channel (3.2 kW of peak power per channel operating at 0.64 percent duty cycle) demonstrated by Peters et al.[5]

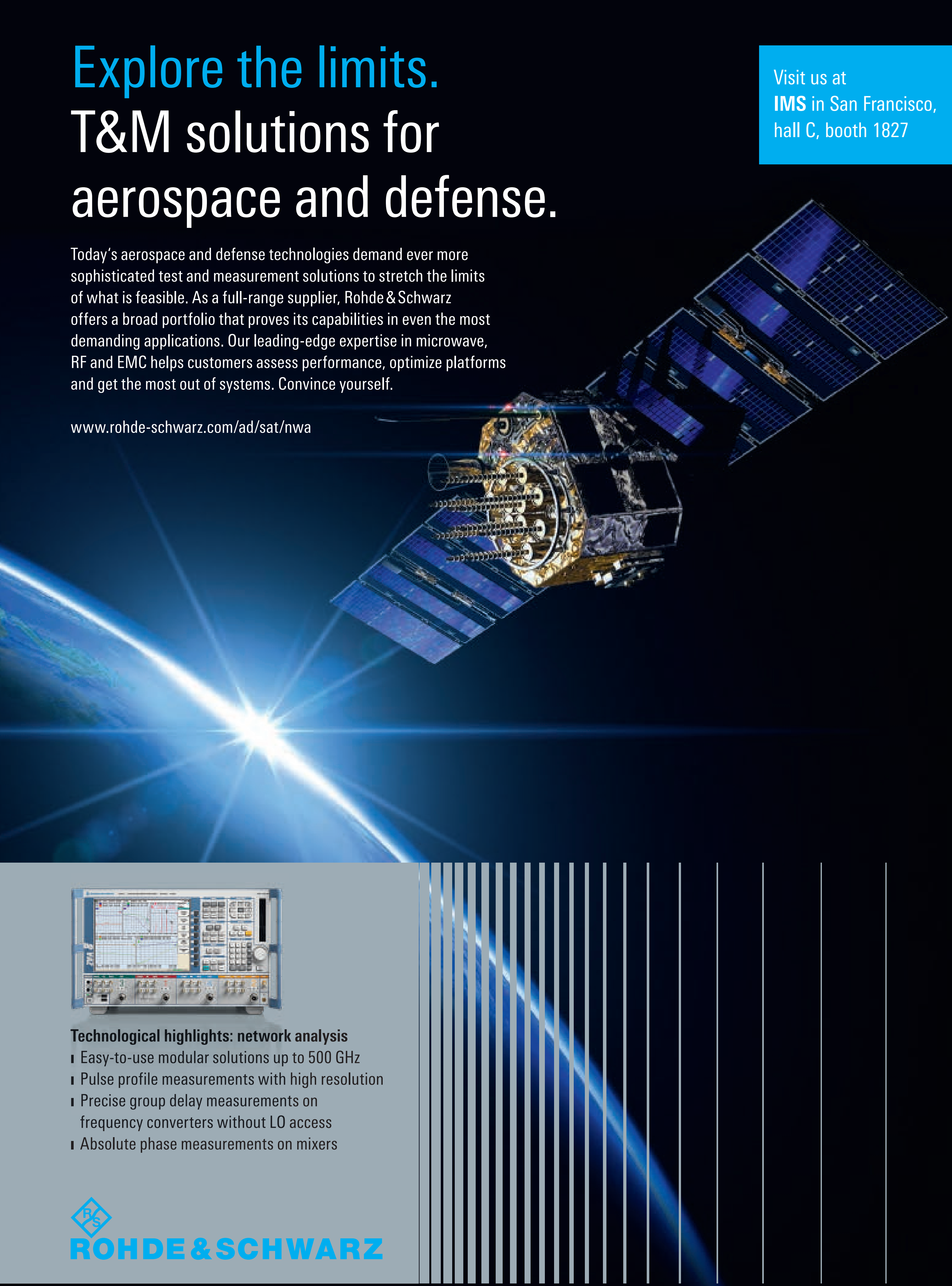
We explored a variety of commercial off-the-shelf (COTS) and custom solutions for the T/R switches for our radars. Initially, we used a COTS single pole double throw (SPDT) switch based on positive-intrinsic-negative (PIN) diodes with a built-in driver. This approach rendered a fully functional system, but suffered from a slow switching time (2.4 μs turn-on, 4.2 μs turn-off), limited peak power handling capability (250 W) and bandwidth (100 MHz), and relatively high cost. (Cilla-Hernandez, et al.,[6] developed a 90 W PIN diode switch with 100 MHz bandwidth for a UHF ice-penetrating radar. They also pointed out the lack of COTS switches with high power handling and fast switching characteristics.) Next, we employed a high-power ferrite-based circulator in combination with a medium power gallium nitride (GaN) switch. This reduced the switching time to about 50 ns but restricted the bandwidth of the system to that of the circulator (30 MHz). More recently, a wideband duplexer based on the circuit proposed by Cofrancesco et al.,[7] was demonstrated employing medium-power silicon (Si) epitaxial planar diodes without active biasing.[8] This configuration had outstanding switching speed and bandwidth performance—less than 50 ns and 300 MHz, respectively—but its peak power was restricted to 250 W.

To further improve radar performance, we increased the peak transmit power to about 1 kW per channel. This required developing the circuit presented in this paper. This new design replaces the Si diodes in the balanced topology with high-power PIN diodes individually biased using a custom driver circuit. (The balanced duplexer topology with active diode biasing was implemented earlier for radar and nuclear magnetic resonance applications [9,10] employing bandwidths ranging from 6 MHz to 25 MHz and peak power levels up to 150 kW. None of these implementations were wideband or fast enough for our application, primarily due to the technology limitations of their time.) First, we developed a prototype that operates in the 100 to 350 MHz range. This design was integrated into a set of compact modules that were then incorporated into a radar on the NASA DC-8 aircraft as part of a NASA Operation IceBridge (OIB) mission in the Antarctic.[11] A second and final design was developed for use in a radar operating over the 150 to 600 MHz band. The new radar was operated on a NASA C-130 aircraft as part of OIB to collect data over the Arctic sea ice and the Greenland ice sheet.

DESIGN DESCRIPTION

Figure 2 shows a simplified block diagram of the T/R switch circuit. It consists of a pair of wideband 90 degree hybrids connected back-to-back; a series PIN diode switch element (D1: Cobham Metelics MEST2G-150-20); and three shunt switch elements (D2-D4: Cobham Metelics MSWSH-100-30). Diodes D1 and D2-D4 can handle up to 150 W and 300 W average, respectively. Each diode is biased individually via RF chokes, using a multi-channel custom driver that accepts standard TTL levels from the digital system. The driver is based on the standard BJT-based configuration widely available in the literature.[12,13] The switching speed is improved by means of a Baker-clamp circuit and by optimizing the lumped components and PCB layout. For the 100 to 350 MHz configuration, we chose the QH8100 90 degree hybrid from Werlatone Inc., while the QH8840 was chosen for the 150 to 600 MHz configuration.

During transmission, the T/R control is set to "high" and PIN diodes D1-D4 are forward-biased with 100 mA. The RF output from the power amplifier is injected into the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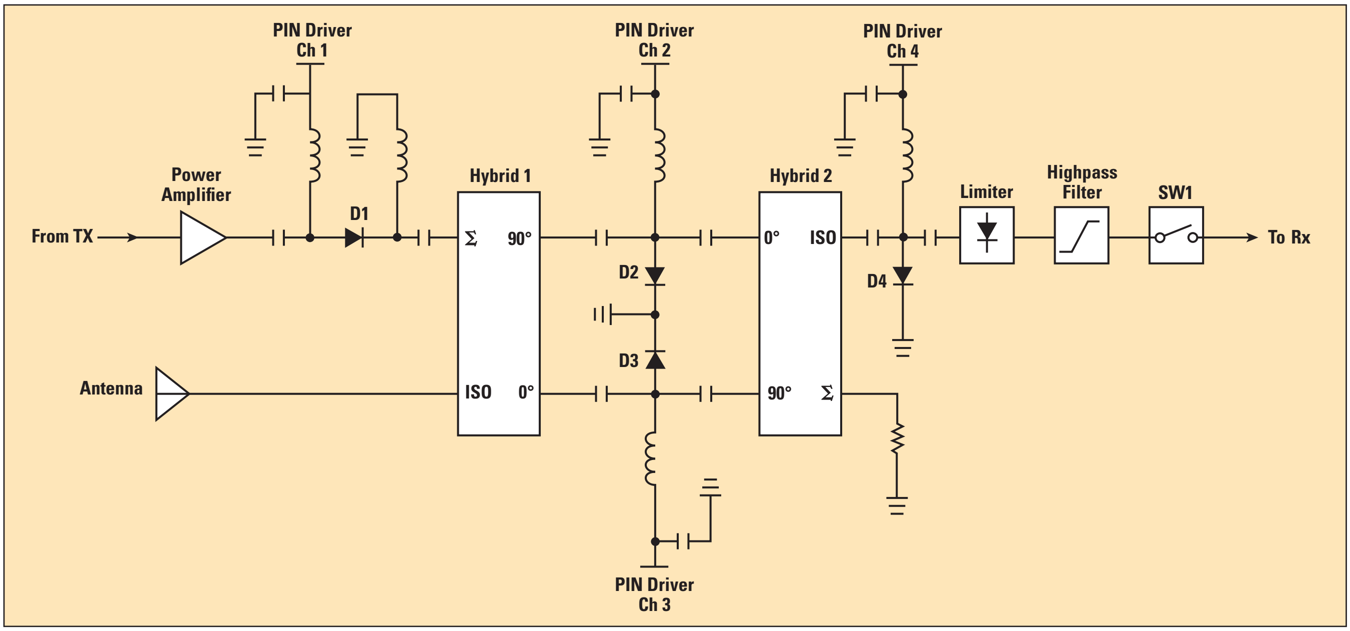
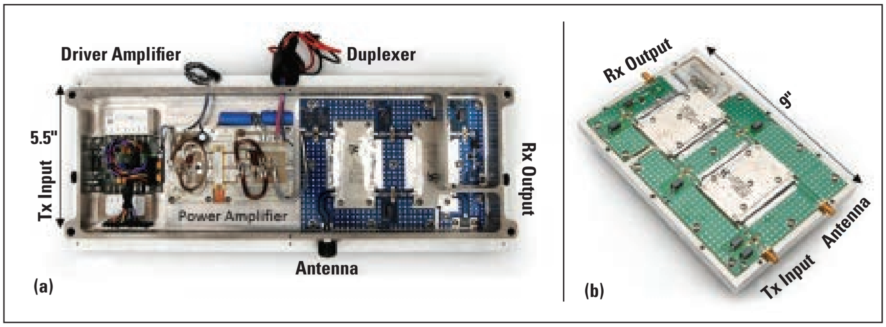


Fig. 2 T/R switch simplified block diagram based on a balanced duplexer configuration.

sum port of the first hybrid through the series diode D1, reaching shunt diodes D3 and D2 with in-phase (I) and quadrature (Q) components. D2 and D3 present a reflective impedance to the I-Q signals, which are re-combined at the isolated port of Hybrid 1. This results in a low-loss path between the power amplifier and the antenna. Diode D4 and the limiter (Cobham Metelics LM200802-M-A-300) are used to protect the receiver from RF leakage. The switch SW1 is added to increase isolation and reduce video feedthrough from the PIN diodes. During reception, the T/R control is set to "low" and the diodes are reverse biased at V_R = -12 V. High voltages are not required since only low-power RF signals are present in this state. The signal from the antenna is split equally by Hybrid 1 then recombined into the isolated port of Hybrid 2, resulting in a small power loss between antenna and receiver. The diode D1 is added to increase receive isolation. A low-loss high-pass filter is placed between the limiter and isolation switch SW1 to reduce low-frequency transients from PIN diode switching. The receiver section is enclosed in a separate cavity to further increase isolation to the transmitter.

For the 100 to 350 MHz version, the high-power switch is integrated with a 1 kW power amplifier and a 10 W driver amplifier. The power amplifier is based on a reference design for the MRFE6VP61K25H from NXP.[14] The driver amplifier is a two-stage design based on Polyfet RF Devices modules. For the 150 to 600 MHz design, the power amplifier is housed on a separate chassis. ***Figure 3*** shows photographs of both designs. The PIN diode drivers are located at the back of each module (not shown).



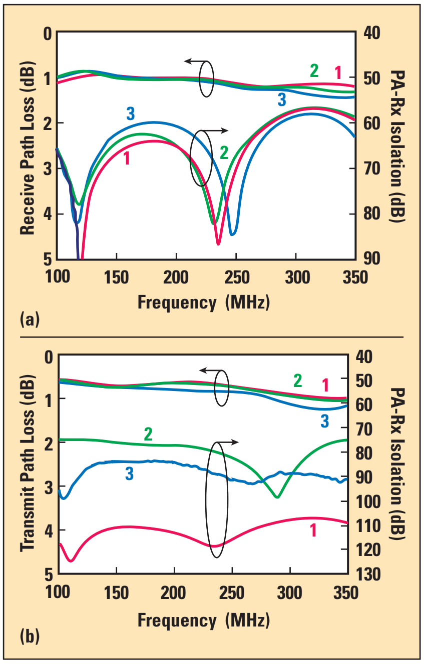
▲ *Fig. 3 100 to 350 MHz T/R module integrated with a driver amplifier, 1 kW power amplifier and PIN diode drivers (a) 150 to 600 MHz T/R switch integrated with PIN diode drivers (b).*

EXPERIMENTAL RESULTS AND DISCUSSION

Small-Signal Simulations and Measurements

The design is first verified over the 100 to 350 MHz range using Keysight's Advanced Design System (ADS) with S-parameters provided by the manufacturers for all the components, including the PIN diodes. To increase the model accuracy, first-order layout effects are considered by incorporating microstrip and coplanar transmission line sections and junctions. The PCB layout for the RF section is accomplished in CadSoft Eagle and imported into ADS for EM/circuit co-simulation. Both transmit and receive modes are simulated and then measured using a 4-port vector network analyzer. The results are presented in ***Figure 4***.

