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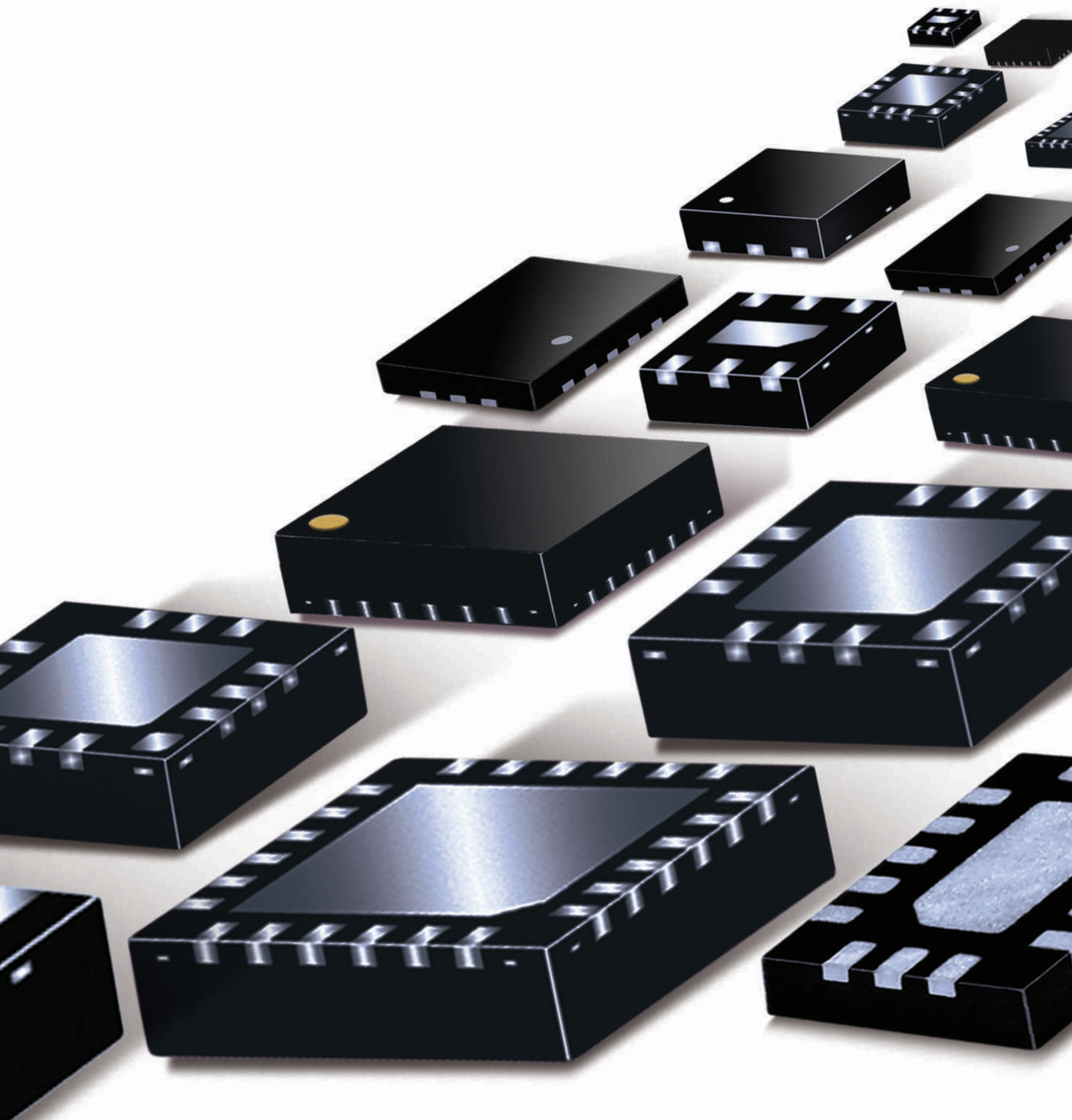

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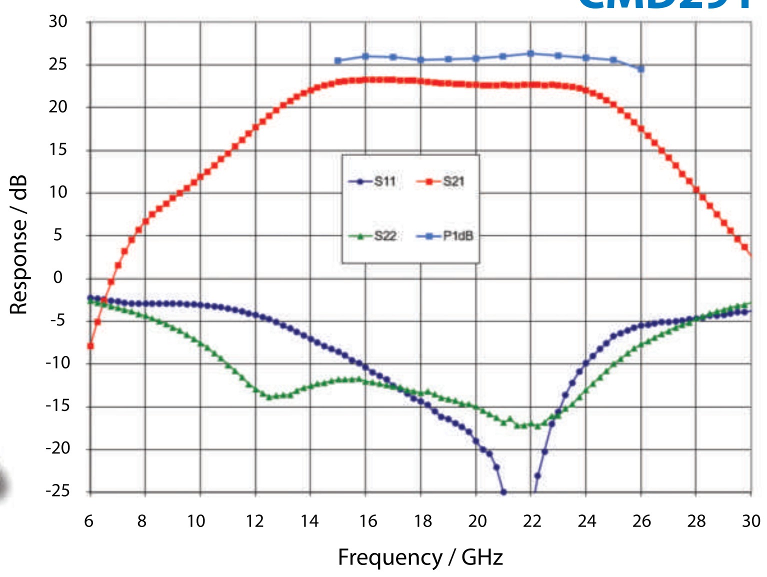

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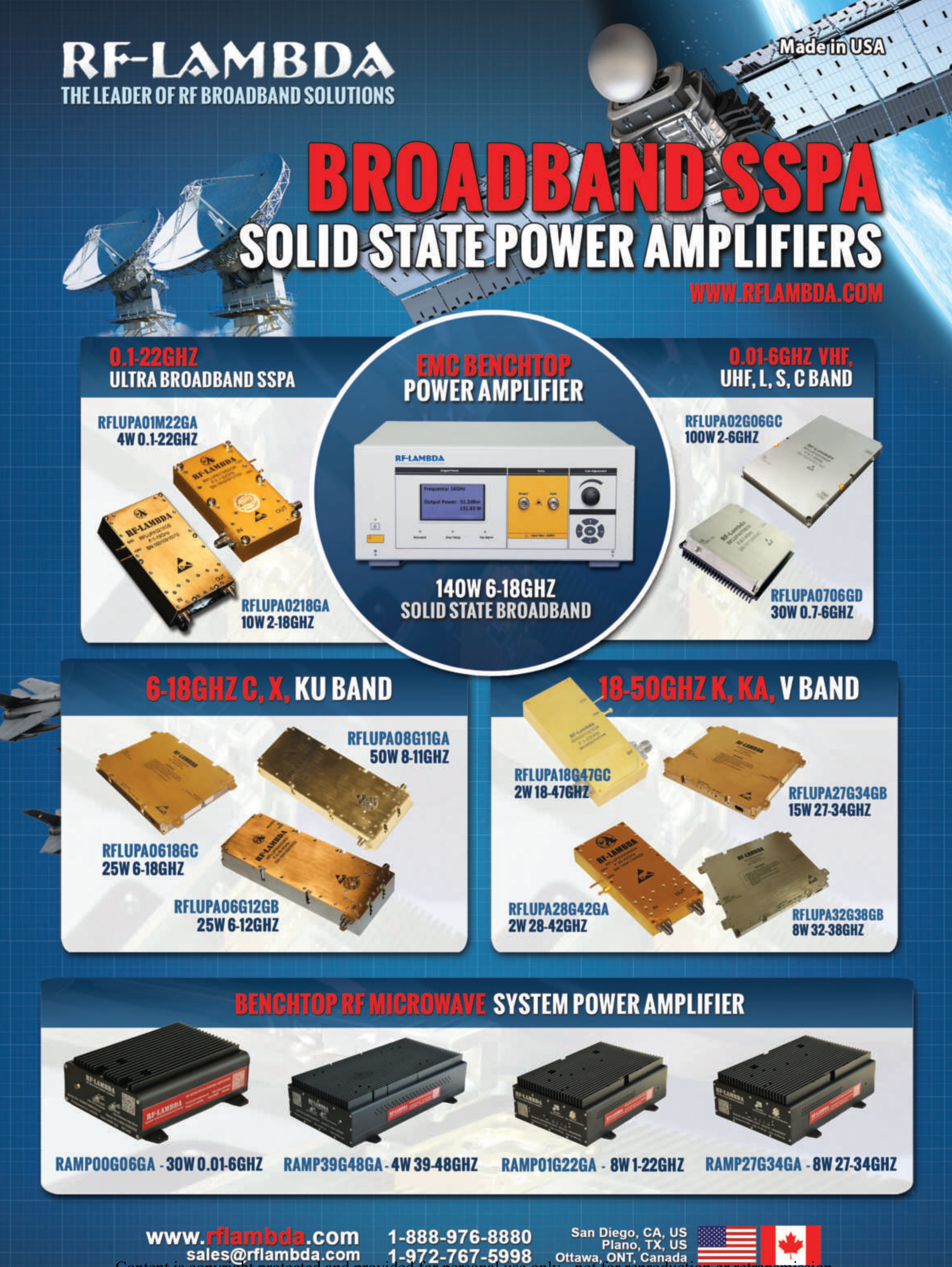
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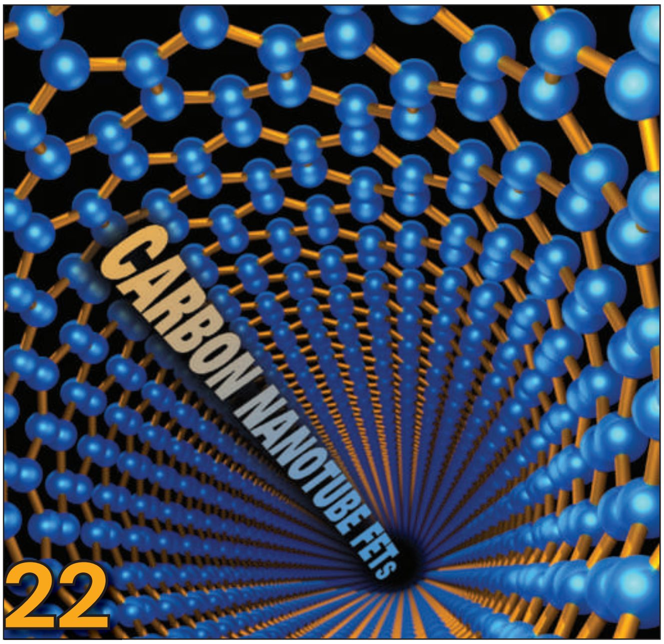