In receive mode, the circuit simulation, EM/circuit co-simulation, and measured results show excellent agreement. The insertion loss between the antenna and receiver ports is less than 1.3 dB with less than 0.15 dB deviation between simulations and measurements. Further, the simulations accurately predict more than 57 dB of isolation between the power amplifier port and the receiver port of the switch. In transmit mode, the circuit and EM/circuit co-simulation yield an expected 0.7 to 0.9 dB of insertion loss between the antenna and the power amplifier ports. The measured insertion loss agrees with simulation to within 0.16 dB. The design target for isolation between the transmitter and receiver in this mode is 70 dB. The circuit simulation overestimates this, predicting a value greater than 105 dB across the band, while co-simulation predicts it to be at least 75 dB. The discrepancy between the two simulated results is expected, because the circuit simulation includes only first-order effects of the PCB layout. Measured isolation is 87 to 96 dB; this exceeds design requirements, but differs from the simulation. The difference between the co-simulated and measured result is due to the fact that the rectangular cavity enclosing the receiver section of the duplexer is not included in the simulation. Similar performance is obtained for the 150 to 600 MHz design in both transmit and receive modes, with a slight increase of insertion loss in the upper part of the band when in



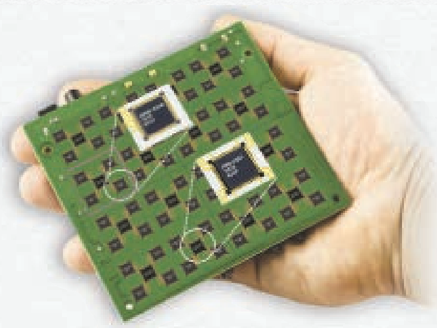
▲ *Fig. 4 Circuit simulation (1), EM and circuit co-simulation (2) and measured small-signal S-parameters (3) for the 100 to 350 MHz module receive (a) and transmit (b) states.*

Silicon Quad Core ICs for X-band RADAR

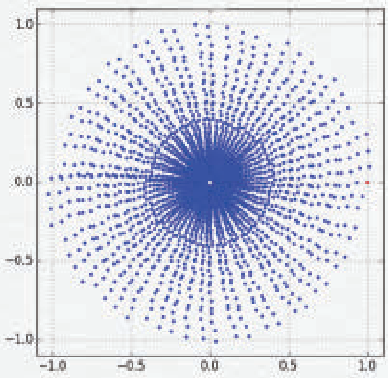
Market	Product Family	Part Number	Description
RADAR and Communications AESA	X-Band Silicon Core IC Solutions	AWS-0101 AWS-0103 AWS-0104 AWS-0105	Dual Beam Low NF Quad Core IC Dual Beam High IIP3 Quad Core IC Single Beam Low NF Quad Core IC Single Beam High IIP3 Quad Core IC

4 channel beam former with T/R duplex
Single Rx for efficient DC power
Dual Rx for dual polarity/monopulse capability
Low NF or high IIP3

Surface mount 7x7 mm QFN



Anokiwave - enabling your AESA



6-bit amplitude/phase control

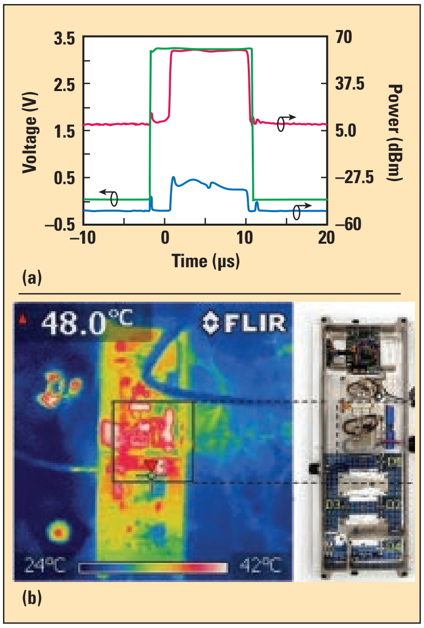


Fig. 5 100 to 350 MHz T/R switch during high power operation, showing transmit signal envelope (red) and feedthrough signal envelope (blue) with a high power, 10 μs RF pulse (a) infrared image of the temperature distribution on the module top face (b).

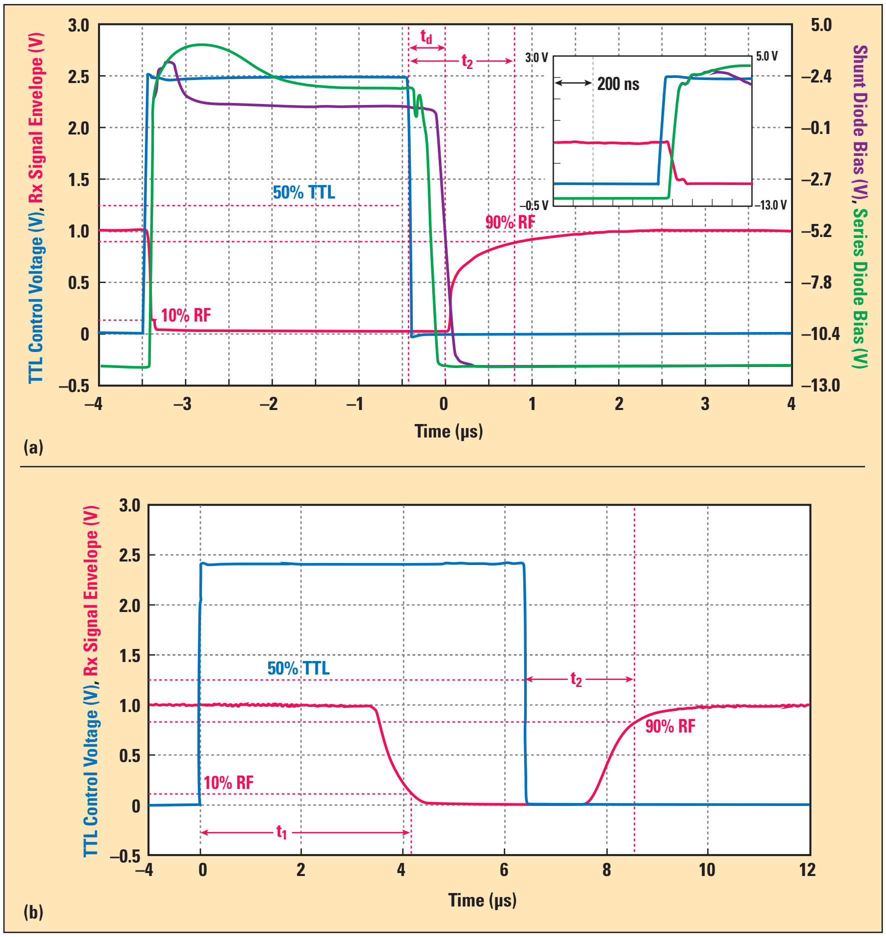


Fig. 6 Measured switching characteristics of two T/R switches: internal design with an inset showing the turn-off time (a) commercial switch used in the earlier version of the radar, showing much slower switching speed (b).

the receive mode (1.6 dB max without including the loss of SW1).

Large Signal Measurements

To verify the power handling capability of the circuit, we excite the high-power amplifier chain with the radar waveform generator. The latter is set to produce both single-tone and chirped pulse signals over the frequency range of the current antennas on the NASA DC-8 (165 to 215 MHz). ***Figure 5*** shows the measured envelope of transmit and feedthrough signals after calibrating for losses in the test setup. Note that the TTL control signal (shown in green in Figure 5a) has a slight time offset to allow the amplifiers to fully turn on before RF power is applied. The measured output power is about 60 dBm across the band. The feedthrough signal ranges between -27 and -36 dBm, which confirms 87 to 96 dB isolation. The highest temperature in the circuit was observed across the series diode D1 (TJmax= 175°C), as shown in ***Figure 5b***.

Switching Time

To verify the circuit switching speed, we inject a low-power CW tone into the antenna port of the circuit while toggling T/R control. We monitor the voltage across the PIN diodes and the signal at the receiver port. The RF pulse duration is set to 1 μs with a PRF of 15 kHz. The top inset of ***Figure 6a*** shows the measured results, indicating a very fast transition from 50 percent TTL to 10 percent RF at the receiver port (200 to ns turn-off time). The transition from 50 percent TTL to 90 percent RF at the receiver port occurs in 1300 ns (turn-on time). These values include driver delays (450 ns max). ***Figure 6b*** shows measured results for a COTS switch used in previous versions of our radars. Its turn-off time is 4.2 μs (21 times slower than our circuit) while its turn-on time is 2.4 μs (almost 2 times slower than our circuit).

Sample Radar Results

We used the 100 to 350 MHz and 150 to 600 MHz switches in two radars employed for extensive collection of ice thickness data over the Antarctic and Arctic. The 100 to 350 MHz design, integrated as a set of six T/R modules, was operated over the 165 to 215 MHz band onboard the NASA DC-8. ***Figure 7b*** shows sample results using the system that incorporates this design, with a 50 MHz bandwidth and 6 kW of total peak transmit power (6 antennas). The echogram was obtained after synthetic aperture radar (SAR) processing and displays the relative received signal intensity in a dB scale as a function of depth and geographic location.

We also include an echogram from data collected over the same area using a lower-power, narrow bandwidth system deployed in 2010 (see ***Figure 7a***). This system employed 10 MHz bandwidth COTS T/R switches with close to 1 kW of total peak transmit power (5 antennas). See Gogineni, et al.,[2] and F. Rodriguez-Morales, et al.,[3] for further details on the radars and the processing techniques applied to obtain these products. The wider bandwidth and

increased transmit power of the new system results in improved resolution and signal-to-noise ratio (SNR), respectively. We estimate an overall SNR improvement of 10 to 14 dB.

The 150 to 600 MHz design was recently tested onboard the NASA C-130H aircraft operating over Southeast Greenland using a two-element antenna array with a 270 MHz bandwidth and close to 2 kW of total peak transmit power. ***Figures 7c*** and ***7d*** show field-processed results from data obtained exercising the T/R switches over the 180 to 450 MHz range. The lower limit of this band is set by the antenna response, while the upper limit is set by the waveform generator. Recent improvements to the digital system will allow us to exercise the entire 150 to 600 MHz bandwidth.

CONCLUSION

Fast, high-power T/R switches and modules for a multi-channel ice imaging radar are capable of handling over 1 kW of peak power (150 W average) with demonstrated switching speeds faster than 1300 ns, including up to 450

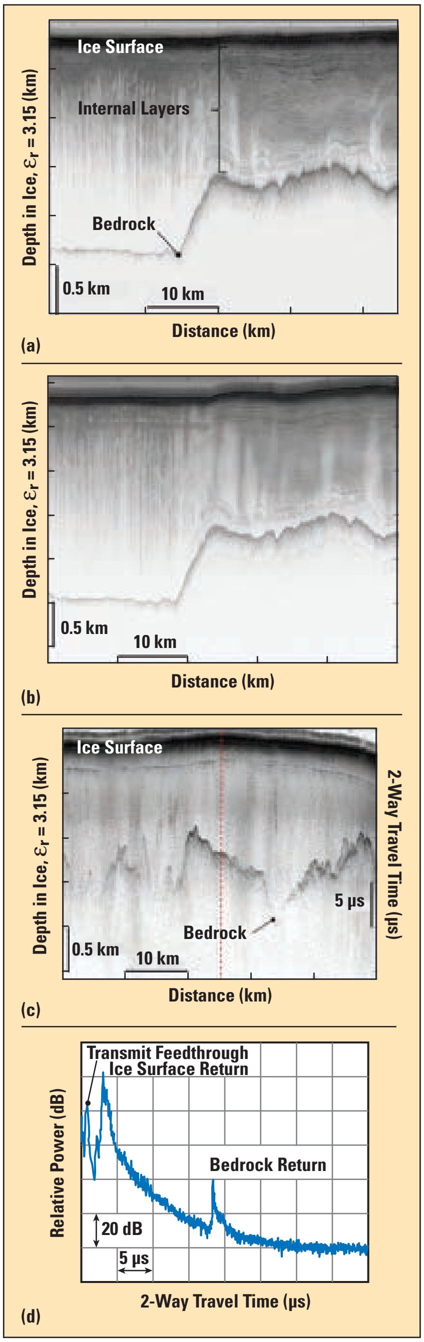


Fig. 7 Radar echograms obtained in Antarctica with an earlier version of the radar (a) data collected over the same area using the new 100 to 350 MHz switch design (b) data collected using the new 150 to 600 MHz switch (c) A-scope showing the relative received power (at the location identified with the red dotted line in (c) as a function of travel time (d).

ns of driver delays. Two different circuits, operating at different frequency bands, were validated in the laboratory and in the field. Sample radar results show the enhanced performance obtained through the higher power and wider bandwidth enabled by these modules. Future work includes the incorporation of faster PIN-diode driver circuits, further miniaturization and increasing peak power. ■

ACKNOWLEDGMENTS

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Design, Integration and Miniaturization of a Multichannel UWB Snow Radar Receiver

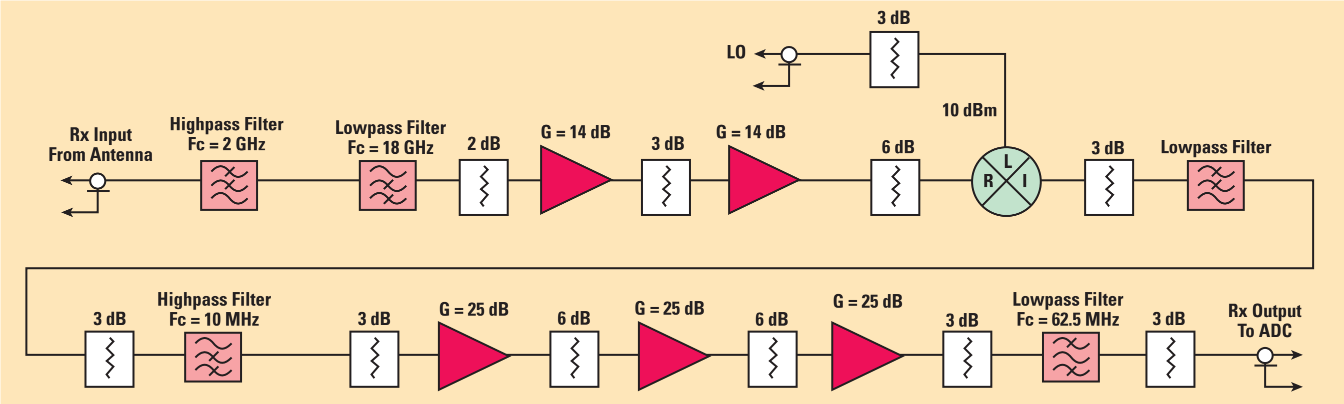
Jay McDaniel, Jie-Bang Yan and Sivaprasad Gogineni
University of Kansas, Lawrence, Kan.

The increasing demand for wider bandwidth radar for finer range resolution to measure surface elevation and snow thickness over sea ice drives the need for ultra-wide bandwidth (UWB) receiver design. This article summarizes the design process for integrating and miniaturizing an UWB multichannel receiver, including receiver subsystem integration, co-simulation as well as the mechanical configuration.

At the University of Kansas Center for Remote Sensing of Ice Sheets (CReSIS), two UWB microwave radars have been developed and deployed to measure surface elevation and snow thickness over sea ice.[1] The 2 to 8 GHz Snow Radar is used for measuring snow over sea ice, while a 12 to 18 GHz Ku-Band altimeter is used for high-precision surface elevation measurements.[2] The systems have been deployed several times over the last decade on NSF and NASA platforms in conjunction with Operation Ice Bridge (OIB). In order to meet additional demands for snow characterization, a new multi-channel, quad-polarized 2 to 8 GHz Snow Radar has been developed with multi-polarization, multi-frequency and multi-look-angle capabilities. This article discusses the design approach and considerations for the multichannel receiver to comply with weight and size restrictions.

FREQUENCY MODULATED CONTINUOUS WAVE (FMCW) RECEIVER

FMCW radar is a form of continuous wave (CW) radar in which the frequency of the waveform is modulated. In most cases, this is linear modulation and the waveform is given the acronym LFMCW. This is commonly known as a chirp. A CW radar can detect only radial velocity using the Doppler Effect, while an FMCW radar can measure both radial ve-



▲ *Fig. 1 FMCW receiver block diagram.*

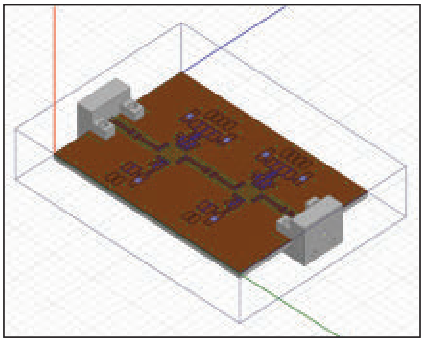
locity and range to the target.[3]

Figure 1 shows a block diagram of the Snow Radar FMCW radar receiver. It consists of two subsystems: the radio frequency (RF) section and the intermediate frequency (IF) section. The RF section performs three tasks: filtering unwanted signals, setting the sensitivity of the receiver and mixing the return waveform with a reference waveform to produce an IF beat frequency.[4] The IF section further filters out undesired signals while amplifying the desired beat frequency to fit within the dynamic range of the analog to digital converter (ADC).

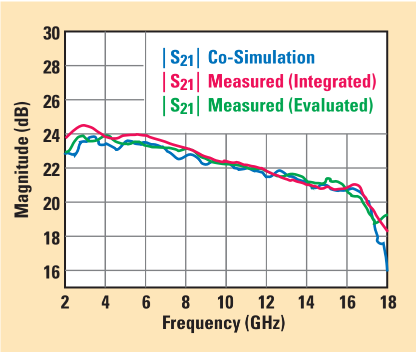
RF FRONT-END INTEGRATION AND MODELING

The first step in miniaturizing the receiver is to integrate the RF attenuators and amplifiers onto a single printed circuit board (PCB). Each component is characterized using a vector network analyzer (VNA) and then component S-parameter data is loaded into the Advanced Design System (ADS) as corresponding SXP files. A co-planar waveguide (CPWG) board topology is chosen due to its UWB and low loss performance. Initial simulation of the CPWG structure is performed in the ANSYS High Frequency Structural Simulator (HFSS) where performance over the 2 to 18 GHz passband is optimized. After circuit board layout using the Easily Applicable Graphical Layout Editor (EAGLE), the design file is exported to HFSS for full board-level electromagnetic (EM) simulation.

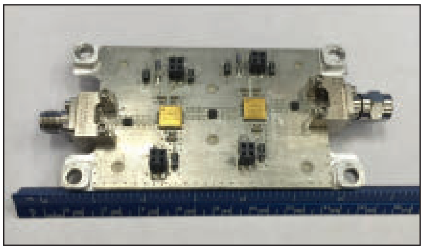
Figure 2 is a screen shot of the board in HFSS. Connectors are included in the design in order to appropriately taper the traces for matching. After running a full EM simulation, the S-parameters of the board are saved and loaded into ADS for co-simulation of the board and components. Co-simulated results and RF measurements of the original discrete component receiver and the integrated receiver board are in close agreement (see ***Figure 3***). More



▲ *Fig. 2 Integrated RF design in HFSS.*



▲ *Fig. 3 Receiver RF chain comparison.*

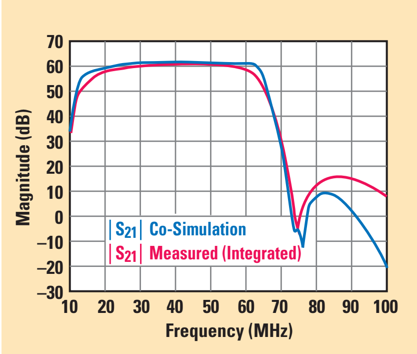


▲ *Fig. 4 Integrated RF chain.*

importantly, measured performance of the integrated board over the passband agrees closely with that of the RF section in the original receiver. A significant size reduction is achieved without sacrificing RF performance.

The final version of the board is shown in ***Figure 4***. It is fabricated on an LPKF mill and populated using a solder re-flow process. The board is epoxy bonded to a custom heat sink. Measurements are performed with a 10 MHz to 26.5 GHz Keysight N5222A VNA.

The benefit of this design process is

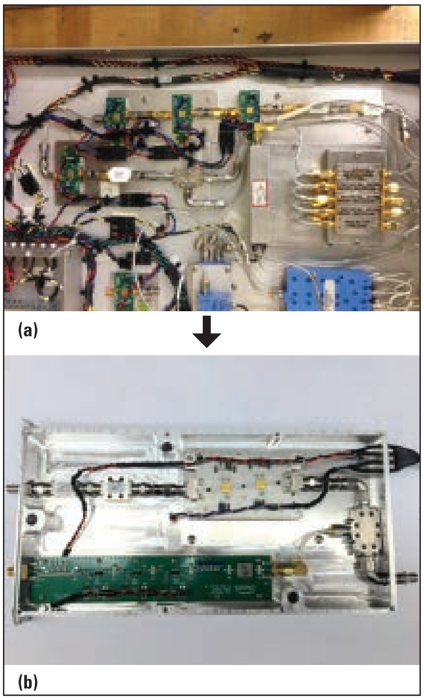


▲ *Fig. 5 Receiver IF chain comparison.*

that board performance is optimized and verified prior to fabrication, avoiding additional fabrication costs and schedule delays associated with a board re-spin.

IF BACK-END INTEGRATION AND MODELING

The same design procedure is used for the IF back-end. Individual IF components are characterized using the same VNA and the S-parameters are uploaded into ADS. The integrated IF board is laid out in EAGLE and then exported to HFSS for EM simulation. The board S-parameters are loaded into ADS to perform a full co-simulation. After minor adjustments, the board is fabricated, populated and tested. ***Figure 5*** shows good agreement between simulation and measurement. Minor differences in the IF passband are due to the individual filter components used in the HFSS



▲ *Fig. 6 Original receiver (a) and new integrated receiver (b).*

simulation. Because S-parameters for the capacitors used were not available, ideal lumped elements were substituted; therefore, cutoff frequencies and roll-offs are slightly degraded in the measured data.

RECEIVER INTEGRATION AND MEASUREMENTS

Figures 6a and ***6b*** show the original receiver and the new integrated receiver, respectively. Integration of

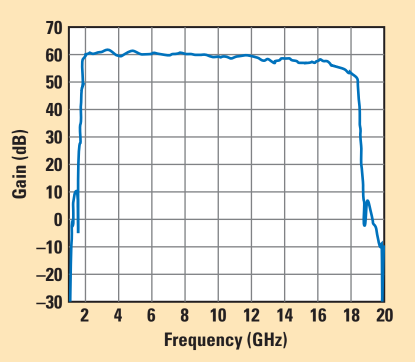


Fig. 7 Measured receiver gain.

the RF and IF chains results in a size reduction of 5.5. The receiver employs a modular concept. The backplane has electromagnetic interference (EMI) filters passing power to the components and filtering unwanted signals coupled onto the twisted pairs. The mixer LO port protruding from the back allows a cable connection to supply LO drive power.

Measurements are made using the Keysight N522A VNA set up in mixer mode. The RF and LO ports are swept

Fig. 8 Front view of the receiver.

from 1 to 20 GHz with the IF frequency set to 40 MHz. The IF bandwidth is set to 5 kHz and the receivers are measured using 32,001 points. The cables used are calibrated for loss and subtracted from the receiver measurement in MATLAB. ***Figure 7*** shows the response of the modular receiver. Gain variation across the 2 to 18 GHz passband is minimal. Components with low gain variation are used and fine-tuning of the RF board further minimizes variations. A highly selective DC to 18 GHz lowpass filter (LPF) and 2 GHz cutoff frequency highpass filter (HPF) define the passband and attenuate out-of-band signals.

MECHANICAL INTEGRATION AND CHASSIS MINIATURIZATION

Enabled by the modular design of the individual receivers, the mechanical design accommodates multiple receivers inside a single chassis. A 4U Techmar case houses up to 18 individual receivers (see ***Figure 8***). The photo shows 12 receiver units in their respective slots. The blank plate at the top of the chassis can be removed exposing six additional slots. The volume of the overall receiver chassis is reduced by a factor of 4 (for 18 channels) when compared to the original discrete component design.

All of the power supplies, power distribution boards and the LO distribution chain fit within the 4U mechanical case. Two power distribution boards bring a single voltage in and distribute it to all the receivers, a built-in feature that supports the modular design. The LO distribution is a chain of amplifiers

and power splitters, allowing a single LO drive signal to be connected to the input of the receiver chassis. It is then split and amplified to satisfy mixer LO drive power requirements.

CONCLUSION

At the Center for Remote Sensing of Ice Sheets, UWB FMCW radars are used to accurately determine snow thickness. With increased demand for additional snow characterization to more accurately model polar climate change, a new multi-channel, quad-polarized, 2 to 18 GHz Snow radar has been developed. With a 5.5 times size reduction of the receiver, along with a modular design, an overall 4 times size reduction of the receiver chassis is accomplished. Elimination of long lead times and reduced cost is achieved by designing and developing the UWB filters in-house, along with other passive microwave components. Through size and weight reduction, UWB multi-channel remote sensing is a plausible option to satisfy future research needs.■

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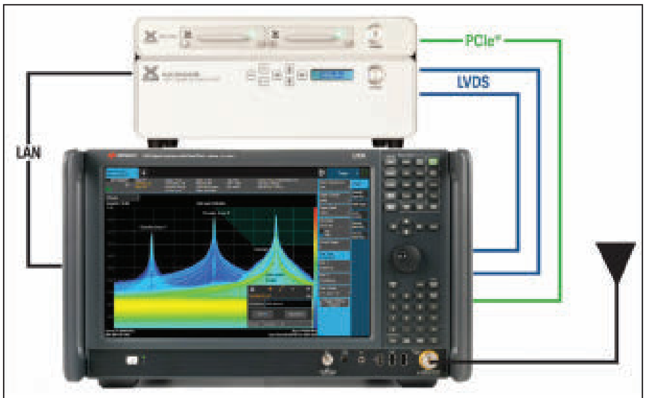
INVITED PAPER

Accelerating "Time to Answers" in RF Streaming Applications

Raj Sodhi
Keysight Technologies
Jim Taber
X-COM Systems

On an electronic battlefield, the frequency spectrum is crowded, chaotic and complex. If a digital RF memory (DRFM) system misidentifies an unfriendly RF emitter, it may respond with an inappropriate jamming signal. If a radar-warning receiver (RWR) fails to identify an emitter, the consequences can be dire.

The ability to fully understand system performance in a real-world signal environment is crucial to the design and validation of the latest radar and electronic warfare (EW) systems. Characterization of these systems can be a daunting task due to the many operating modes they employ. For each mode, it's often necessary to validate pulse widths, pulse-repetition intervals, modulation formats, frequency agility and many other signal parameters. It's also important to understand timing relationships, especially when dealing with threat-response interactions.



▲ *Fig. 1 Integrated solution to support wideband RF streaming and analysis.*

There are two key measurement challenges. First, it is necessary to capture 100 percent of the RF energy output during a test that includes highly unpredictable signals-of-interest. Second, the resulting mountain of data must be analyzed and interpreted.

Fortunately, the latest digitizers and digital interfaces enable the creation of RF streaming solutions that can capture gap-free data for seconds, minutes or even days, ensuring that no signal is missed. Post-processing software tools make data reduction and analysis more manageable, accelerating the time-to-answers by uncovering signal anomalies, pulse-timing relationships and more (see ***Figure 1***). This integrated combination of commercial, off-the-shelf hardware and software supports wideband RF streaming and analysis. It includes an IQC5255B recorder (top) and Spectro-X signal analysis software from X-COM Systems as well as a UXA signal analyzer (bottom) and 89600 VSA software from Keysight Technologies.

UNDERSTANDING THE RECORDING SCENARIO

To ensure accurate capture of the signal environment, it is necessary to consider the real-world setting in which recording occurs. These may include mobile or fixed-site scenarios, on-

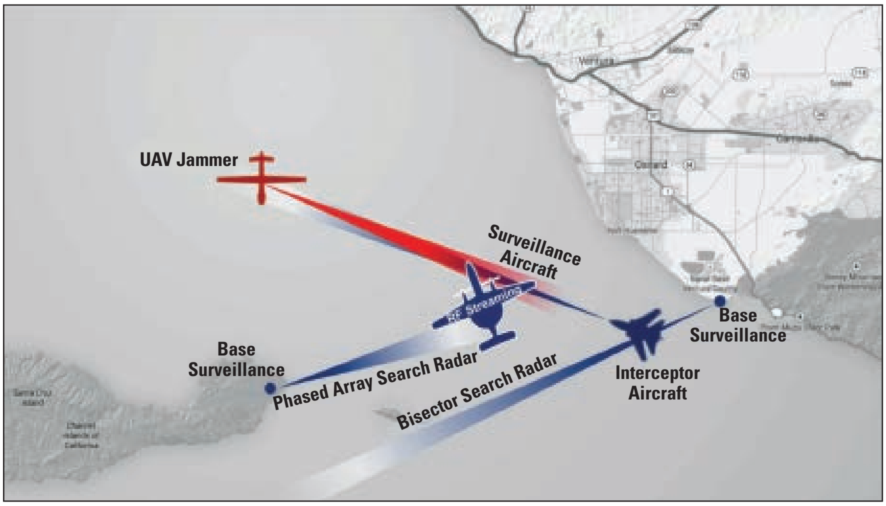


Fig. 2 RF streaming system captures gap free I/Q data from four emitters.

site operation or remote control, and manual or automated data collection.

Figure 2 provides an example. A streaming solution onboard a surveillance aircraft is tasked with recording the RF interaction between the interceptor aircraft and an unmanned aerial vehicle (UAV) jammer. The system also captures signatures from two surveillance radars, enabling analysis of their effects on interceptor/jammer interaction.

DEFINING STREAMING REQUIREMENTS

In any RF recording system, the main performance considerations are RF frequency range, real-time analysis bandwidth, spurious-free dynamic range (SFDR) of the receiver, IF amplitude flatness, IF phase linearity and maximum recording time. To fully capture signals, the solution must provide sufficient phase-continuous I/Q bandwidth; it is very difficult to extract pulse-descriptor words (PDW) if a wideband signal straddles one or more measurement channels.