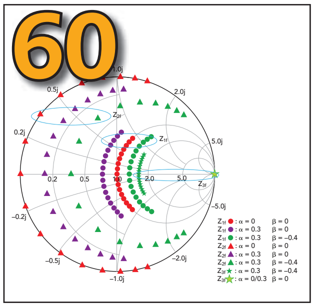

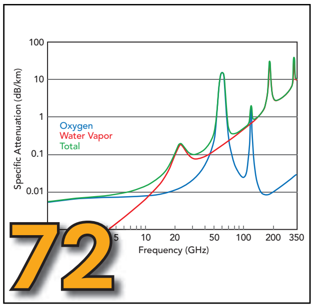

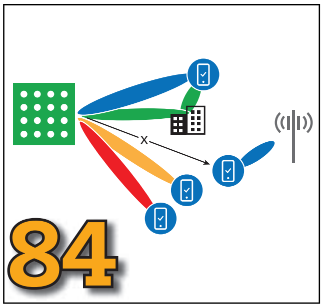

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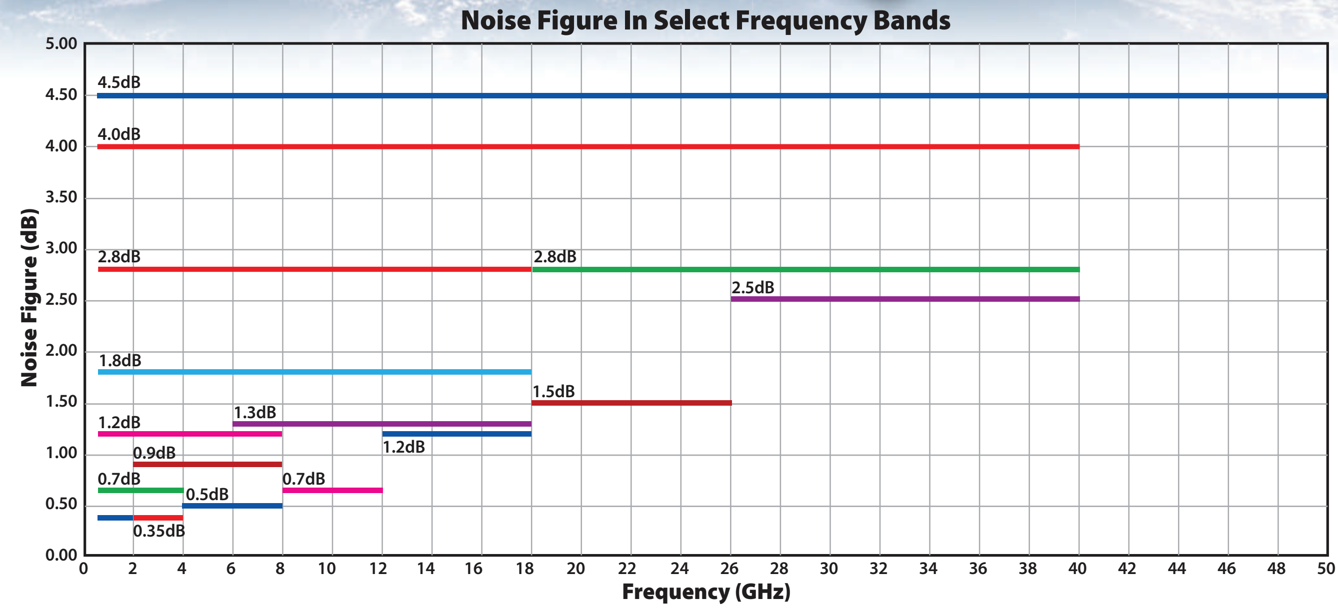
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Noise Figure (dB)
Frequency (GHz)
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4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
4.5dB
4.0dB
2.8dB
2.8dB
2.5dB
1.8dB
1.5dB
1.3dB
1.2dB
1.2dB
0.9dB
0.7dB
0.7dB
0.5dB
0.35dB

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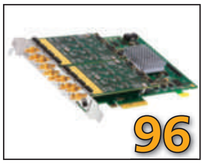

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Tech Brief

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Greg Baker, cofounder and CEO of fabless RFIC start-up **Altum RF**, discusses the rationale for launching a new RFIC venture, the underserved market opportunities and how the company aims to address them.

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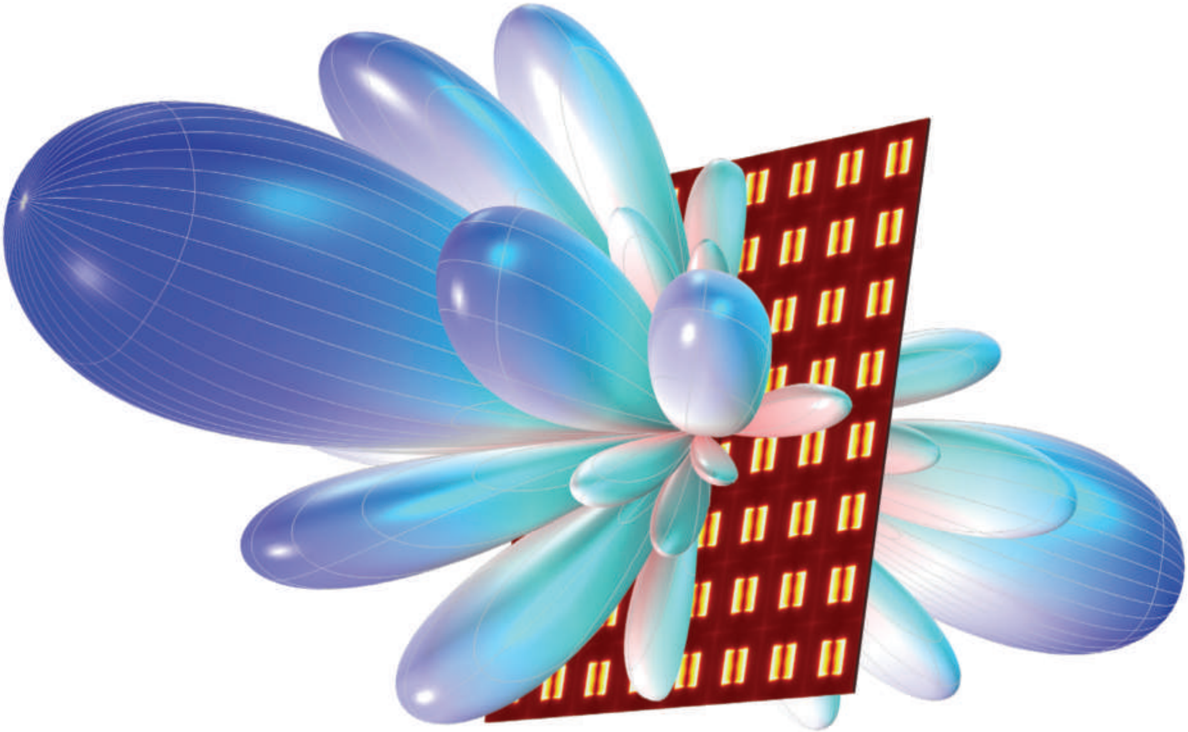

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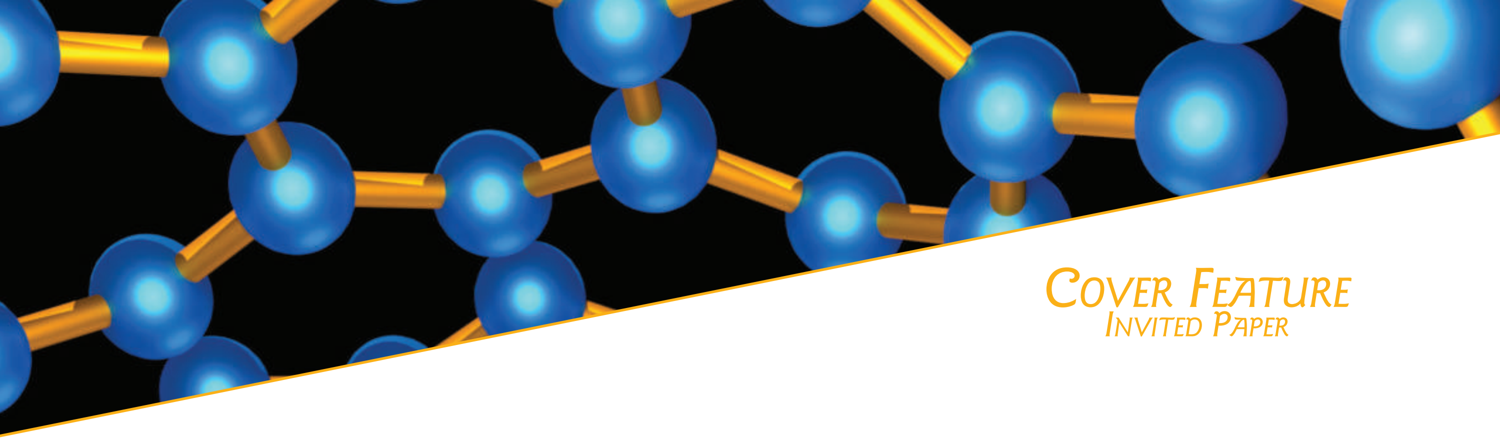

Cover Feature
Invited Paper

Solving the Linearity and Power Conundrum: Carbon Nanotube RF Amplifiers

Philbert F. Marsh, Christopher Rutherglen, Alexander A. Kane, Tyler A. Cain and Kosmas Galatsis
Carbonics Inc., Culver City, Calif.