Better SFDR represents improved receiver sensitivity and ensures the system's ability to record the actual RF environment, even with small signals hiding adjacent to larger ones. Flatness of the amplitude or phase response across the analysis bandwidth impacts modulation quality, with inaccuracies causing high error vector magnitude (EVM) in communication signals or significant phase errors in chirped radar signals.

In addition to RF performance, it is useful to consider the recording capabilities of the system. Attaching metadata to the recording enables association of precise time stamps and geo-data with specific RF events, simplifying post-processing by allowing analysts to fast-forward through the data set and quickly find points of interest. The configuration of the recording system can also be included to document items such as instrument settings and software or firmware version numbers. This helps users to compare data and understand discrepancies in data collected at different times.

GENERATING AND HANDLING MASSIVE DATA SETS

This is a "big data" process; streaming an I/Q signal with 100 MHz of bandwidth at 16-bit resolution for 10 minutes will produce 300 GB of data. At 255 MHz bandwidth, or 300 MSa/s, every second consumes 1.2 GB of storage space. To sustain the necessary gap-free recordings at these rates, every component in the data-processing chain must be able to keep up. ***Figure 3*** shows a high-level view of signal flows inside an RF streaming solution. Individual data streams are directed to separate drives in a redundant array of independent disks (RAID).

The key element is an FPGA that controls the system and configures it for recording or playback. It manages

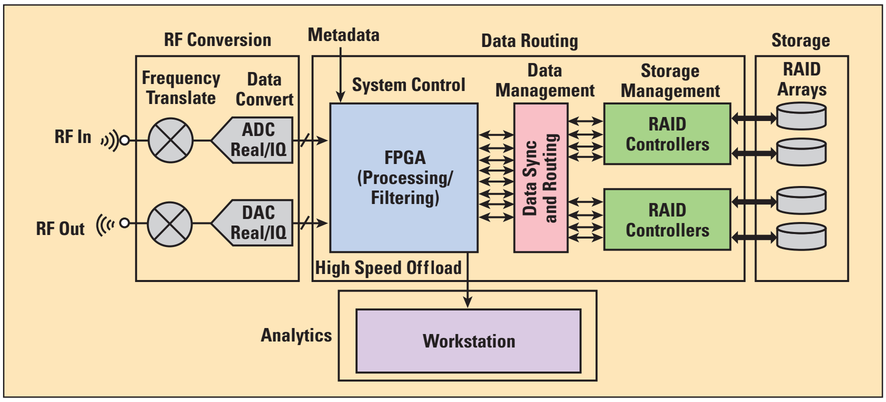


Fig. 3 Signal flows inside an RF streaming solution.

TABLE 1				
MAXIMUM RECORDING TIME				
		Approximate Recording Time		
Bandwidth	Memory	Seconds	Hours	Days
10 MHz	15 TB	300,000	83	3.5
100 MHz	15 TB	30,000	8.3	0.35
255 MHz	15 TB	12,500	3.5	0.14

the routing of I/Q samples and provides deterministic association of metadata with I/Q data.

Referring back to the system in Figure 1, the recorder can be configured with 2 or 4 TB of onboard memory or, optionally, 15 TB in the form of an external RAID array. At 15 TB, the recorder can capture more than three hours of data at a full bandwidth of 255 MHz. ***Table 1*** provides approximate recording times based on the bandwidth setting of the signal analyzer.

The relationship between bandwidth, memory and time can be expressed using the following equation:

$$\text{Maximum time (sec)} = \frac{\text{Memory capacity (bytes)}}{\text{Bandwidth (Hz)} * (\sim 1.25) * (4 \text{ bytes/sample for I/Q data})}$$

Where the value 1.25 is an approximate span-to-sample rate conversion factor.

CAPTURING REAL WORLD SCENARIOS

When the environment contains numerous emitters of varying amplitudes, it can be difficult to find low level signals in the presence of much larger ones. In the streaming solution described above, the signal analyzer provides 78 dBc of SFDR across the full 50 GHz frequency range, and this is recorded with the high-resolution 16-bit I and Q capture capability of the recorder to produce deeper views of signal behavior.

Seamless integration between the signal analyzer and recorder makes it possible to configure and initiate recording directly from the analyzer's front panel, streamlining recording control and eliminating the need for an external PC or laptop. An added benefit is the ability to simultaneously view the live spectrum measurements on the analyzer screen while a recording is in progress.

CONVERTING DATA INTO INFORMATION

After data collection is complete, users have many questions: What happened on mission day? Is the data good? Did the system under test perform as expected? Were there any RF anomalies or unexpected emitters?

Advanced signal processing tools turn raw data into useful information and actionable results. For example, the ability to search through large sets of data and isolate specific signal behavior is essential to helping a system engineer or signal analyst determine whether the system performed as expected or if there were any timing anomalies or unexpected RF emitters.

These capabilities can be implemented in signal analysis software that provides the ability to quickly zoom in on desired recording segments using automated signal- and pulse-search algorithms. Functions that range from basic frequency, time or amplitude filtering to highly advanced pulse pruning based on pulse width, pulse repetition interval (PRI) and more, make it easy to search through vast sets of data and uncover rare events or signals. For example, zooming in on interceptor/jammer interaction in the time domain makes it easy to see the relative timing of pulses as shown in ***Figure 4***. It may also reveal signal anomalies such as the one that appears after the fifth blue pulse in the trace on the right.

Once a time segment has been identified for study, the interaction can be replayed as both frequency and spectrogram displays for visual inspection. Displays such as the persistence density plot of emitter/jammer interaction (see ***Figure 5***) help reveal signal behavior in the frequency domain. A spectrogram (see ***Figure 6***) makes it easier to understand dynamic signal behavior in multiple dimensions by displaying time on the y-axis, frequency on the x-axis and amplitude via color scale. The anomaly is visible at multiple times in the spectrogram plot.

After the analyst has located a signal or event of interest, it can be quickly exported to the vector signal analysis software for deeper analysis. This is as simple as snipping out a section of the recording by drawing a rectangle around the emitters of interest. With optional pulse-analysis capabilities, the VSA software can be used to tabulate pulse parameters, measure modulation quality, compute PDWs and evaluate timing relationships (see ***Figure 7***).

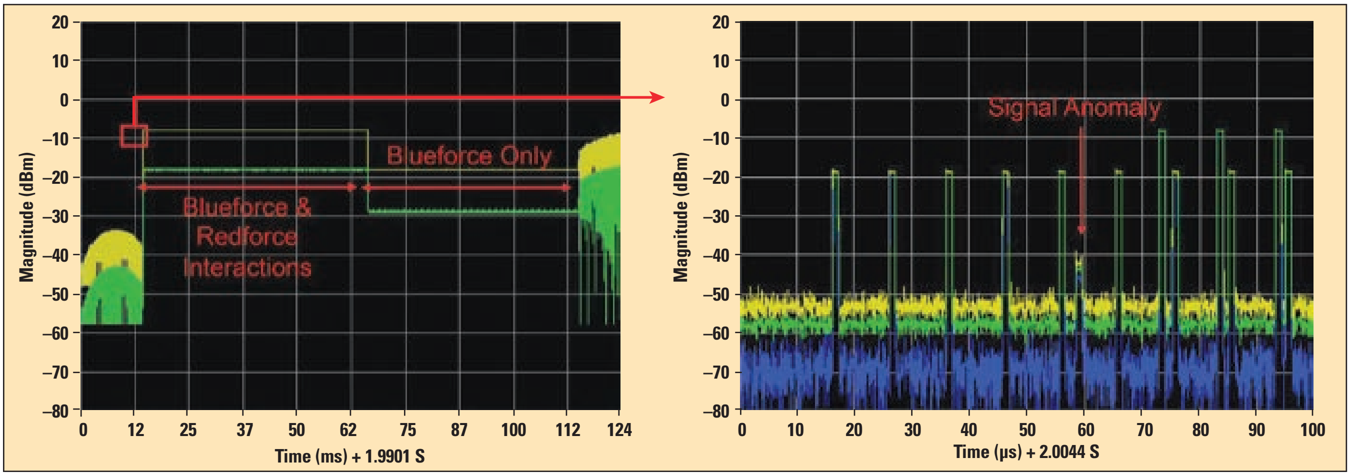
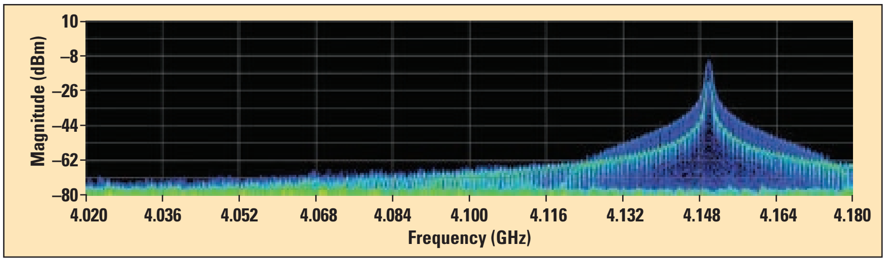


Fig. 4 Successive zooming in the time domain to reveal signal details down to the sample level.

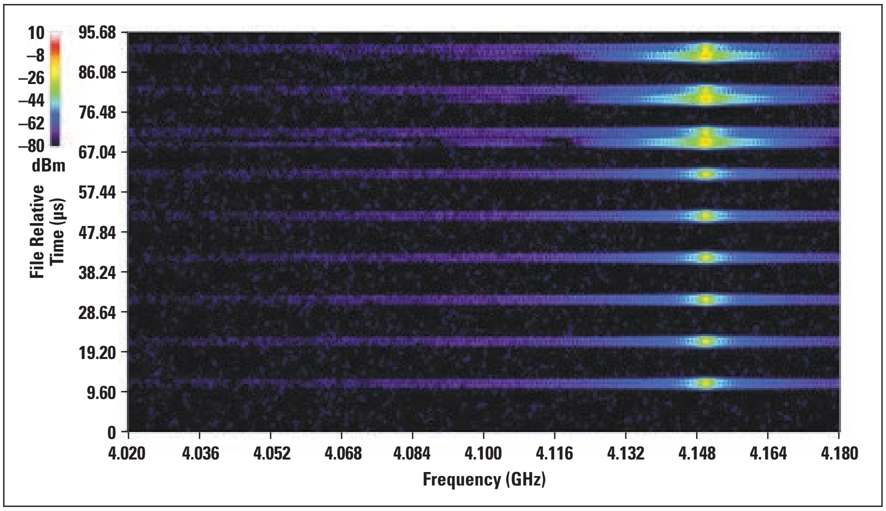
Features such as frequency-mask and time-qualified triggers can pinpoint issues down to a single pulse within thousands, and automatic detection of modulation per pulse enables faster, easier analysis of pulse characteristics. Extensive, flexible displays and markers enable viewing of virtually every facet of a signal, giving valuable insight into signal behavior.

CONCLUSION

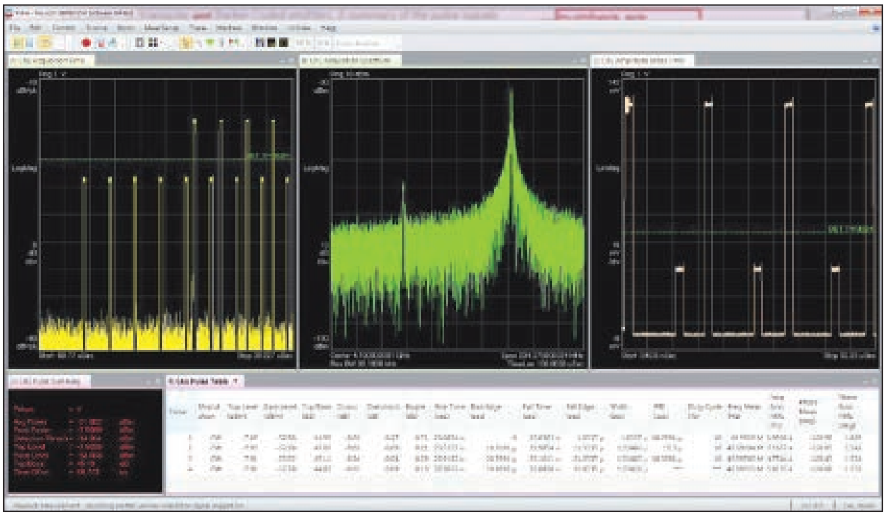
In a crowded, chaotic and complex signal environment, high-performance RF streaming provides a record of what happened over long periods of time. An integrated combination of measurement performance and analysis capabilities help users accelerate time-to-answers as they push the envelope in next-generation radar and EW systems.■



▲ *Fig. 5 Persistence density plot of emitter/jammer interaction.*



▲ *Fig. 6 Spectrogram displays time on the y-axis, frequency on the x-axis and amplitude via a color scale.*



▲ *Fig. 7 VSA software simplifies in-depth pulse analysis through automatic synchronization to pulsed signals and auto-detection of modulation on a pulse.*

INVITED PAPER

Mastering the Thermal Challenges of Advanced Defense Subsystems

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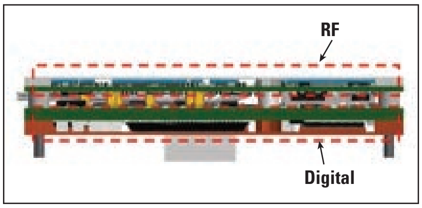
With the continued drive to smaller form factor, such as smaller munitions and unmanned systems, the defense world is pushing the boundaries of electronic system integration and processing densities. Although smaller and smaller footprints are now becoming a reality, the challenge of thermal dissipation is often not considered. Yet meeting the thermal challenges, to ensure long term reliability and repeatable system performance, is becoming a more significant part of the system design, particularly considering the extreme temperature ranges over which many aerospace and defense systems must operate. To meet system size, weight and power (SWaP) needs, an increasing proportion of system design time needs to be allocated to the thermal challenges.



▲ *Fig. 1 A receiver module with integrated RF and digital subsystems. The module is 3.25" × 0.5" × 1.4" and dissipates 27 W in the RF section and 22 W in the digital section.*

Consider a typical RF receiver and transmitter (see ***Figure 1***), which could be the basis for a military radio, element digitization for a radar system or a communications link for an UAV or advanced munition. Depending on the frequency of operation and specific application, the system requires the integration of a number of functions and technologies to achieve optimum performance. The RF front-end requires power and low noise amplifiers, most likely based on GaAs or GaN. The mixing stages, intermediate amplifiers and synthesizers will be developed using GaAs or SiGe, with the digitizers and FPGA nodes on CMOS. This may result in four or five different technologies across the signal chain, with many more variations of process geometries. Integrating these can result in the need to dissipate 50 W or more in a few square inches and limited thermal pathways. GaN-based power amplifiers (PA), widely used in radar and electronic warfare (EW) systems, present other challenges with their system requirements and power density. For example, the PA shown in ***Figure 2*** integrates two GaN MMICs, each dissipating 80 W. Multiple PAs are grouped close together to increase overall power.

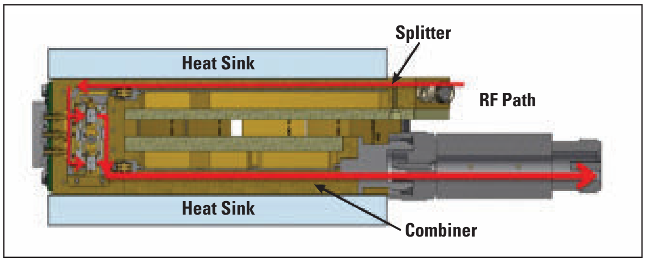
To optimize SWaP and cost, a thorough understanding of the thermal design is necessary to keep the temperatures of critical

components within their operating bounds. Each technology and application has its own challenges from a thermal perspective, and the drive to reduced SWaP concentrates heat densities. The dissipation needs to be reviewed from multiple perspectives, as heat generated in the channel of a MMIC flows in a continuous chain through numerous layers and interfaces until it ultimately reaches the ambient environment. The entire chain must be reviewed to optimize system thermal performance, SWaP and cost.

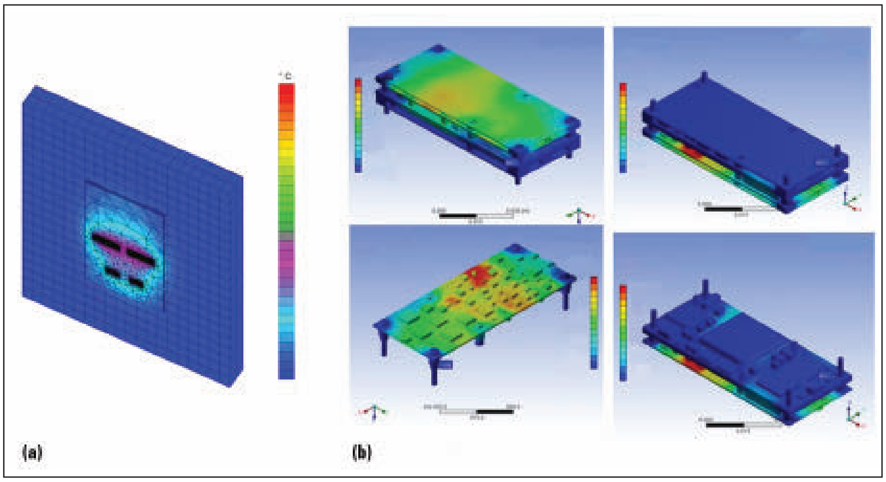
Although the focus on system size reduction is certainly making the thermal challenge more complex, some relief is available from advanced process nodes and increasing device integration. Advanced SiGe and CMOS nodes are enabling significant power reduction, and increasing integrated digital signal processing is increasing integration. This supports increased functionality, often at power parity with previous generation architectures. The higher operating junction temperature of GaN reduces the cooling requirements for these individual components. However, process node migration is not enough to meet the thermal challenges. System miniaturization is seemingly moving faster.

SIMULATION IS KEY

While building and testing prototypes continues to be critical in confirming design assumptions, the development times and high costs preclude efficient optimization based on hardware testing. Detailed simulation is essential and enables the rapid evaluation of multiple system variations. Trade-offs need to be evaluated from the entire system perspective. Multiple model levels and tools are required, as the geometry can scale six orders of magnitude, from sub-micron gates to meter-long housings. Heat generating and transfer mechanisms can include conduction, convection, radiation and EM energy. Simulation enables fast performance and cost trade-offs, optimizing from the device gate to system-level component placement, part design and material selection, as well as fan and heat sink specification (see ***Figure 3***).



▲ *Fig. 2 Cross-section of a power amplifier combining dual, 80 W GaN MMICs.*



▲ *Fig. 3 Die (a) and board (b) thermal simulations.*

The maximum freedom comes from system designers who have control over the entire system chain, from the MMIC gate to the ambient environment. This allows a comprehensive approach to the thermal challenges, enabling trade-offs that may change device location and require device modifications. Accomplishing this often requires multiple models and software packages. Specialized analysis techniques such as computational fluid dynamics (CFD) for convection to fluids/air and electromagnetic simulations for RF losses can be used, with a handoff between each. For example, a rack mounted, air cooled, high power, solid-state amplifier used in radar or EW systems may need the following:

- Finite element analysis (FEA) with micron-scale meshing, including die level and heat spreader analysis
- Electromagnetic loss analysis to determine the power generated in RF lines
- FEA at the chassis level
- CFD analysis for airflow and convection to the ambient environment.

The greatest temperature deltas will typically occur at the locations of greatest heat concentration, which are ultimately near the gates. Typically, 70 percent of the temperature rise from ambient to junction is within the MMIC. With GaN power densities in radar systems now above 6 W/mm in some cases, simulating the trade-offs is critical.

SELECTING THE RIGHT MATERIALS

The choice and use of very high thermal conductivity materials to spread the heat are obviously critical. For example, with high power GaN die that are used in the latest PAs for radar, the substrate is typically SiC, and the first attach layer is AuSn solder. Over just 5 mils of material, the heat flux density may reduce from 13,000 W/mm^2 to 24 W/mm^2. As the heat continues to flow through the system, spreading will continue to reduce the flux density. The choice of materials is limited by matching the coefficient of thermal expansion (CTE), electrical conductivity to ground and the cost and ability to manipulate the material.

CTE mismatches can result in cracking of substrates or delamination of bonding layers, such as solder and epoxy. Cold storage and operating temperatures, critical aspects of aerospace and defense performance criteria, tend to cause the greatest CTE stresses, as the solders and epoxy are designed for processing at elevated temperature. Even mild delamination can have catastrophic effects on the thermal

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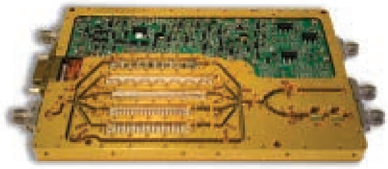

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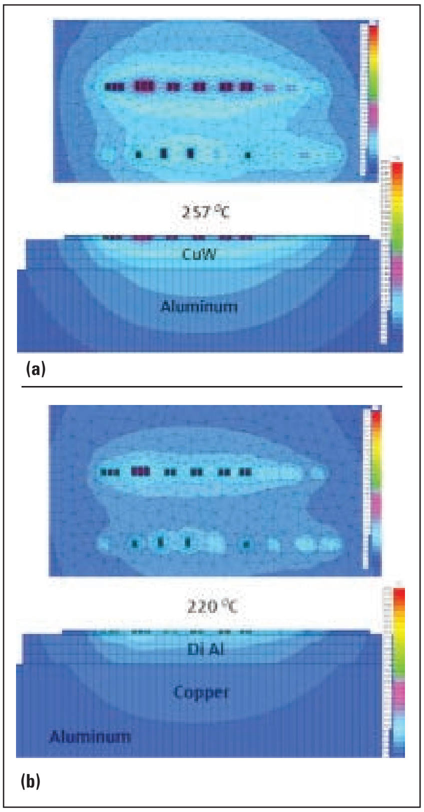
performance of a die, if the separation is in an area of high heat concentration — directly under a high power FET, for example. Comparing the hot spot temperatures on IR images of a design to known good images of the same design is a useful method for identifying early delamination when evaluating new materials.

Epoxy and sintered silver manufacturers are developing products with lower modulus of elasticity to absorb the CTE stresses while still retaining relatively good thermal performance. Heat conductivity close to the die is a key material research area, with extremely high thermal conductivity materials such as diamond being reviewed. As defense systems continue to look for reduced SWaP and cost, performance trade-off decisions for cost, weight and size are always intertwined in system architecture and thermal trade-offs. The use of materials such as diamond composites may seem hard to justify; however, using even small pieces of these materials as die heat spreaders in areas of high heat concentration can substantially reduce device temperatures and enable cost and weight savings in other parts of the system. ***Figure 4*** compares two thermal simulations: a 60 W GaN die attached to a CuW carrier on an aluminum base vs. a diamond-aluminum matrix material carrier on a copper insert in an aluminum base. The latter reduced the junction temperature by some 37°C, providing improved system performance and life, while enabling other SWaP and cost tradeoffs elsewhere in the system.

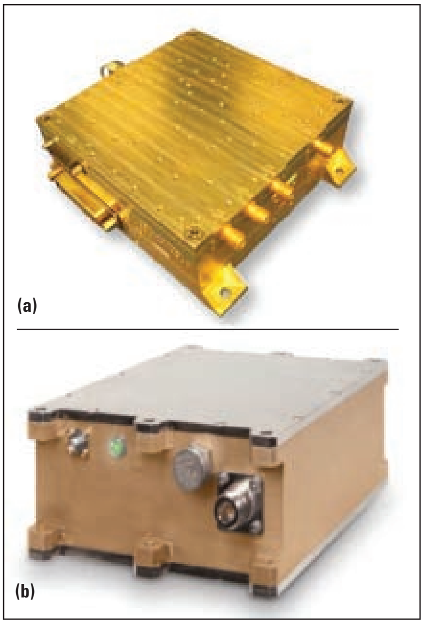
In other examples, convection cooled systems, such as rack mounted, can be challenged with large temperature differences across the heat sink base and from the heat sink fins to the ambient air. Heat sink and fan choices have significant cost and performance impact and must be specified from a system perspective. For a



▲ *Fig. 4 Thermal performance of 60 W GaN die attached to CuW and Al (a) vs. diamond-aluminum matrix on Cu and Al (b).*

given heat sink volume, better performance is driven by a higher convective heat transfer rate that requires greater back pressure, such as from tighter channels or staggered/slotted fins that break up boundary layers. This, in turn, requires larger and more power-hungry fans. The fan choice also impacts performance. Axial fans are typically the easiest to design with, providing high volume for low pressure systems, while centrifugal fans or blowers are able to push against higher pressure but with lower volume.

Lastly, the choice of heat sink material can significantly impact cost. In many cases, skived copper heat sinks seem to provide a good balance between performance and cost. Embedded heat pipes are also excellent low weight devices for enhancing the effective thermal conductivity of heat sink baseplates, although they do not work in all environments. High g-force environments pose a particular issue.



▲ *Fig. 5 Examples of products using the integrated thermal design methodology: "man portable," 5 W linear PA and up-converter (a) and 2 kW HPA (b).*

PUTTING IT ALL TOGETHER

Although it may seem that the thermal challenges are ominous, with many trade-offs, using a systematic approach can achieve solutions that balance cost, size and performance. Advanced simulations provide the backbone for quick decisions, enabling detailed analysis from the gate in the die to the system, as well as the impact of the heat sinks and heat spreaders. These advanced simulations help with trade-offs, from materials choices to cooling techniques and optimal layout. Applying these techniques with appropriate design decisions can yield systems with high heat concentration. ***Figure 5*** shows two examples: a 37 W linear PA with integrated up-converter and a 2 kW solid-state high power amplifier (HPA). Both product designs utilized detailed simulation, which led to careful component integration, layout and material selection to balance performance and cost. The up-converter was designed to be "man portable," so minimizing size and weight was an important requirement. Having the system and MMIC designed by the same team helped in balancing reliability, cost and performance. ■

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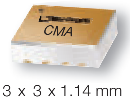

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INVITED PAPER

In-Situ Antenna Measurements: Coupling the Antenna to the Circuit

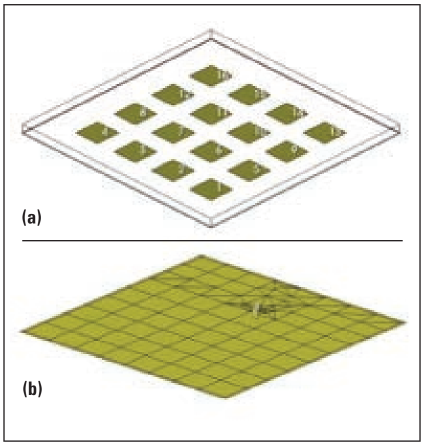
John Dunn
National Instruments, Austin, Texas

Electromagnetic (EM) simulation software is commonly used to simulate antennas with multiple feeds, including phased arrays, stacked radiators with different polarizations and single apertures with multiple feed points. These types of antennas are popular for communication systems where multiple-input-multiple-output (MIMO) and polarization diversity antenna configurations are being used. It is expected that their use will explode with the rollout of 5G wireless systems.

The antenna's beam is controlled by changing the phase and amplitude of the signals going into the various feeds. The problem for simulation software is that the antenna and the driving feed network influence each other. The antenna's pattern is changed by setting the input power and relative phasing of the signals at its various ports. At the same time, the input impedances at these ports change with the antenna pattern. Since input impedance affects the performance of the nonlinear driving circuit, the changing antenna pattern affects overall system performance.

Until now, engineers have had to simulate the coupled antenna/circuit effects manually using some sort of iterative process. For example, the antenna is first driven with idealized sources having known phasing at the input ports. The impedance of the ports is then used as the load impedance for the driving circuit. The process is iterated over and over until convergence is reached. This procedure is awkward at best. Fortunately, new in-situ technologies within RF/microwave design software now provide a more efficient and accurate way to reach the final result.

These new in-situ measurement features enable the circuit and antenna to talk to each other, thus automatically accounting for the coupling between the antenna and the circuit in an easy-to-use framework. The designer identifies the antenna data source, the circuit schematic driving the antenna and the measurement under consideration; for example, power radiated over scan angle. This concept is illustrated in the following phased-array example, where the antennas are simulated in a NI AWR Design Environment™ (inclusive of Microwave Office circuit design software, AXIEM 3D planar EM and Analyst™ 3D finite-element method (FEM) EM simulators).