Stephen A. Maas
Nonlinear Technologies Inc., Long Beach, Calif.

Mohammed R. AlShareef
National Center for MEMS Technology, Riyadh, Saudi Arabia

Carbon nanotube (CNT) transistor technology has intrinsic linearity due to its ballistic transport properties and is CMOS compatible for monolithic integration.

RF environments are becoming ever more crowded with unwanted RF signals entering the broadband RF front-end amplifier, resulting in receiver-generated third-order intermodulation distortion (IMD3) products. By their nature, IMD3 products often fall near the frequencies that the receiver is tuned to and are generally difficult to filter. Consequently, receiver-generated IMD3 products can swamp weak desired signals and, when present in large numbers, form an effective noise floor that exceeds the noise floor from the receiver noise figure, reducing dynamic range. In digital communications, the resulting reduced sensitivity shows up as an increased bit error rate (BER) that limits range and data transfer speed. As such, a higher amplifier output third-order intercept point (OIP3) is desirable, because for each dB increase in OIP3, IMD3 levels fall 2 dB for a given fundamental signal power. While increasing transistor size and DC bias power can increase OIP3, many systems—satellites and mobile/portable devices—face restrictive power budgets. OIP3 can also be increased with circuit-based linearization; however, these perform worse as frequency increases. For a given circuit approach, the OIP3 improvement can still benefit from improvements in the underlying transistor technology. It is more desirable to fundamentally improve the transistor intrinsic linearity than to rely exclusively on the above approaches.[1]

A transistor's intrinsic linearity transfer curve, i.e. drain current (I_d) versus gate voltage (V_{gs}), can be represented by its linearity figure of merit: OIP3/P_{dc} in dB, where P_{dc} is the DC bias power consumption. Newer and denser modulation schemes, such as 256-QAM for 5G, demand RF front-ends with high OIP3/P_{dc} ratios for high sensitivity and band use efficiency, combined with low power use. Military battlefields are signal-rich and require high OIP3/P_{dc} ratios[1] for high dynamic range and sensitivity, combined with long battery life.

Owing to the maturity of present semiconductors, it is likely that new, truly disruptive improvements in OIP3/P_{dc} or frequency performance will require a rethinking of potential RF semiconductor device materials and structures beyond incumbent technologies. In the interest of cost control and scalability to monolithic integration, the new device structures must also be CMOS compatible.

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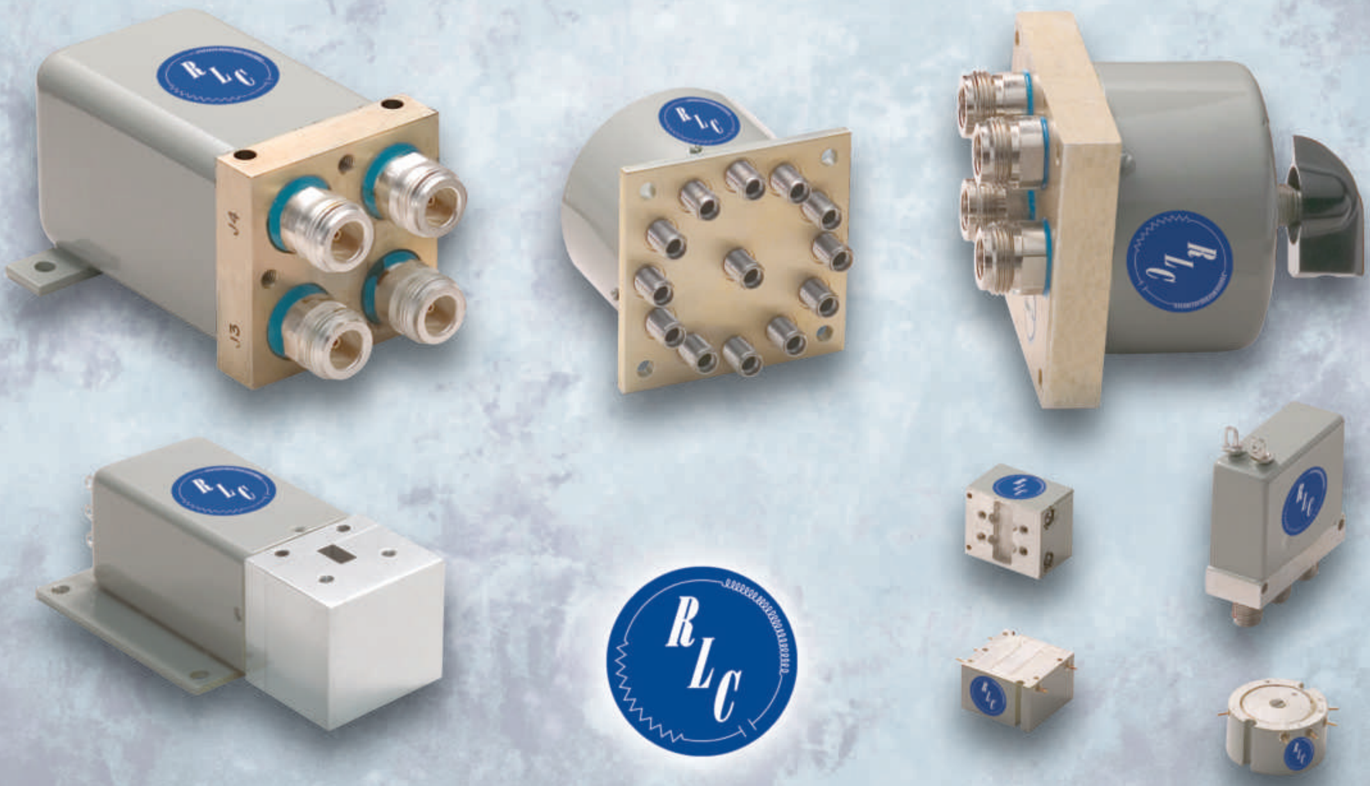

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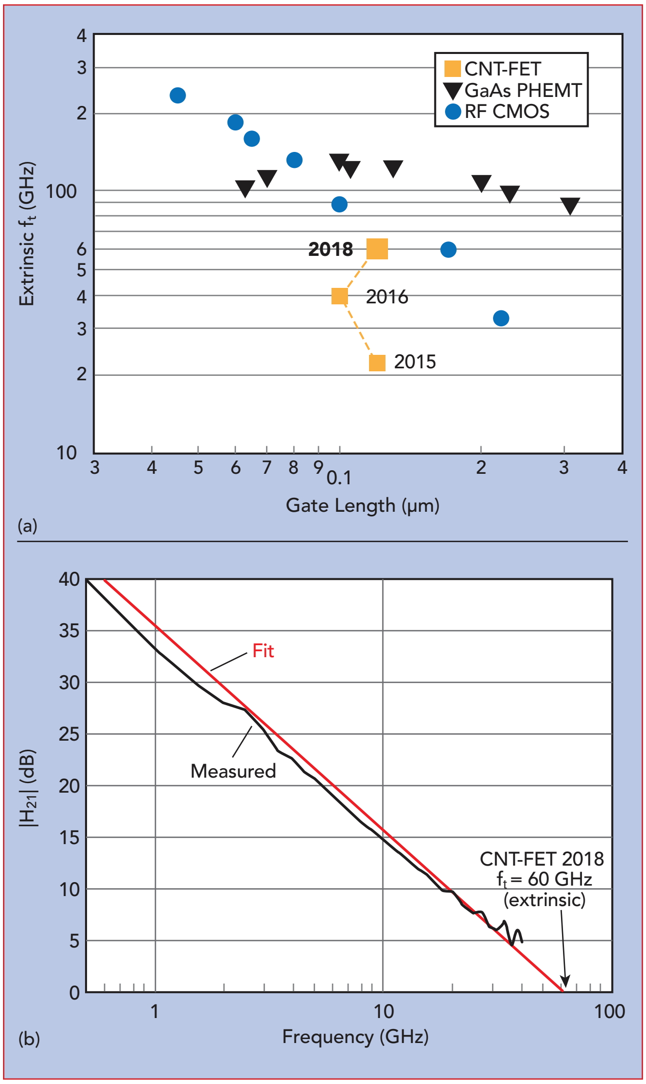


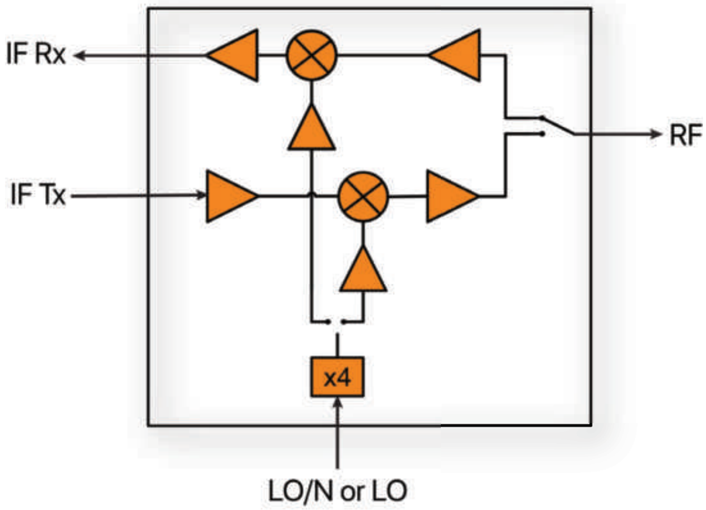
▲ Fig. 1 **Comparison of Carbonics CNT-FET[4-5] f_t vs. GaAs PHEMT and RF CMOS technologies (a). A 110 nm gate length CNT-FET fabricated in 2018 achieved an extrinsic f_t of 60 GHz (b).**

One technology is CNT field-effect transistors (CNTFET) fabricated from aligned semiconducting CNTs, which operate via one-dimensional carrier transport. Since their discovery in 1991, these ~1.5 nm cylindrical molecules of carbon have been talked about as an emerging high performance electrical material. Although CNTs have long been known to have impressive transport properties, such as high current and transconductance exceeding 25 µA and 20 µs per tube, for much of that time the twin engineering challenges of achieving high purity semiconducting CNTs (> 99.9 percent) and dense, aligned arrays (> 40 CNTs/µm) have prevented the full manifestation of these properties in a practical device. Now, these challenges have been overcome to improve device performance.