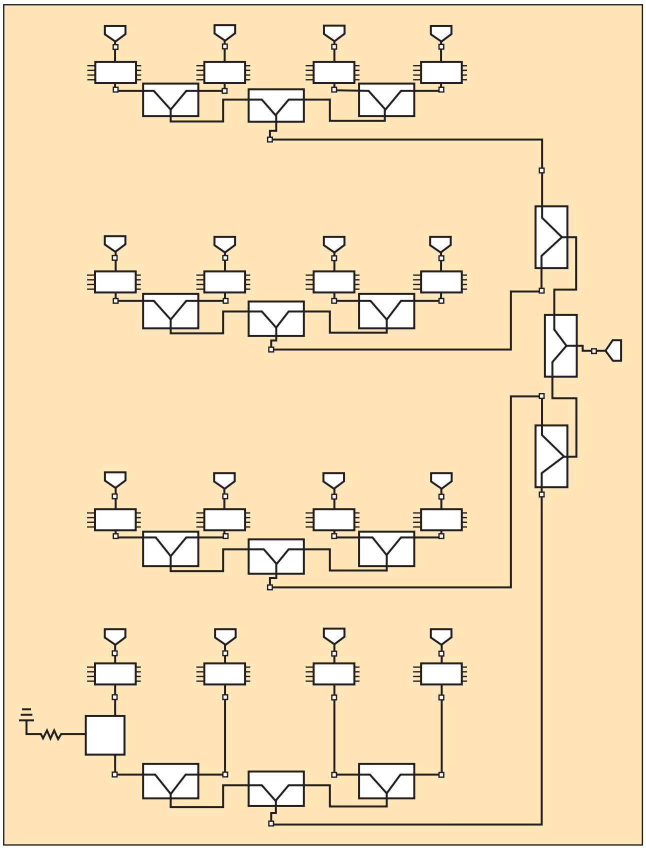


▲ *Fig. 1 4 × 4 patch array (a). Single element mesh, with its driving pin to the ground plane (b).*

PATCH MICROSTRIP ARRAY SIMULATION EXAMPLE

In this example a 4 × 4 patch array is simulated. It is driven by a corporate feed network with a phase shifter and attenuator at each element. A monolithic microwave integrated circuit (MMIC) power amplifier is placed at each element before its corresponding phase shifter. The array is simulated just once in the EM simulator. The resulting S-parameter file is then used by the circuit simulator, which includes the feed network and amplifiers. As the phase shifters are tuned over their values, the antenna's beam is steered. At the same time, each amplifier sees the changing input impedance at the antenna input it is attached to; and this, in turn, affects the amplifier's performance. The power amplifiers are nonlinear, designed to operate at their P1dB compression points for maximum efficiency. They are, therefore, sensitive to the changing load impedances presented by the array.

Combined circuit and EM simulations are necessary for a number of other reasons. First, antenna element interaction can degrade antenna performance. An extreme example is scan blindness, where element interaction causes no radiation to occur at certain scan angles. Coupling between elements can also lead to feed network resonances. In order to optimize the feed network to account for deficiencies in the antenna, the entire array and circuit, combined, must be optimized. It is also necessary to simulate the feed network, itself, as resonances can build up within it by the loading of the ports.



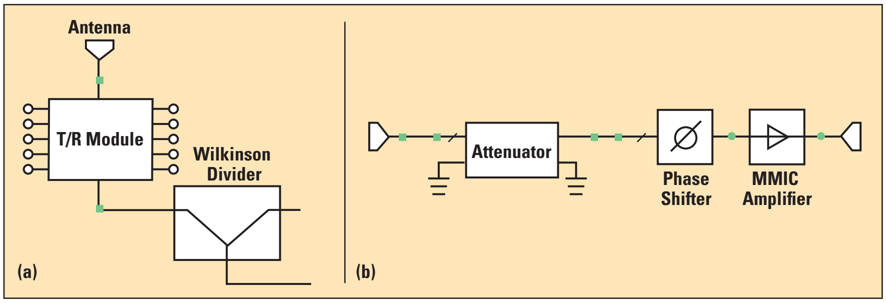
▲ *Fig. 2 Patch array corporate feed network.*

Important, though often not performed, is nonlinear circuit simulation of the power amplifier that drives the antenna. For this, the antenna's S-parameters must include a DC simulation point, and values at the various harmonics used in the harmonic balance simulation. Otherwise, system performance degradation is possible due to poor matching at harmonic frequencies.

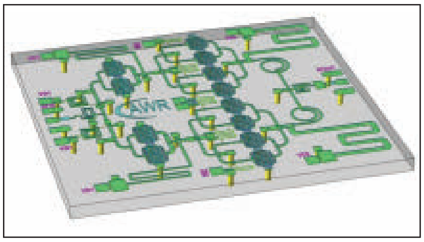
Figure 1 shows the 4 × 4 patch antenna array. Each patch is fed individually by a pin to the ground below. The port is placed at the bottom of the pin. A 3D planar EM simulator is ideal for planar patch arrays since the patch is not in a package, and radiation effects are therefore included automatically. It should be noted that the simulation techniques described in this article do not depend on a specific EM simulator. For this example, antennas are simulated using Analyst, which is a 3D finite element (FEM) EM software application.

The corporate feed network is shown in ***Figure 2***. Each element is driven by a MMIC amplifier, and controlled by a phase shifter and attenuator. RF power is input from the right side. Wilkinson dividers are used to split the signal and feed the sixteen patches. ***Figure 3*** shows the feed for a typical patch. The transmit module is shown in detail in ***Figure 3b***. Each transmit module has a phase shifter, attenuator and MMIC amplifier. The beam is steered by setting the phase and attenuation at the input to the MMIC amplifier and then routing the resulting signal to the patch. Phase and attenuation are controlled by variables in the software, which can be tuned and optimized as desired. In this manner, the beam is scanned.

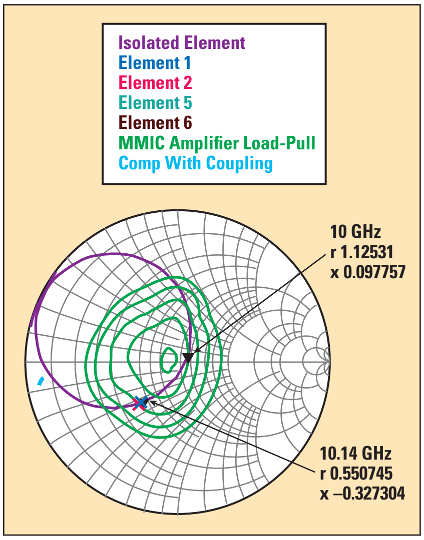
Figure 4 shows a 3D view of the MMIC amplifier. It is a two-stage, eight-FET amplifier, designed to work in X-Band. In this example, the



▲ *Fig. 3 Wilkinson divider and transmit module (a), block diagram of the transmit module (b).*



▲ *Fig. 4 MMIC amplifier.*

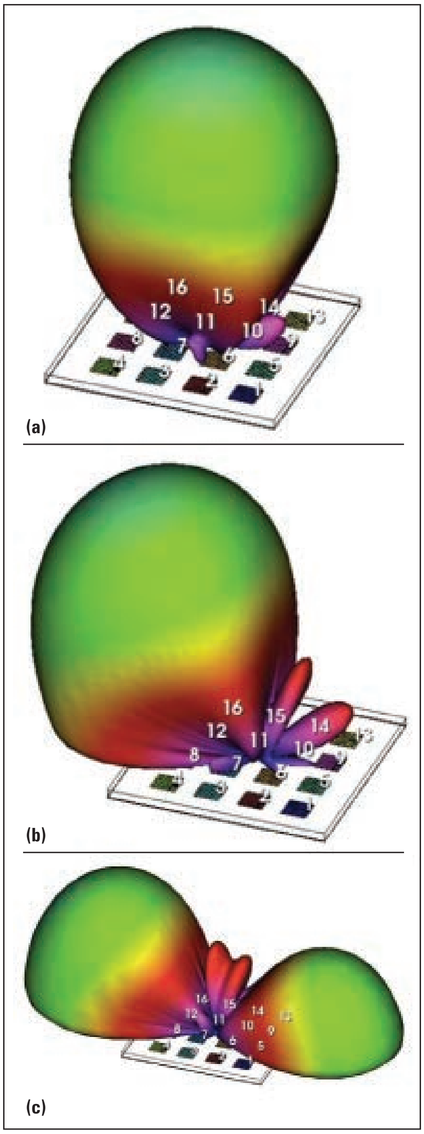


▲ *Fig. 5 Circuit simulation results.*

entire feed network is simulated by the circuit simulator. A more realistic example would simulate the layout of the feed network in an EM simulator to make sure the models are accurate and there is no unintended coupling between sections of the network.

SIMULATION RESULTS

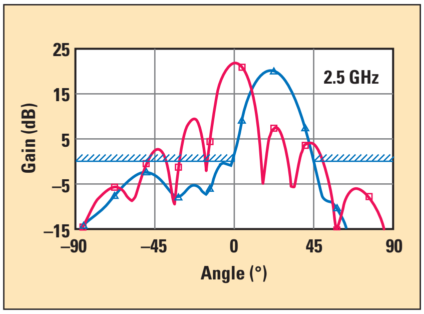
Typical circuit simulation results are shown in ***Figure 5***. The Smith chart shows the input impedance to an isolated element and to elements when the entire array is simulated. Load-pull contours for power delivered to the load are also shown. The system is designed to work at 10 GHz. The purple curve shows the input impedance for an isolated patch from 6 to 14 GHz on a 50 ohm normalized Smith chart. The marker shows the normalized impedance at 10 GHz. The four crosses show the input impedances of four typical elements at 10 GHz. Note that the interaction between the elements in the array shifts the input impedance of each element relative to that of an isolated patch. The green contours are load-pull simulations for the MMIC amplifier, showing the power delivered



▲ *Fig. 6 Beam of the array as it is scanned through typical values of theta and phi. Broadside excitation (a), beam at $\theta = 30°$ and $\phi = 0°$ (b), beam at $\theta = 75°$ and $\phi = 0°$ (c).*

to a load. The shifting of the impedances of the antenna feed results in a 0.5 dB degradation of power to the elements. (The power contours are in 0.5 dB increments.)

Examples of the antenna pattern are shown in ***Figure 6***. The beam is steered by controlling the relative phase and attenuation to the transmit modules. In practice, the harmonic balance takes substantial time to run with 16 power amplifiers; therefore, the beam is steered with the amplifiers turned off. The designer then turns on the power amplifiers for specific points of interest. Note ***Figure 6c*** shows a second lobe created



▲ *Fig. 7 Antenna pattern optimized for gain above 20 dB at a 20° scan angle and with sidelobes below 0 dB at angles below 0° and above 45°.*

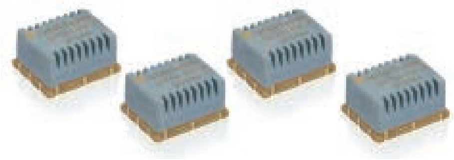
when the main lobe is at a near grazing angle.

In ***Figure 7***, the antenna pattern is optimized for a specific scan angle. This example is for an 8 × 8 patch array. For simplicity, the amplifiers are not included in the optimization. Before completing the design, the amplifiers are turned on to determine their effect on performance. The plot is of total power in the beam, scanning in the theta direction with phi at zero degrees. The blue bars show the optimizer goals. The purple pattern is the original broadside pattern. The optimizer changes the phase and attenuation at the feeds to the patches. The resulting blue curve meets the goals for the main beam with acceptable sidelobe levels.

CONCLUSION

In today's complex communication systems utilizing antennas with multiple feed points, the interaction between the circuit (typically including a highly nonlinear power amplifier), the feed network and the antenna must be accounted for. The beam is steered by the circuitry, and as the beam changes the input impedance of the antenna changes, which affects the circuit. The antenna and the circuit are connected, so both must be included in the simulation.

The traditional method of simulating antennas with multiple feeds is to simulate coupled antenna/circuit effects manually, using an iterative process that is time consuming and frustrating. Modern RF/microwave design software couples the circuit and antenna simulation together. The load impedances of the array are incorporated into the circuit simulation. This automates the process, saving design time and delivering products to market faster. ■



High Reliability RF Switches Provide High Power in a Small Package

Fairview Microwave
Allen, Texas

In the evolution of front-end mobile applications, the number of antennas is growing to reflect the demand for more frequency bands and better signal quality. RF switches play a vital role in the circuitry in these smart mobile devices, as they route signals through an array of antennas. With the use of GaN in communications systems, RF components are offering higher power density in smaller packages, increasing system range and sensitivity. The switches in these systems need to keep up with these capabilities, particularly power handling. RF switches are integral to Wi-Fi access points and base stations, switching between transmit and receive signals. In test and measurement, switches automate routing among test instruments and the device under test, simplifying setups that conventionally require manually connecting and disconnecting various ports to gather the needed data. Military systems and satellite communication also require robust, high performance and high power RF switches.

To meet these wide market needs, Fairview Microwave offers a family of four high reliability, high power, surface-mount (SMT), single pole double throw (SPDT) electromechanical switches (see ***Table 1***). Two models cover DC to 3 GHz and two extend the upper end to 8 GHz. All are 50 Ω. Failsafe and latching actuators are available for each frequency range. A latching actuator will maintain the chosen RF path with or without the operating voltage, while a failsafe actuator will switch back to the de-energized state when no voltage is applied. All the switches operate with a control voltage of 24 V; the failsafe models require an actuating current of 25 mA and the latching models require 32 mA.

TABLE 1

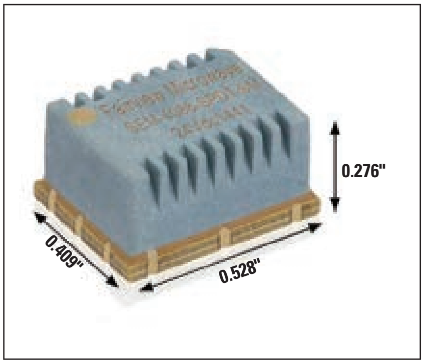
SPDT ELECTROMECHANICAL SWITCH FAMILY

SEMS-xxxx-SPDT-SM	Frequency Range (GHz)	Actuator	Maximum Insertion Loss (dB)	Minimum Isolation (dB)	Maximum VSWR
4088	DC to 3	Failsafe	0.3	40	1.35:1
4089	DC to 3	Latching	0.3	40	1.35:1
4090	DC to 8	Failsafe	0.8	30	1.4:1
4091	DC to 8	Latching	0.8	30	1.4:1

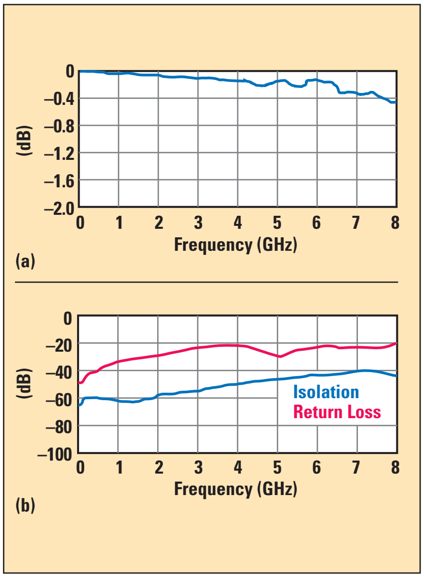
TABLE 2

SWITCH PERFORMANCE VS. FREQUENCY

		SEMS-4090 & 4091				
		SEMS-4088 & 4089				
Frequency Range	GHz	DC to 1	1 to 2	2 to 3	3 to 6	6 to 8
VSWR (max)		1.1:1	1.2:1	1.35:1	1.35:1	1.4:1
Insertion Loss (max)	dB	0.1	0.2	0.3	0.4	0.8
Isolation (min)	dB	50	45	40	35	30
Average Power Handling at 25°C	W	400	280	175	50	35



▲ *Fig. 1 All the switches in the SPDT family are in small footprint, rugged SMT packages.*



▲ *Fig. 2 Typical insertion loss (a) isolation and return loss (b) of the SEMS-4090-SPDT-SM switch.*

Fairview Microwave's electromechanical switches are compact (see ***Figure 1***), requiring minimum real estate on a printed circuit board (PCB), and lightweight, weighing only 1.81 g. Despite the small size, these switches have rugged housings to prevent damage or degraded performance during vibration and mechanical shock. Designed for high reliability, the switches operate from -40° to +85°C, deliver lifetimes of over 2 million switching cycles, are RoHS compliant and have a gold-plated mounting surface to enhance the contacts and resist oxidation.