These devices offer intrinsically superior transfer curve linearity and, therefore, higher OIP3/P_{dc} ratios compared to incumbent semiconductor devices.[2] CNT transistor technology developed by Carbonics combines the intrinsic linearity advantages of CNT electronic transport properties with an approach that has been shown to both theoretically[2] and empirically[3] maximize OIP3/P_{dc}. CNT-FET technology has achieved new records for f_t (see ***Figure 1***), increasing from 22 GHz in 2015 to 60 GHz in 2018, and Carbonics' CNT-FETs have achieved an OIP3/P_{dc} of 15.7 dB, and an OIP3 of 11.5 dBm. Low voltage operation (< 3 V) and CMOS compatibility provide a path to monolithic integration of the digital and analog worlds.

CNT-FET SPECIFICATIONS AND ON-WAFER MEASUREMENTS

As a proof of feasibility beyond on-wafer measurements, two L-Band amplifiers (amplifiers 1 and 2) have been built and demonstrated. The CNTs have molecular structures similar to graphene (i.e., hexagons of carbon atoms), except that they are formed into tubes and the direction of the rollup (i.e., the chirality vector) determines their electronic properties.[6] Some chiralities have zero bandgaps (i.e., metallic) and others have non-



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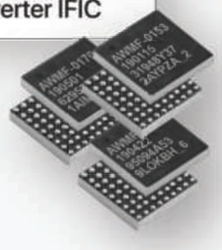
AWMF-0153	26.5 - 29.5 GHz	Tx/Rx Up and Down Converter IFIC
AWMF-0161	37 - 40 GHz	Tx/Rx Up and Down Converter IFIC



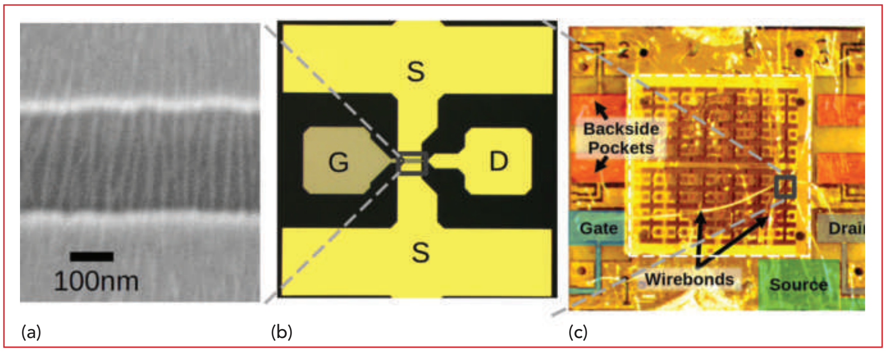


Fig. 2 SEM image of an aligned monolayer of high purity semiconducting carbon nanotubes spanning the FET channel prior to forming the T-gate (a), CNT-FET (b) and CNT-FET die mounted on an alumina chip carrier (c).

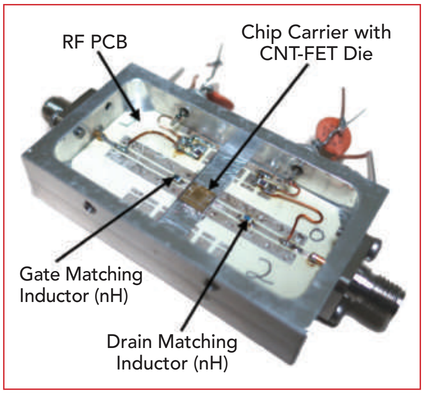


Fig. 3 Packaged CNT-FET amplifier.

zero bandgaps (i.e., semiconducting CNTs).

Present CNT production processes cannot control chirality. Hence, approximately one third of the as-grown CNTs are metallic, with the remainder semiconducting. Only the semiconducting CNTs are useful for CNT-FETs because the current in metallic CNTs cannot be modulated by electric fields through an insulator, required to construct a useful field-effect transistor. CNTs used for CNT-FETs must be sorted to remove those that are metallic.

The CNT-FETs in this work are constructed from high purity semiconducting CNTs having a very small

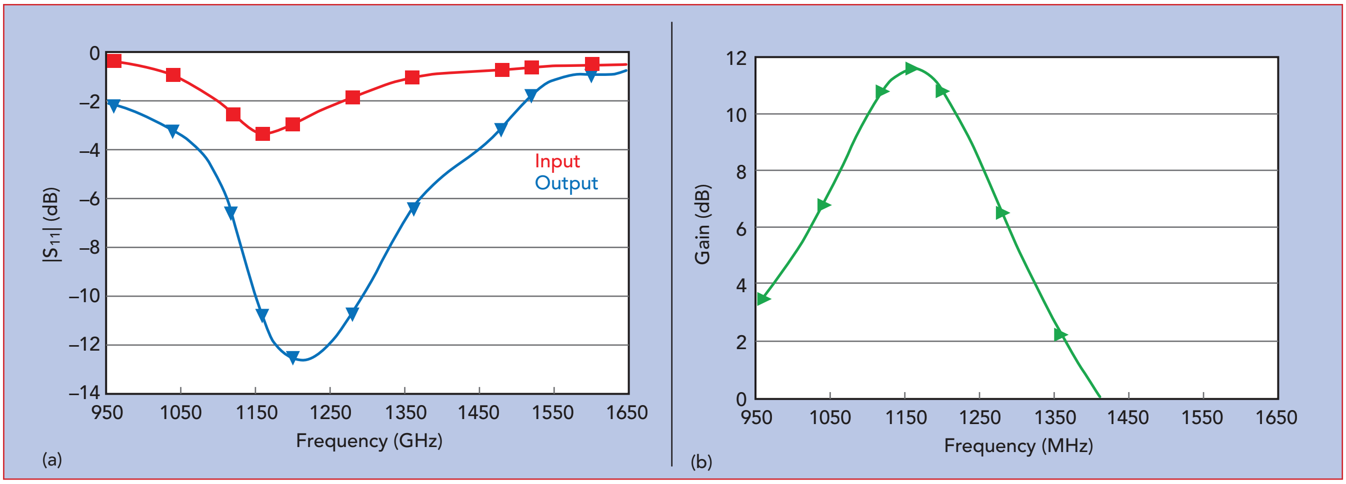


Fig. 4 Input and output $|S_{11}|$ (a) and gain (b) of amplifier 1.

fraction of metallic CNTs, on the order of 0.1 percent. This ensures minimal transistor leakage current. These are then deposited as a monolayer on a quartz wafer using Carbonics' proprietary ZEBRA wafer deposition process, producing the CNT monolayer shown in ***Figure 2a***. The CNT-FETs used in both amplifiers have gate widths of 50 µm and gate lengths of 140 nm. ***Figure 2b*** shows a CNT-FET, similar to those used in the amplifiers, fabricated on a quartz substrate. The CNT-FETs used in the amplifiers come from wafers with on-wafer measurements showing extrinsic f_{max} and f_t reaching up to 60 GHz and 43 to 60 GHz, respectively, at V_{ds} = −1.5 V. CNT-FETs used in amplifiers 1 and 2 have maximum drain currents, I_{dmax}, of 143 mA/mm and 228 mA/mm, respectively, with on/off ratios at V_{ds}= −1 V of 233 and 121, respectively, which indicates a very low metallic CNT fraction.

DEVICE, CHIP CARRIER AND AMPLIFIER STRUCTURE

The quartz substrate CNT-FETs are diced and selected for mounting to alumina chip carriers as shown in ***Figure 2c***. The hard alumina chip carriers accommodate wire bonding while enabling softer, low loss RF material to be used for the RF printed circuit boards (PCB). Laser fabrication tools are employed to fabricate and pattern the metallization of the 254 µm thick alumina chip carriers, steps conducted at the University of California, Los Angeles Center for High Frequency Electronics (UCLA CHFE). This technique enables the formation of excavated pockets behind the pads to reduce parasitic capacitance. The chip carrier design includes probe pad structures to allow wafer probes to directly measure the S-parameters of the mounted CNT-FET while automatically including the RF characteristics of the die to chip carrier bond wires. After mounting, the CNT-FET chip carriers are probed on the chip carrier pads, enabling accurate design of

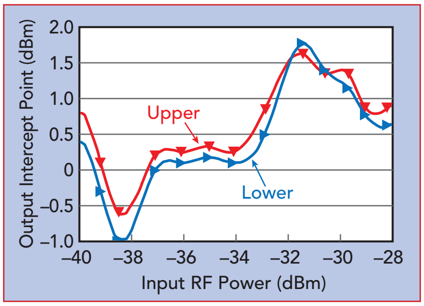


Fig. 5 Amplifier 1 OIP3 with 1160 and 1171 MHz input tones.

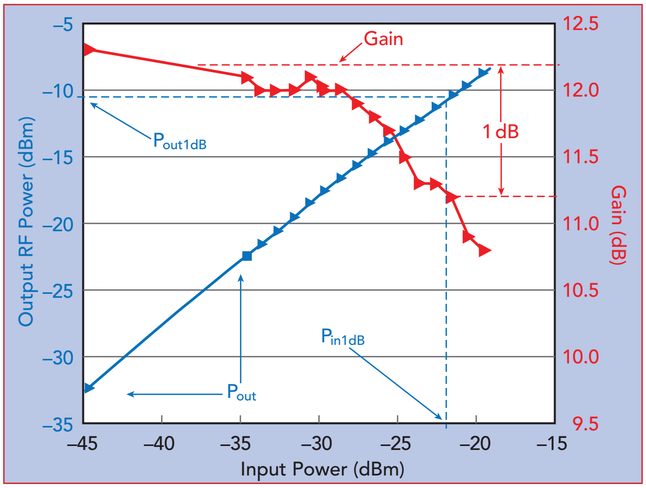


Fig. 6 Amplifier 1 output power and gain vs. input power, measured at ~1.2 GHz.

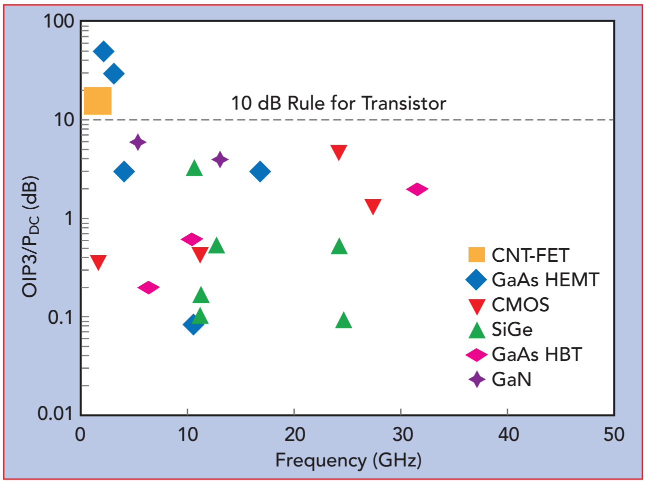


Fig. 7 Linearity comparison of 2018 CNT-FET vs. incumbent process technologies.[1] Here, the CNT-FET OIP3/P_{dc} = 15.7 dBm at 1.5 GHz.

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the RF amplifier PCB's impedance-matching and bias structures without needing to model the carrier.

Amplifier 1's CNT-FET, mounted on the chip carrier, demonstrated an f_t and f_{max} of 3 and 7.9 GHz, respectively, while amplifier 2's CNT-FET measured 5 and 8 GHz. The large decrease from the measured on-wafer f_t and f_{max} is likely due to bond wire parasitic inductance and resistance. At 1.2 GHz, the maximum stable gain (MSG) for amplifiers 1 and 2 wire bonded in the chip carriers is 16 and 17 dB, respectively.

NI AWR Microwave Office® is used to design the amplifier input and output matching circuits to achieve maximum gain near 1.2 GHz. The selected CNT-FETs' small gate peripheries result in very small input capacitances < 0.6 pF, which results in high capacitive gate impedances of approximately 220 Ω at 1.2 GHz. This necessitates matching gate inductances on the order of 31 nH. Under such conditions, the use of lumped elements saves space and yields higher Q and gain than possible with microstrip elements alone.

The microstrip tuning and bias network elements are etched onto a Rogers R04350B RF substrate. Passive components are bonded on the PCBs using conductive epoxy. The PCBs are then glued into their aluminum housings and connectors added. Finally, alumina chip carriers, containing the CNT-FETs are mounted using conductive epoxy and the electrical connections are made using wires attached with conductive epoxy (see ***Figure 3***).

MEASUREMENT RESULTS AND DISCUSSION

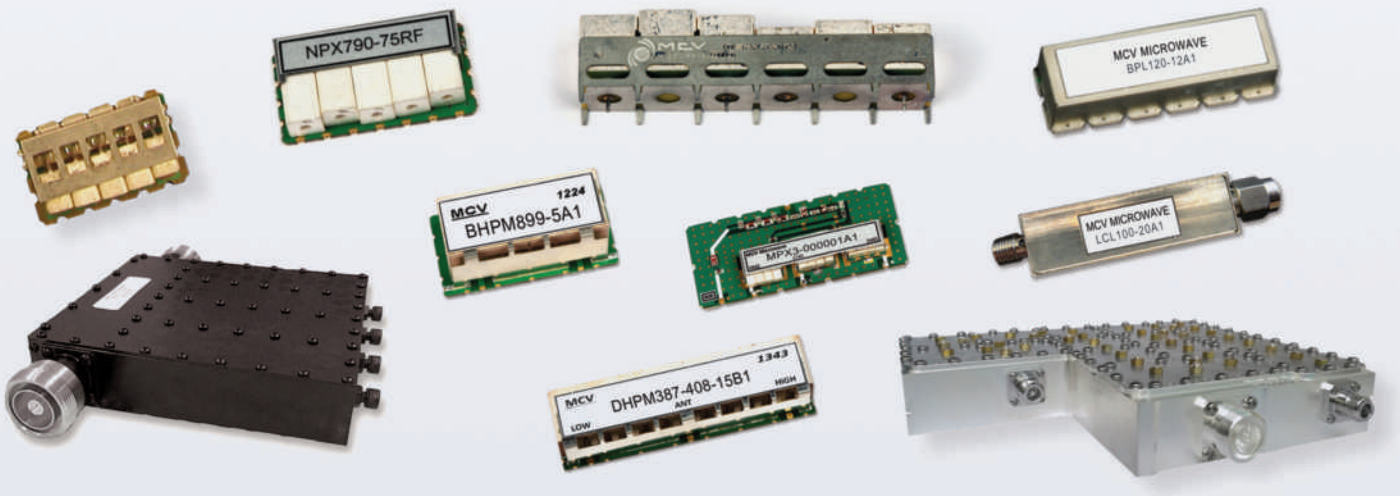
Gain, return loss, OIP3 and 1 dB gain compression were measured with a scalar analyzer. At V_{ds} = −1.16 V and V_{gs} = −1.1 V, amplifier 1 produced a peak gain of 11.6 dB, while the peak gain of amplifier 2 was 10 dB (see ***Figure 4***). For amplifier 1, the gain was 4.4 dB below its MSG, while amplifier 2's gain was 7 dB below its MSG. Amplifier 2's gain, $|S_{11}|$ and $|S_{22}|$ responses versus frequency were similar to those of amplifier 1.

OIP3 was measured by applying two RF signals at 1149 and 1182 MHz. The two OIP3 values—the lower and upper frequency IMD3 products—are plotted in ***Figure 5*** for amplifier 1. Amplifier 1's OIP3 ranged from −1 to +1.8 dBm. For comparison, amplifier 2's OIP3 was from −1.8 to +0.4 dBm. The measured 1 dB compression point for amplifier 1 was −10.3 dBm (see ***Figure 6***), while the 1 dB output compression point for amplifier 2 was −11.9 dBm. This implies OIP3 to P_{1dB} differences of approximately 10 and 12 dB for amplifiers 1 and 2, respectively, which meets or exceeds the 10 dB rule of thumb for most semiconductor devices.

Overall, these results go beyond the work by Eron et al.[7] who demonstrated an L-Band CNT-FET amplifier fabricated from CVD-grown CNTs. However, that CNT-FET[5] had significant metallic CNT content and, consequently, relatively high leakage current compared to the CNT-FETs discussed here.

Optimize The Future

Advanced Filter Design Capabilities



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FUTURE DIRECTIONS AND POTENTIAL

The empirical results achieved and described in this article demonstrate the capability of CNT-FET technology employing aligned CNT ZEBRA wafers. In this circuit design, however, the die was designed for optimal wafer probing; consequently, the large die requires long bond wires, on the order of 2 mm, which is the primary performance limitation.

A new mask set and redesign of the chip carrier should improve the performance of subsequent CNT-FET circuits; much-improved frequency response, lower noise figure and higher OIP3 are expected. Additionally, the CNT-FETs used in these amplifiers are mid-2018 iterations. More recent CNT-FETs fabricated in January 2019 benefit from the technology's rapid trajectory since this first amplifier project and their results, to be published, show f_t and f_{max} performance that already approaches that of GaAs PHEMTs and compares favorably to RF CMOS (see Figure 1), while also having the advantage of being compatible with CMOS. Rough projections based on single-tube measurements puts the upper range of CNT-FET device performance at transconductance values of 1200 μs/μm, current densities of 1500 μA/μm and f_t around 300 GHz for 100 nm gate-length devices. Consequently, there is substantial headroom for continued advancement of the CNT-FET technology.

These latest CNT-FET OIP3 and OIP3/P_{dc} on-wafer results already compare favorably to CMOS and other technologies[1] (see ***Figure 7***). Carbonics sees CNT RF technology entering commercialization with discrete and MMIC products for the defense and aerospace markets within the next two to five years. It is suitable for highly sensitive front-end signal processing of high frequency signals used in radar, communications and other military systems, particularly well-suited for front-end modules and circuits such as mixers, oscillators, low noise amplifiers and power amplifiers. As the technology matures, more complex products and monolithic integration with CMOS are envisioned.■

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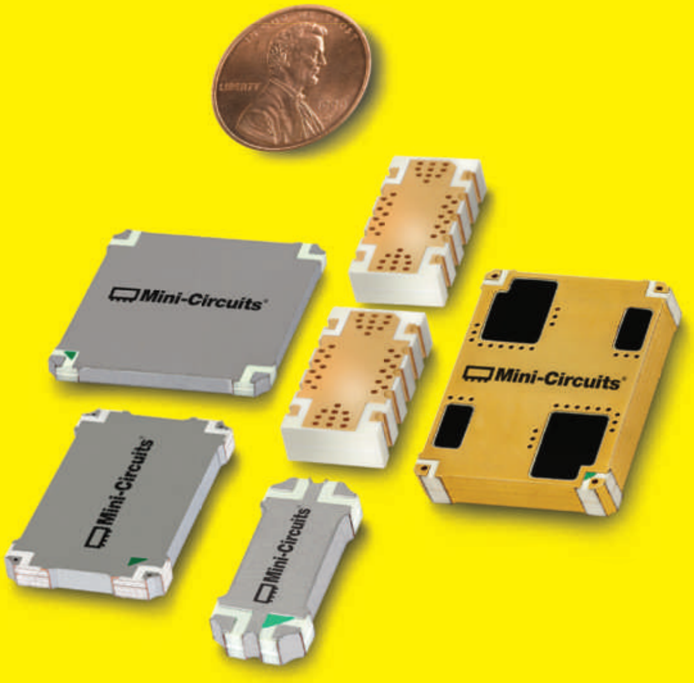
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Cliff Drubin, Associate Technical Editor

Sensor Technology Guides Next-Gen Missile to Readiness

BAE Systems worked closely with Lockheed Martin (LM) to deliver Long-Range Anti-Ship Missiles (LRASM) to the U.S. Air Force, achieving Early Operational Capability (EOC) for the B1-B bomber ahead of schedule. The Air Force accepted delivery of production LRASM units following successful simulation, integration and flight tests that demonstrated the missile's mission readiness.