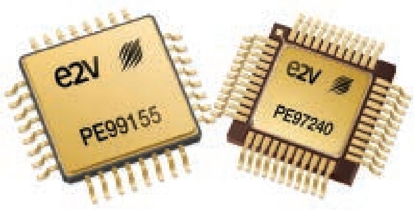
Table 2 summarizes the performance of the switch family over frequency. The maximum input power handling is 400 W CW at +25°C up to 1 GHz. Above 1 GHz, power handling declines to 175 W at 3 GHz and for higher frequency switches, 35 W at 8 GHz. Maximum insertion loss is 0.1 dB at 1 GHz and rises to 0.3 dB at 3 GHz and 0.8 dB at 8 GHz. Isolation is 50 dB minimum at 1 GHz, dropping to 40 dB at 3 GHz and 30 dB at 8 GHz. Maximum VSWR ranges from 1.1:1 at 1 GHz to 1.35:1 at 3 GHz and 1.4:1 at 8 GHz. ***Figure 2*** shows the performance vs. frequency of the SEMS-4090 model.

To ease designing the switches into a system, Fairview Microwave offers PCB layout software that can be downloaded from the product pages on Fairview's website.

Pricing begins at $239 for the 3 GHz switches and $263 for the 8 GHz models. All products in the family are available for same day shipping, and all are classified EAR99 for export.

This family of SPDT electromechanical switches serves a wide variety of markets and applications that demand high reliability, low loss and high power handling performance. The small size and rugged package enable use in systems with limited PCB footprint.

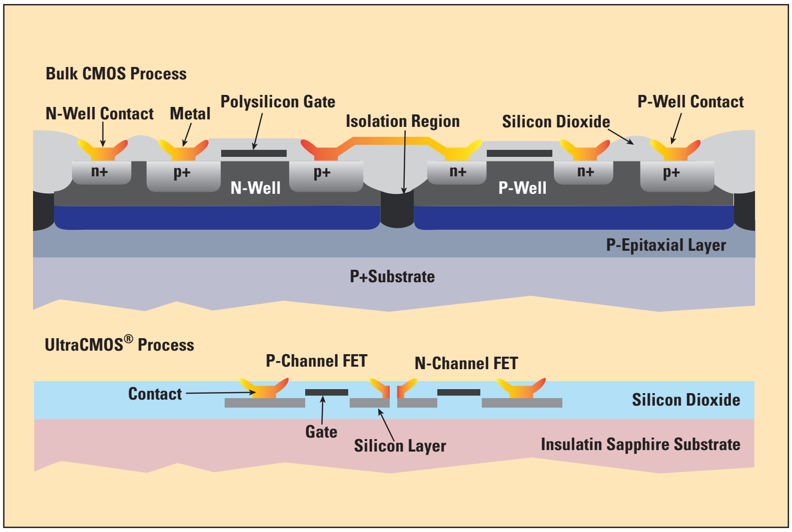
Fairview Microwave
Allen, Texas
www.fairviewmicrowave.com



High-Reliability, Radiation-Tolerant Space Products

Peregrine Semiconductor
San Diego, Calif.
e2v inc
Milpitas, Calif.

Three…two…one…blast off! As a rocket or satellite launches into space, it exits the protection of the Earth's atmosphere and enters an environment that poses design challenges. From extreme temperatures and radiation to power consumption, there are simply more factors in play when designing electronic systems for space. Space applications require higher levels of performance and reliability from semiconductors.



▲ *Fig. 1 Peregrine's high-reliability products do not contain the bulk parasitics found in standard CMOS devices, making latch-up impossible.*

RADIATION 101

To meet the tough demands of the space environment, semiconductor products must be radiation-tolerant. The effects of radiation can be devastating if the ICs are not properly designed and tested to survive in this harsh environment. The primary radiation concerns in space are total ionizing dose (TID), enhanced low dose rate sensitivity (ELDRS) and single event effects (SEE).

TID degradation or gain drift of component parameters change circuit supply and leakage currents, threshold voltages and propagation times. Program missions will determine the level of TID tolerance required. For example, low-Earth orbit (LEO) missions have lower lifetimes and may require 30 to 50 kRad(Si), while deep space, longer lifetime

missions may require 100 kRad(Si) or more.

ELDRS can degrade certain types of bipolar devices more severely at very low dose rates than at higher dose rates. Semiconductors based on bipolar technology are subject to "enhanced" total ionizing dose degradation at very low dose rates.

SEEs occur when a high energy particle passes through the active region of a semiconductor, triggering nondestructive effects such as upset, multiple bit upset or analog transients or destructive effects such as latch-up, gate rupture and burnout. As a high energy charged particle enters the silicon at a high velocity, it exerts a force on the bound electrons and separates them from the lattice, freeing substantial local charge to be collected across any junction within a diffusion length. The collection produces current spikes that have various effects on the circuit. Non-destructive or "soft error effects" momentarily or permanently change the state of a device or cell/node, affecting its functionality. These types of errors are defined as single event upset (SEU), single event transient (SET) and single event functional interrupt (SEFI) errors. Destructive or "hard-error effects" interrupt device function and can permanently damage the device without prompt external mitigation. These types of errors are defined as single event latch-up (SEL), single event gate rupture (SEGR) and single event burnout (SEB).

RADIATION-TOLERANT SEMICONDUCTORS

Peregrine Semiconductor addresses the demands of the space market with its UltraCMOS® technology, an inherently radiation-tolerant platform. For high-reliability products, UltraCMOS circuitry is processed on an ultra-thin silicon layer atop a dielectric sapphire wafer. Variable capacitances in the junction region are virtually eliminated, reducing the overall current drain and improving the transistor's voltage handling and linearity. Peregrine's high-reliability products do not contain the bulk parasitics found in standard CMOS devices, making latch-up impossible (see ***Figure 1***).

Products based on UltraCMOS technology are SEE tolerant, SEL immune and can deliver 100 kRad(Si) TID. The ultra-thin epitaxial layer in UltraCMOS technology produces the lowest possible SEU charge collection of any production silicon technology and simplifies the circuit design to achieve SEU, SET and SEFI immunity. UltraCMOS device construction eliminates four-layer devices and all forms of latch-up, including SEL. The device design rules constrain operating voltages to less than one-third BVox, which prevents any SEGR. SEB is not observed in this technology, where high current bipolar junction transistor (BJT) gain is absent by construction. CMOS technology does not use bipolar (minority carrier) elements and does not exhibit ELDRS. UltraCMOS technology is an ELDRS-free process.

Peregrine manufactures a broad portfolio of high-reliability products for space applications, including phase-locked loops (PLL), prescalers, mixers, digital step attenuators (DSA), switches and point-of-load (POL) DC-DC converters. Two new Peregrine products showcase the capabilities of UltraCMOS technology in space: the PE97240 PLL and the PE99155 POL DC-DC buck regulator.

The PE97240 is an integer-N PLL that provides superior phase noise performance for signal precision and frequency stability. It is radiation tolerant to 100 kRad(Si) TID and immune to SEL. Power consumption is a low 75 µA at 2.7 V, enabling engineers to reduce power demand. Offered in an RoHS compliant, 44-lead, hermetically sealed CQFP package, the PE97240 consists of a dual modulus prescaler, counters, a phase detector and control logic. The PE97240 has an integer-N frequency synthesizer that generates multiple output frequencies from a single reference input frequency. This divided down output enables reference and phase detection at lower frequency, and it handles both frequency and phase lock. With PLLs, phase noise is an important measure of the signal's spectral purity. Lowering phase noise reduces phase jitter and noise, which offers RF engineers high signal precision and solid frequency stability. Phase noise is a product of thermal noise, which is expressed by the floor figure of merit (FOMfloor) and low frequency flicker noise, which is expressed by the flicker figure of merit (FOMflicker) within the system. The PE97240 achieves an industry-leading maximum FOMfloor of 227 dBc/Hz with the 5/6 prescaler and -225 dBc/Hz with the 10/11 prescaler; the PLL also sets the bar with a FOMflicker of -265 dBc/Hz with the 5/6 prescaler and -259 dBc/Hz with the 10/11 prescaler.

Peregrine's UltraCMOS technology also addresses the demands of power management. The PE99155, a POL buck regulator, regulates the power for NASA's SpaceCube 2.0 Hybrid Science Data Processor. Peregrine's PE99155 helped the NASA design team meet its goal of delivering "order-of-magnitude im-

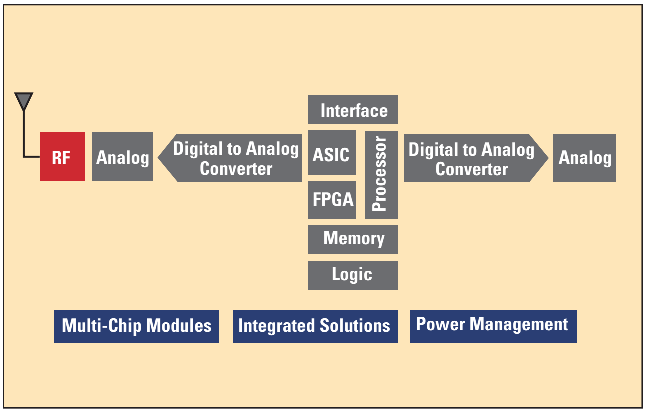


Fig. 2 e2v's product offering spans the entire signal chain from RF to the back end, including data converters, memory and high performance data processing.

provements" in on-orbit computing performance over traditional flight computing systems. The SpaceCube 2.0 design uses four of Peregrine's PE99155 power management chips to provide regulated power at multiple supply voltages for the processing elements, memory and associated circuitry, like oscillators and gigabit transceivers. Peregrine's flexible and small form factor design allowed all of the regulation functions to be placed on a single printed circuit board (PCB), realizing area and overall power consumption savings over the SpaceCube 1.0 power design, which required multiple PCBs using conventional linear regulator bricks.

AVAILABLE THROUGH e2v

Peregrine's entire portfolio of RFICs and DC-DC power management space products is now available through e2v. Announced in February 2016, this strategic relationship combines Peregrine's expertise and track record in high reliability RF and power management products with e2v's leadership position in aerospace and defense semiconductor products. The agreement broadens e2v's product offering to include RF. The e2v portfolio now spans the signal chain from RF to back-end, including data converters, memory and high performance data processing (see ***Figure 2***). e2v has a portfolio of over 3,600 QML-approved products — one of the largest high reliability portfolios in the market. Through relationships with semiconductor manufacturers like Peregrine, e2v supports complete QML solutions to help aerospace customers solve their design challenges.

Peregrine Semiconductor
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www.psemi.com

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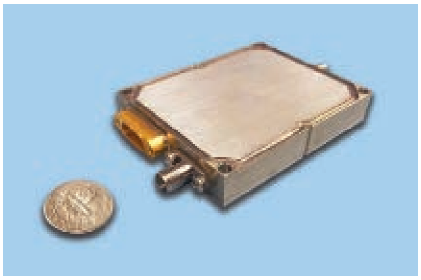

0.1 to 6 GHz GaN Amplifiers Redefine SWaP

Teledyne Microwave Solutions' new wideband, modular GaN amplifiers lower the form factor threshold for 0.1 to 6 GHz. At only 2.1 cu in (2.5" long × 2" wide × 0.42" high), this non-ITAR amplifier line maximizes power density and efficiency, while maintaining the rugged characteristics necessary for harsh airborne requirements.

Teledyne Microwave Solutions (TMS) leveraged its 50 year amplifier engineering heritage to create a line of GaN amplifiers that can quickly be tailored to the specific needs of customers, utilizing one of the industry's most comprehensive repositories of parts. With wider bandwidths that enable more design flexibility, the amplifiers were designed and are manufactured with great attention to the thermal requirements needed for high reliability. The calculated MTBF is greater than 40,000 hours at +85°C, making the amplifiers suitable for airborne applications and challenging land environments.

Depending on the frequency band, the output power ranges from 15 and 40 W. Each amplifier includes preamp and driver stages to produce a minimum gain of 50 dB. Internal control circuitry ensures safe startup, so supply voltages can be applied in any order. In addition to normal DC bias, the 15 pin Micro-D connector provides other convenient control and interface features, including a TTL Tx enable/disable command (100 ns typical and 200 ns maximum switching time), an automatic over temperature shutdown and alarm (also TTL) and the ability to monitor unit temperature via an analog voltage proportional to case temperature.

The new line consists of five base model wideband, GaN amplifiers: TSA-213241, TSA-213242, TSA-213243, TSA-213244 and TSA-213245. Contact TMS to discuss modifications to meet your exact requirements.

VENDORVIEW

Teledyne Microwave Solutions
Mountain View, Calif.
www.teledynemicrowave.com

Ultra-Broadband Solid-State HPAs

Exodus Advanced Communications has released the latest in a family of ultra-broadband, high power, solid-state amplifiers. With a linear GaAs FET hybrid, class AB design to achieve maximum output, the AMP3033 amplifier module delivers 7 W CW typical output power from 24 to 31 GHz. Minimum power is 4 W from 24 to 25 GHz and 6 to 7 W across the rest of the band. The amplifier has a minimum power gain of 38 dB and 4 dB peak-to-peak maximum flatness with constant input power (+3 dBm maximum).

The AMP3033 operates from a nominal +20 VDC bias and draws 4 A typical, 6 A maximum, and is protected for load VSWRs up to 5:1. This module features a small form factor (4.33" × 4.33" × 1.06"), making it suitable for a number of applications, including EMI/EMC susceptibility testing, millimeter wave component testing and electronic warfare. The AMP3033 is also available as a rack mounted chassis. The power amplifier (PA) is assembled in a 19" rack mountable cabinet and features self-contained air cooling and AC operation. An optional state-of-the-art controller that supports Ethernet TCP/IP, RS422/485 and remote Bluetooth connectivity is available. A front panel touch screen is also available as an option.

Exodus Advanced Communications designs and manufactures solid-state RF PAs covering frequency bands from 100 kHz to 47 GHz, achieving module output power greater than 1 kW and complete systems exceed 10 kW. Other standard ultra-broadband products include a family of 10, 20 and 40 W PAs covering 6 to 18 GHz and up to 250 W over 2 to 6 GHz. Exodus PAs integrate discrete LDMOS, GaAs and GaN devices with ceramic substrates using hybrid chip and wire assembly processes. In-house capabilities include RF circuit, system mechanical and electrical and digital circuit design, control software development and prototype verification.