BAE Systems' long-range sensor and targeting technology enables LRASM to detect and engage protected ships in all weather conditions, day or night, without relying on external intelligence and navigation data. BAE Systems and LM are working closely together to further mature the LRASM technology. The companies recently signed a contract for the production of more than 50 additional sensors and are working to achieve EOC on the U.S. Navy's F/A-18E/F Super Hornet in 2019.

LRASM EOC (Source: BAE Systems)

Traditionally, anti-ship missiles face a challenge penetrating sophisticated enemy air defense systems from long ranges. Consequently, warfighters can require multiple missile launches and overhead targeting assets to engage enemy warships from beyond the reach of counterfire systems. LRASM is a precision-guided anti-ship missile designed to give the U.S. Navy the ability to strike high-value targets from long ranges while avoiding counterfire. The system uses semi-autonomous guidance and target cueing data to precisely locate and attack targets, reducing reliance on ISR platforms, networking links and GPS navigation, which could be compromised by enemy electronic weapons.

Directed Energy Systems Down Multiple Drones in USAF Demo

Raytheon Co.'s advanced high-power microwave and mobile high energy laser systems engaged and defeated multiple UAS targets during a recent U.S. Air Force demo. The mature HPM and HEL technologies offer an affordable solution to the growing UAS threat.

The HEL system, paired with Raytheon's Multi-Spectral Targeting System, uses invisible beams of light to defeat hostile UASs. Mounted on a Polaris MRZR all-terrain vehicle, the system detects, identifies, tracks and engages drones.

Raytheon's HPM uses microwave energy to disrupt drone guidance systems. High-power microwave operators can focus the beam to target and instantly defeat drone swarms. With a consistent power supply, an HPM system can provide virtually unlimited protection.

"After decades of research and investment, we believe these advanced directed energy applications will soon be ready for the battlefield to help protect people, assets and infrastructure," said Dr. Thomas Bussing, Raytheon Advanced Missile Systems VP.

HPM_HEL System (Source: Raytheon Co.)

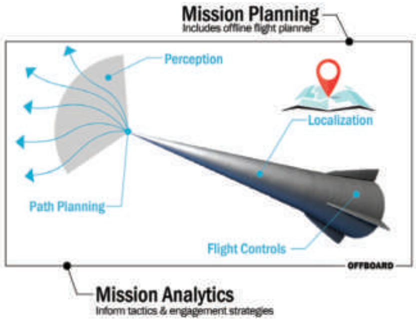
Future Hypersonics Could Be Artificially Intelligent

A test launch for a hypersonic weapon—a long-range missile that flies a mile per second and faster—takes weeks of planning. So, while the U.S. and other states are racing to deploy hypersonic technologies, it remains uncertain how useful the systems will be against urgent, mobile or evolving threats.

Sandia National Laboratories, which has made and tested hypersonic vehicles for more than 30 years, thinks AI and autonomy could slash these weeks to minutes for deployed systems. To prove it, Sandia recently announced the formation of Autonomy New Mexico, an academic research coalition whose mission is to create artificially intelligent aerospace systems.

A hypersonic boost-glide vehicle—the type tested by Sandia—launches into space aboard a rocket, then detaches and uses only its momentum to sail across the upper atmosphere before finally plunging back to Earth and its target.

"At extreme speeds, the flight is incredibly challenging to plan for and program," said Alex Roesler, a senior manager at Sandia who leads the coalition.



Autonomous Flight Components (Sandia National Laboratories Image)

In theory, AI could generate a hypersonic flight plan in minutes for human review and approval, and in milliseconds a semi-autonomous vehicle could self-correct in flight to compensate for unexpected flight conditions or a change in the target's location. A human monitoring the flight could regain control by turning off the course-correcting function at any time.

Autonomous technologies, such as self-driving cars, are designed to perform complicated tasks without human intervention. They require a broad range of technologies that work in tandem, including advanced computing, AI and machine-learning algorithms, sensors, navigation systems and robotics.

Members collaborating with Sandia represent the Georgia Institute of Technology; Purdue University; the University of Illinois, Urbana-Champaign; the University of New Mexico; Stanford University; Texas A&M University; The University of Texas at Austin; and Utah State University.

System Helps Pilots Fly Drones Beyond Line of Sight

Raytheon's Ground Based Detect and Avoid (GBDAA) system is now operational at Springfield-Beckley Municipal Airport and will be used to test the safety and efficiency of small drone operations in the 200 square mile drone test range.

"GBDAA allows drone pilots to make safe decisions about flight maneuvers beyond visual line of sight without using ground observers or chase planes," said Matt Gilligan, VP of Raytheon's Intelligence, Information and Services business. "The data gathered at this test site will go a long way toward ensuring the safe integration of drones throughout the national airspace system."

Contracted by the U.S. Air Force through the Department of Transportation's VOLPE center, GBDAA is a key component of SkyVision, the only mobile beyond visual line-of-sight system certified by the FAA to provide drone operators with real-time aircraft display data, satisfying a key "see and avoid" requirement.

SkyVision operators inside the mobile unit will give drone pilots situational awareness and proximity alerts by syncing their display with the drone pilot's display, allowing for safe passage through the airspace by showing airborne tracks from multiple sensors.

GBDAA is based on Raytheon's Standard Terminal Automation Replacement System (STARS), which is used by air traffic controllers at more than 400 FAA and military locations to provide safe aircraft spacing and sequencing guidance for departing and arriving aircraft.

GBDAA comes in numerous configurations to meet varying mission needs; the U.S. military uses a fixed version to manage larger unmanned systems like the Predator, Reaper and Global Hawk.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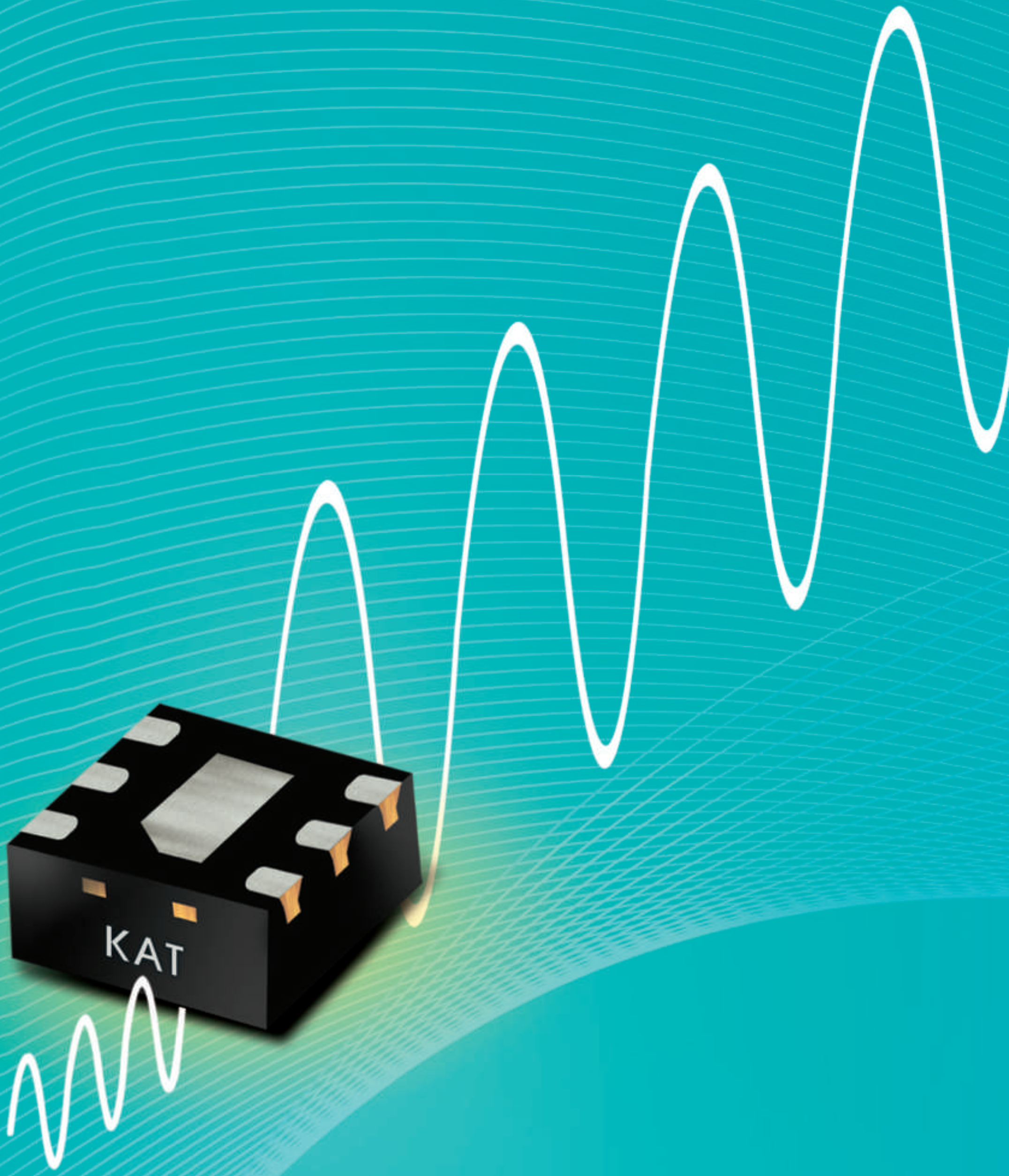
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Companies "Aggressively Pursuing Tech" for Productivity and Profitability

The recent Hannover Messe 2019 conference reflected on the rapidly changing industrial manufacturing landscape in which companies are relying on technology to increase productivity and profits. "The interesting takeaway from Hannover Messe 2019 is that companies are not hunkering down but are aggressively pursuing technology as an avenue to increase productivity and drive profit margins," said Stuart Carlaw, chief research officer at ABI Research.

> A dozen technologies complement industrial manufacturing's digital transformation initiatives.

"Hannover Messe 2019 can be viewed as the inflection point in industrial digital transformation. There is a perfect storm of need, appetite, capability, fear and greed that will drive this market aggressively," added Carlaw. "One note of caution is that the rate of technological progress is fast outpacing the ability of most companies to understand, deploy and maximize new technology solutions in terms of operational benefits. This modern skills gap will only get wider."

Some observations and trends include:

- The appetite to connect hardware is growing. The majority of the marketplace is focused on connecting assets and trying to get data off them at present. The tech provider world needs to assume less and listen more.
- In 2018, wireless was somewhat of a "dirty word." At Hannover Messe 2019, it was abundantly clear new forms of wireless connectivity, including LTE and 5G, were taking the lion's share of commercial interest.
- The need for digital transformation is not just in the realm of the large organization. There was a growing focus on the sub-1,500 employee company and enabling those firms to benefit from connectivity and increased data analysis.
- Technologies capturing attention included 5G, artifical intelligence (AI), Industrial IoT (IIoT), augmented reality (AR), digital twins, data analytics, autonomous materials handling, cobots, exoskeletons, generative design, additive manufacturing and blockchain.
- A passionate debate at the show was the continued conundrum of edge or cloud for data management and execution of decision functions and data storage.
- There are some very powerful commercially driven partner ecosystems emerging that look set to shape the market of the future.

Threat Factors Drive Cities' Resilience Spending

City governments worldwide are becoming increasingly aware of the importance of making their cities able to withstand or recover quickly from a range of predictable and unpredictable disasters and catastrophes, driving global public spending on urban resilience projects from $97 billion in 2019 to $335 billion in 2024, according to a new report from ABI Research.

"Due to their very high population concentrations, cities are much more vulnerable to the catastrophic potential of earthquakes, tsunamis, volcano eruptions, sea level rise and flooding, food shortages, wildfires, extreme heat, hurricanes, tropical storms and typhoons, terrorist attacks, civil unrest, cyber-attacks, war, diseases and epidemics, nuclear or chemical contamination, extreme air pollution and many other emergency situations. So much so that many cities have already appointed a chief resilience officer," explained Dominique Bonte, vice president, end markets at ABI Research.

While the smart cities concept is very much geared toward ensuring livability of citizens in the present, resilient cities guarantee future livability in the face of a changing urban environment not only in terms of acute shocks, but also of chronic stresses related to economic, financial, environmental, social and institutional crises.

"The significant growth of global public spending on urban resilience projects includes spending on both physical and information and communications technology (ICT) infrastructure and services. Resilience spending is currently dominated by cities in developed regions. The cities of New York and Miami Beach have announced budgets of $500 million and $400 million, respectively, for flood prevention, sea-level-rise mitigation and coastal areas reinforcement. By 2024, cities in developing regions will account for 40 percent of all resilience spending," Bonte said.

> Climate-related risks alone account for $122.98 billion of GDP under threat for a sample of 279 cities.

Resilience strategies and solutions include many components ranging from detection and prediction via advanced sensors and AI-based analytics to alert systems, evacuation procedures, rescue missions, relief response modes in the immediate aftermath and recovery for survivors and the city as a whole in the longer term.

Critical resilience technologies and paradigms include predictive modeling and digital twins (already explored by cities like Cambridge, England and Rotterdam, Netherlands), cybersecurity, redundant infrastructure and system designs, decentralized service

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provisioning, demand-response optimization, sharing economy and cross-vertical integration, physical robustness and robotics.

Key suppliers of resilience technologies covered include NEC, Bosch and ZTE. Organizations like 100 Resilient Cities (100RC), the United Nations' Making My City Resilient campaign and the U.S. National League of Cities' (NLC) Leadership in Community Resilience program are promoting best practices for designing resilient cities.

Commercial Vehicle Telematics Growth

Global commercial telematics system revenues will nearly double by 2024 to over $29 billion, with subscriptions to exceed 86 million in the same timeframe, according to ABI Research. Increasing opportunities in last-mile delivery, led by e-commerce, the need for greater transparency and connectivity as well as the emergence of Level 2 SAE commercial vehicles, all will enable the technology to achieve a subscription CAGR of approximately 14 percent.

"The commercial telematics industry continues to attract investments, acquisitions and geographic expansion to capture recurring revenue streams as well as new vertical and market penetration opportunities," said Susan Beardslee, principal analyst at ABI Research. Services-based commercial vehicles including utilities, cable/telco and trades will see a 19 percent CAGR from 2019 to 2024.

> Driven by emerging markets, ADAS technology and cold chain.

Telematics for cold-chain applications represent a significant opportunity, especially for fresh and processed food, as food safety concerns grow in light of multiple recent recalls. Global revenues will grow to nearly $2 billion by 2024 for this category alone. Commercial telematics providers that offer cold-chain solutions include MiX Telematics, Trimble, Verizon, Gurtam and Orbcomm.

ADAS capabilities will increasingly be integrated with factory-installed telematics and transmit data to those telematics devices. Trucks will begin to ship this year with SAE Level 2 automation and grow to over 224,000 units shipped by 2024, at a nearly 18 percent CAGR for use cases such as driver behavior monitoring and insurance telematics.

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

IN MEMORIAM

How far would he go? That is what we all wondered about **Chuck Swift** as we struggled to keep up with him. Whether it was at an IEEE event like the 1989 MTT-S Symposium he chaired in Long Beach, Calif., or at the 38th annual Christmas Party he threw for his Phi Kappa Psi fraternity at UCLA this past December his drive never slackened. With his wife Dolly, Chuck founded the family business in July 1958 and co-owned it until her death in January 2018.

When Chuck was 12, he moved with his parents to Gardena, Calif. from Ames, Iowa, where his older siblings remained to finish high school. Always adventurous, he hitchhiked solo back to Ames when he was in the 10th grade to see his sister graduate. After serving in Japan during the occupation, he attended UCLA where he met Dolly while negotiating for better terms at the campus bookstore where she worked.

He loved gadgets and people and going places. He threw the whole family in a car, on a plane or on our motorcycles and headed out across country to visit customers, suppliers, relatives and friends. He whistled and sang and joked his way past receptionists, purchasing agents, design engineers, company presidents, doormen, bouncers and maître d's, leaving each with a smile and something blinking in their eyes.

▲ *Chuck Swift*

Chuck taught us how to tie our shoes, ride bicycles, sail boats, fly an airplane and make a living. He was always open to a challenge—letting us teach him to snow ski when he was almost 50.

He mourned the passing of friends saying, "Why should I go to his funeral? He's not coming to mine." A celebration of life will be held for Chuck in June.

Written by: Andy Swift

MERGERS & ACQUISITIONS

Gowanda Components Group (GCG) announced the merging of **REM-tronics Inc.** with the GCG family. REM-tronics is a contract manufacturer of high-reliability products for the aerospace, industrial, medical and military industries. They are located in Dunkirk, N.Y. Terms of the deal were not disclosed, but GCG has stated that REM-tronics will maintain its operations in Dunkirk under the new name Gowanda REM-tronics. In addition to Dunkirk, GCG has five other production facilities located within the U.S. This is the eighth addition to the GCG family within the last seven years.

Cree Inc. has announced the completion of the sale of its Lighting Products business (Cree Lighting) to leading electrical and telecom solutions company, **IDEAL INDUSTRIES**. The transaction includes Cree's LED lighting fixtures, lamps and corporate lighting solutions business for commercial, industrial and consumer applications. The transaction, which was previously announced on March 15, has now been closed and is effective hereafter. The sale of its lighting business represents a pivotal chapter for Cree as the company sharpens its focus to become a semiconductor powerhouse in SiC and GaN technologies.

Mercury Systems has announced the complete acquisition of **The Athena Group** and **Syntonic Microwave** for a total value of $46 million. A privately-held company based in Gainesville, Fla., The Athena Group is a leading provider of cryptographic and countermeasure IP vital to securing defense computing systems. A leader in differential power analysis (DPA) technology, they offer a complete portfolio of provable DPA-resistant solutions. Athena's sophisticated patented technologies meet mandated DoD requirements and mitigate reverse engineering attempts on mission-critical systems. Embedded in millions of ASIC and next-generation FPGA devices, their solutions are designed to solve today's toughest security obstacles, enabling key applications such as artificial intelligence (AI), mobile communications and cloud computing.

COLLABORATIONS

Keysight Technologies Inc. announced a collaboration with **Telia Finland** to accelerate commercial 5G New Radio (NR) deployments. 5G networks will revolutionize industrial IoT (IIoT) to support reduced latencies, higher reliability and a greater number of connected devices. Telia, a leading mobile operator, selected Keysight's Nemo 5G NR field measurement solution to verify 5G NR coverage and quality of service in their commercial industrial 5G NR network. Telia deployed the network using base station equipment from Nokia at a mill located in Finland to improve the site's operational effectiveness.

ipoque GmbH, a **Rohde & Schwarz** company, announced a strategic research partnership with **Helmut Schmidt University** in Hamburg to establish a program of exchange and collaboration. The R&S subsidiary provides market-leading network analytics solutions for more secure, reliable and efficient networks. The joint research will focus on AI, machine learning and big data analytics and runs for four years. Keeping the networks of the future secure and reliable is an important challenge as IP traffic rates, protocol complexity and the number of cyberattacks continually increase. The potential of future technologies to further enhance network analytics and security solutions will be a main topic in the partnership.