VENDORVIEW

Exodus Advanced Communications
Las Vegas, Nev.
www.exoduscomm.com

Metal Clad Fibers for Weight-Sensitive Applications

ARACON® metal clad yarns and EMI shielding braids have been supporting weight reduction in high-reliability applications for more than two decades. Micro-Coax manufactures ARACON using aramid fibers and a special sequence of chemical processes to deposit a metalized coating around every individual microfilament. The result is a strong, highly flexible, heat resistant alternative to conventional metal wires. Recent improvements in the manufacturing process allow a cost to implement of under $300 per lb, breaking an economic threshold that will enable use in a much wider range of applications, including commercial aircraft, drones and smart fabrics.

Switching conventional wire over to ARACON fibers offers dramatic weight savings — as much as 80 percent less than nickel-plated copper shields. Three different yarn sizes allow for a wide variety of multi-strand, braided and woven form factors. In its braided form, the transfer impedance approaches 120 mΩ/m at 1 GHz. This, combined with smaller braid apertures of the microfilaments, allows for shielding effectiveness of more than 40 dB, verified up to 18 GHz.

Connection or termination of the fibers can be addressed mechanically (i.e., clamping) or by soldering. The silver-plated version of the product can easily be soldered by conventional techniques, without the use of active flux. The material is also resistant to uncontrolled soldering-wicking, which further improves the reliability of the connections. These conventional termination methods allow the product to be incorporated in host wire and cabling applications, such as quad-ax, coaxial or other shielded constructions.

Micro-Coax Inc.
Pottstown, Pa.
www.araconfibers.com
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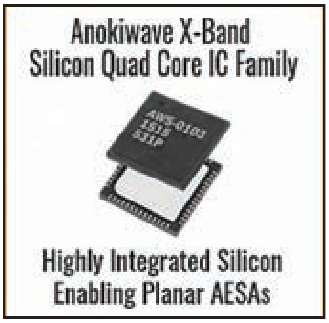
Company Showcase



X-Band Quad Core ICs

VENDORVIEW

Anokiwave's X-Band Quad Core ICs are for commercial RADAR and 5G markets. Each IC includes an integrated 4-channel beam former, LNA and PA supporting four radiating elements with 6-bit phase/gain control. The ICs feature either a low NF or a high IIP3. Additional features include gain compensation over temperature, temperature reporting, forward power telemetry and fast beam switching. Silicon technology enables very high integration of functionality thus enabling planar antenna design with reduced system size, weight and cost.

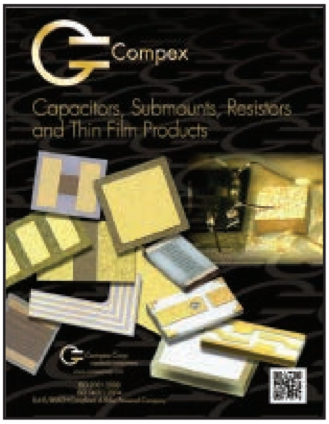
Anokiwave
www.anokiwave.com

Electronic Warfare Solutions

VENDORVIEW

Berkeley Nucleonics announces a new eight-page Electronic Warfare Solutions Short Form catalog. The catalog features BNC's full lines of RF/microwave signal generators (up to 26 GHz), real-time spectrum analyzers (up to 27 GHz with 100 MHz real-time bandwidth), phase noise test systems (5 MHz to 26 GHz+) and wide band RF receivers (up to 27 GHz). New OEM integration provides the highest output power, lowest harmonic levels and broadest frequency range among contemporary signal generators of its size and cost.

Berkeley Nucleonics Corp.
www.berkeleynucleonics.com



Single Layer Electronic Components

The single layer specialists, Compex Corp. manufactures the highest quality and broadest variety of capacitors, resistors, submounts, mounting shorts and custom thin film structures. All parts are built directly to the customer's specifications, can be sampled at no charge and delivered in just a few days. Compex has a global network of representatives that work closely with customers to provide a high level of expertise and convenience. Allow the Compex staff to recommend the perfect part for your application.

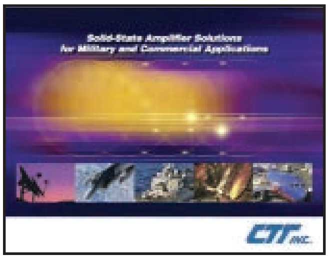
Compex Corp.
www.compexcorp.com

Solid-State Power Amplifier

VENDORVIEW

CPI Beverly Microwave Division's VSC3644 is a C-Band 4 kW modular GaN, high power, solid-state power amplifier, operating from 5.2 to 5.9 GHz at 10 percent duty. Designed to be modular, this amplifier consists of four blind mated, ruggedized, SSPAs and is designed around GaN semiconductors from Wolfspeed. Benefits include: BIT and controls via EIA-422 remote connection, blind mate DC and control connectors, high gain, excellent pulse fidelity and outstanding spectral performance. For use in maritime, defense radar and weather radar applications.

CPI Beverly Microwave Division
www.cpii.com/bmd



Solid-State Amplifier Solutions

CTT announces a new 48-page product catalog: Solid-State Amplifier Solutions for Military and Commercial Applications. The new catalog features over 830 amplifier products, of which over 365 are all new. Product offerings include new GaN power amplifier technology for narrowband, wideband and ultra-wideband applications. Many new GaAs-based power and low-noise amplifier designs are also listed, including new Ka-Band, low-noise amplifiers. The catalog also includes application information and case outline drawings. Visit CTT's website for a free download.

CTT Inc.
www.cttinc.com

Programmable Attenuators

Fairview Microwave Inc. released a new family of digitally controlled programmable attenuators with performance up to 40 GHz and up to 60 dB attenuation range with 0.03 dB minimum step size. In-stock and available to ship today, these programmable attenuators are commonly used in electronic warfare, military and space communication systems, radar, and test and measurement applications. Fairview's digitally controlled attenuators perform the important function of adjusting the amplitude of signal levels in RF, microwave, and millimeter wave systems.

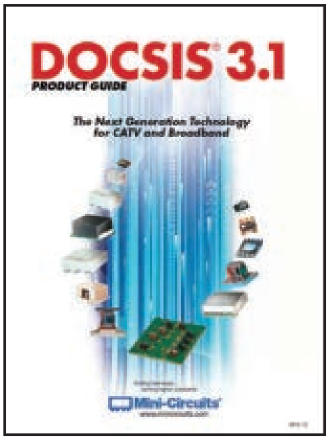
Fairview Microwave Inc.
www.fairviewmicrowave.com

Field Terminated Assemblies

VENDORVIEW

To suit to the needs of their customers, HUBER+SUHNER has developed this innovative solution – the Eacon – a field terminated microwave assembly. Eacon 2C/4C/6C stands for a simple, flexible and fast way to assemble microwave cable and connectors in the field without compromising performance. The new field terminated microwave cable and connectors are lightweight, waterproof and built for frequencies up to 18 GHz – ready for use in the defense market. Visit aerospacedefense.hubersuhner.com for more information.

HUBER+SUHNER
Aerospacedefense.hubersuhner.com



DOCSIS 3.1 Product Guide

VENDORVIEW

Mini-Circuits presents its product offering for the next generation of CATV and broadband applications in their DOCSIS® 3.1 Product Guide. Inside you'll find detailed information on a wide range of RF components from passive devices including transformers, couplers and splitter/combiners, to active elements including amplifiers, equalizers and more—all designed and carefully specified to meet DOCSIS 3.1 standards. The DOCSIS 3.1 product guide is a convenient reference to make an informed decision as you evaluate parts for your design.

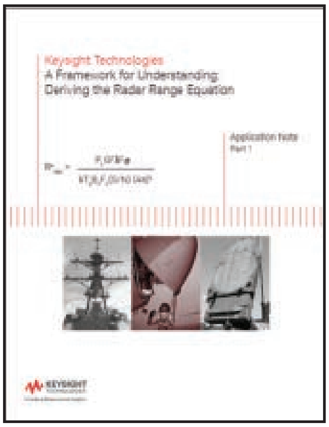
Mini-Circuits
www.minicircuits.com

Up/Down-Converting Transceiver

VENDORVIEW

Planar Monolithics Industries Inc. has developed a transceiver that fits into a 3U OpenVPX form factor utilizing the high speed VITA 67 RF connector and up-converts a 100 MHz to 4 GHz transmit signal to the 2 to 18 GHz range and down-converts a 100 MHz to 18 GHz received signal to the 100 MHz to 4 GHz range for analog to digital conversion. PMI is a manufacturer of electronic components for defense applications and a leading supplier of high reliable, low cost systems offering unique innovations in RF and microwave components and integrated assemblies from DC to 50 GHz.

Planar Monolithics Industries Inc.
www.pmi-rf.com

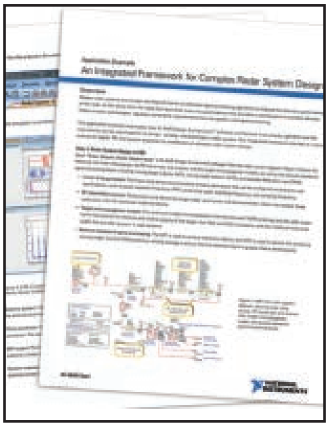


Radar System Fundamentals

VENDORVIEW

Keysight Technologies' new application note, "A Framework for Understanding: Deriving the Radar Range Equation," covers the fundamentals of the radar range equation, which captures essential variables that define maximum distance at which a given radar system can detect objects of interest. This mathematical foundation provides a powerful framework for understanding, characterizing and verifying the actual performance of any radar system. Subsequent application notes in this series will focus on four sections of the block diagram: transmitter, receiver, duplexer and antenna.

Keysight Technologies Inc.
www.keysight.com/find/radar



Complex Radar System Design

VENDORVIEW

Modern radar systems are complex and rely heavily on advanced signal processing algorithms. The radio front-end must meet specifications, often a combination of available devices, implementation technologies and regulatory constraints. This new application note showcases how NI AWR Design Environment, LabVIEW and PXI instruments work together to design, validate and prototype a radar system, providing a unique avenue for digital, RF and system engineers to collaborate on complex radar system design. Visit www.awrcorp.com/sites/default/files/AN-RDR-EMP-2015.6.23.pdf.

National Instruments
www.awrcorp.com

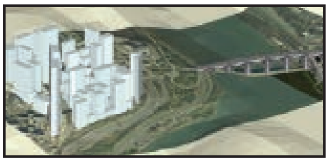
Filters, Multiplexers and Multi-function Assemblies

VENDORVIEW

When being first to react makes all the difference in the world, choose Reactel for your mission-critical filter requirements. You can count on Reactel to satisfy the most demanding requirements for units used in extremely harsh environments. The full-line catalog features RF and microwave filters, multiplexers and multi-function assemblies for the military, industrial and commercial industries. To request a copy visit the company's website or e-mail reactel@reactel.com.

Reactel Inc.
www.reactel.com

Company Showcase



Wireless InSite

To keep up with rising demand and new technologies, the wireless industry is researching a wide array of solutions for 5G, including massive MIMO. As a leading provider of wireless simulation tools, Remcom is developing an innovative MIMO simulation capability. Remcom's Wireless InSite provides an efficient method to predict channel characteristics for large-array MIMO antennas in complex multipath environments. Learn more at www.remcom.com/5g-mimo.

Remcom
www.remcom.com/5g-mimo

Aerospace & Defense Selector Guide

VENDORVIEW

Richardson RFPD is an AS9120-certified, global component distributor specializing in advanced connectivity solutions, and A&D is their largest market. The company's GaN technology portfolio and wide range of MMICs, RF transistors, PAs and diodes from leading brands like ADI, MACOM, Microsemi, NXP and Qorvo serve a range of A&D applications, including radar, avionics, EW and communications. Among the latest additions to Richardson RFPD's A&D line are New Edge products and the Metelics diodes now offered by MACOM.

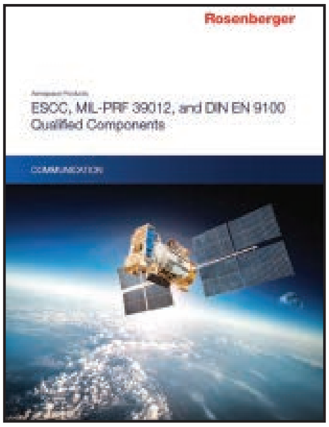
Richardson RFPD
www.richardsonrfpd.com

Test & Measurement Catalog 2016

VENDORVIEW

The Rohde & Schwarz Test & Measurement Catalog 2016 contains more than 200 pages of information about the company's test and measurement instruments, systems and software. It includes a short description and photos of each product, the most important specifications and the ordering information. You can download this catalog as a PDF from the Rohde & Schwarz website or order a copy from customer support (Order number: PD 5213.7590.42, version 06.00).

Rohde & Schwarz GmbH & Co. KG
www.rohde-schwarz.com



Aerospace Product Brochure

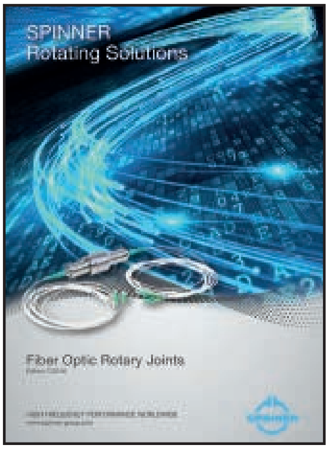
Rosenberger is a qualified manufacturer of connectors and cable assemblies for the aerospace industry. The new brochure gives an overview of the company's aerospace products in accordance with ESCC, MIL-PRF 39012, or DIN EN 9100 – cable assemblies, board-to-board connections, board-to-cable connections, SMD types and PCB connectors. Rosenberger's globally implemented common corporate philosophy is focused on meeting future business challenges and satisfying customers' most exacting and ever more demanding requirements. For more information visit www.rosenberger.com.

Rosenberger
www.rosenberger.com

Precision Connectors

SGMC Microwave offers an extensive line of 2.4 mm, 2.92 mm, 3.5 mm and SMA precision right angle in-series and between-series adapters suited for customers' application needs. Visit the company's website or call (321) 409-0509 to find out more about their precision right angle coaxial connectors. SGMC is a registered ISO 9001:2008 manufacturer of precision coaxial connectors including cable connectors, adapters and receptacles. Located in Melbourne, Fla., SGMC provides the microwave and mmWave industry with high quality products that are precision grade and readily available.

SGMC Microwave
www.sgmcmicrowave.com



Rotating Solutions

VENDORVIEW

The new SPINNER Rotating Solutions Fiber Optic Rotary Joints Brochure showcases major design advancements in the SPINNER single and multichannel portfolio. The new single-channel SPINNER FORJ 1.14 comes with an outer diameter of just 14 mm, specifying a < 1 dB insertion loss. The brochure also presents the pressure compensated single-channel SPINNER FORJ 1.17 pc for deep sea applications. Where the roughest of environments are a reality, the multichannel SPINNER FORJ x.65 accommodates up to 20 channels — and now comes in a sea water resistant IP65 design.

SPINNER GmbH
www.spinner-group.com

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