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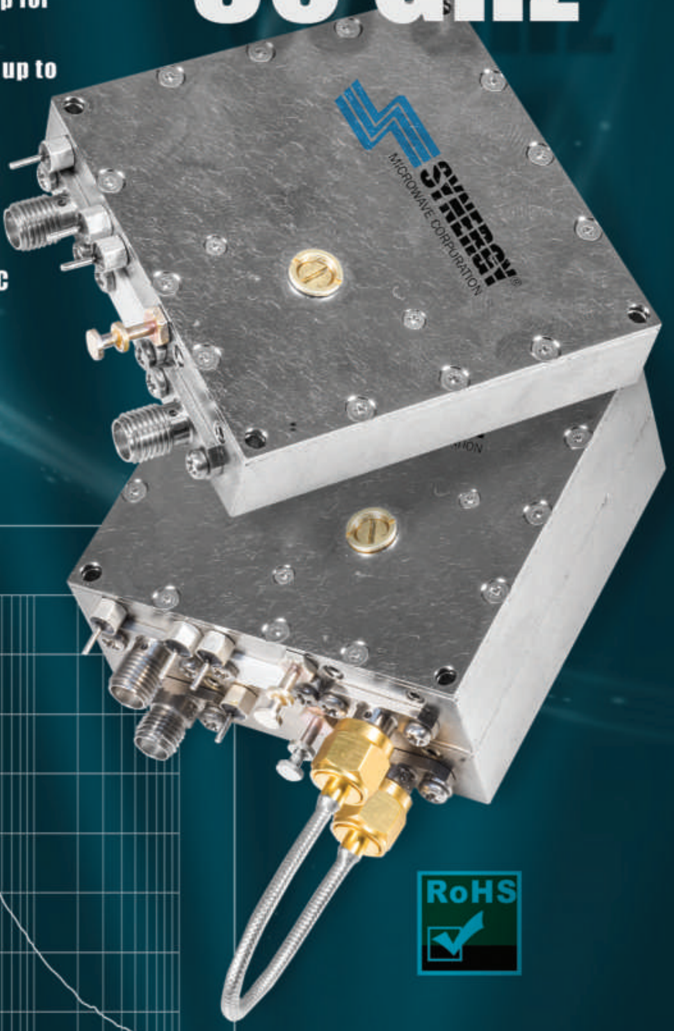

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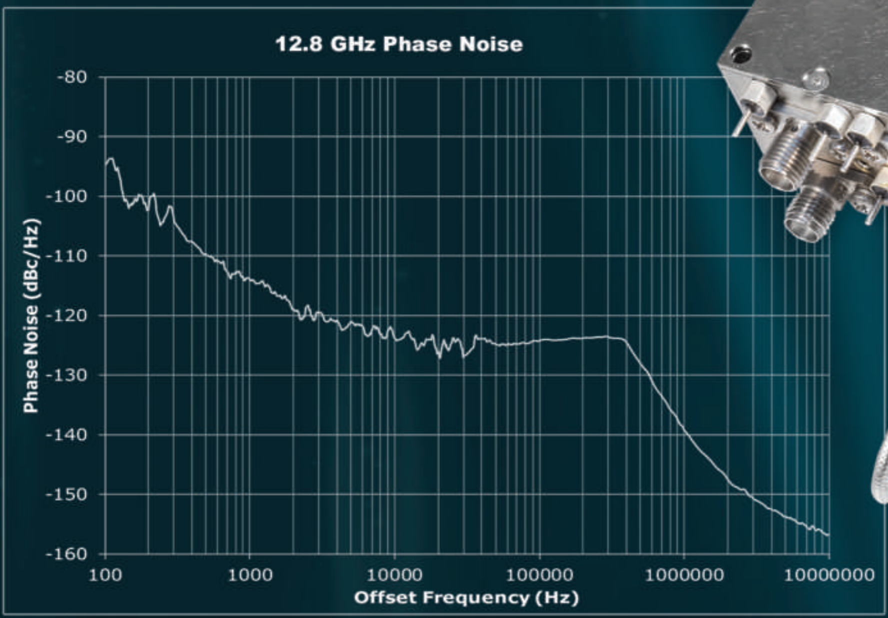

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MACOM has partnered with **Goertek** to supply, market and distribute GaN on Si based RF power components into China's base station market. Goertek is an electronic components company based in Shandong, China. MACOM will create a company that will enter into an agreement to establish a joint venture company with Goertek. Goertek and MACOM will each contribute $25 million in working capital to the joint venture. MACOM retains rights to sell GaN on Si products outside of China, Hong Kong and Macau. Goertek will provide total consideration to MACOM of up to $134.6 million, including $30 million up front. MACOM will further be entitled to royalties and dividend preferences in the joint venture.

NEW STARTS

EDI CON announced that this year, in conjunction with ***Microwave Journal*** and ***Signal Integrity Journal***, it will host an online, interactive event—**EDI CON Online**—for high frequency and high speed design engineers on September 10-12, 2019. The interactive technical sessions will occur at no cost to attendees, and sponsors will have the opportunity to present workshops and keynote sessions as part of the daily schedule. The sessions on September 10^{th} will focus on 5G and IoT, September 11^{th} on radar and antennas and September 12^{th} on signal integrity, power integrity and EMC/EMI. Attendees select the sessions in a single sign-on registration portal and can participate in the sessions live (with Q&A sessions) or watch later on demand.

ACHIEVEMENTS

Custom MMIC is honored to be the only semiconductor supplier to receive **BAE Systems**' distinguished GOLD Supplier award for 2018. As part of their "Partner 2 Win" Supplier Program, BAE Systems conducts a comprehensive annual review of all their key suppliers and brings the top performing suppliers together for an evening of appreciation and to acknowledge their outstanding support over the previous year. Dave Folding, VP of operations, and Erik Sauve, director of quality, attended the Partner 2 Win Supplier Symposium ceremony held on April 2, 2019 and accepted the award on behalf of the Custom MMIC team.

CONTRACTS

CACI International Inc. announced it has been awarded a prime position on the multiple-award, indefinite delivery/indefinite quantity **U.S. Army R4** contract, with a ceiling value of $982 million, to provide electronic warfare and cyber capability research and development. This five-year award from the Army's Program Executive Office, Intelligence, Electronic Warfare and Sensors (PEO IEW&S) represents new work for CACI. Through this contract vehicle, CACI will integrate high-end EW and cyber services, solutions and products to support Army cyber operations. Additionally, CACI's recent acquisition of LGS Innovations will assist the company in better developing both software and hardware capabilities sought by the Army.

Harris Corp. has been awarded a $212 million contract to supply electronic jammers to protect **U.S. Navy's** F/A-18 Hornet and Super Hornet aircraft against electronic threats. The contract, which represents the largest order on the program to date, was received during the third quarter of Harris' fiscal 2019. Harris will manufacture and deliver Integrated Defensive Electronic Countermeasures (IDECM) jammers for the F/A-18C/D/E/F variants, with deliveries under the new contract expected to be completed by August 2022. The Harris ALQ-214A(V)4/5 is the key onboard EW jamming system for the IDECM program, protecting the aircraft from electronic threats, including sophisticated integrated air defense systems.

The **U.S. Air Force Research Laboratory** selected **Science Applications International Corp.** to research laser bioeffects, advance vision science, conduct modeling and simulation, and perform safety engineering, awarding the company a $58 million Optical Radiation Bioeffects and Safety contract. The research program will enhance airman combat survivability by enabling U.S. forces to counter optical hazards and threats. Under the 75-month, cost-plus, fixed-fee contract, SAIC's team will cover wide-ranging research to define thresholds for biological injury and correlate optical exposure with performance. SAIC will also leverage machine learning capabilities from its Solutions and Technology Group as they seek to enhance laser injury assessments.

Comtech Telecommunications has announced that during the third quarter of fiscal 2019, its subsidiary, **Comtech Xicom Technology**, a part of Comtech's Commercial Solutions segment, received a contract valued at more than $5.5 million for high-power SATCOM amplifiers to relay data for the early detection of missile launches. Comtech Xicom manufactures high-power amplifiers, a wide variety of tube-based and solid-state power amplifiers for military and commercial satellite uplink applications. The product range encompasses power levels from 8 W to 3 kW, with frequency coverage in sub-bands within the 2 to 52 GHz spectrum.

Saab has received an additional order for the Sea Giraffe AMB naval radar, designated AN/SPS-77 by the **U.S. Navy**, for installation on the U.S. Navy's newest Littoral Combat Ships LCS 36 and LCS 38. The order, placed by General Dynamics, is further testament to Saab's continued growth in the U.S. market. Saab will carry out the work in Syracuse, N.Y. and Gothenburg, Sweden. Saab received the first order for Sea Giraffe AMB for the Littoral Combat Ships in 2005. Since that time, Saab has continuously developed the standard Giraffe AMB sensor to meet multiple missions in the U.S. sea services from open-ocean blue-water applications into the littorals.

Forsway announced that it has been awarded a co-funded development contract from the European Space Agency (ESA). The scope of the development project entails integration of the Forsway Xtend Hub with the 5G/network function virtualization (NFV) architecture. Forsway's comprehensive 5G project aims to enable and simplify a communication service provider's (CSP) ability to significantly accelerate slow or congested networks

using satellite services. The 5G/NFV architecture will make it possible for a CSP to seamlessly integrate the hybrid Forsway Xtend Hub directly into their core network.

PEOPLE

▲ Greg Baker

Altum RF announced **Greg Baker** as its CEO. As founder and CEO, Baker brings more than 25 years experience to Altum RF in the RF and microwave semiconductor industry, including component design, business development, marketing and sales. With his extensive experience, Baker provides a clear understanding of product development, operations and supply chain management, customer partnerships, sales channels and strategic marketing. Most recently with MACOM as senior VP and general manager, RF & Microwave BU, Baker also previously served as CEO of Nitronex LLC.

▲ Ian Crane and the Flann team

Flann Microwave has announced the appointment of **Ian Crane** as its new chief operating officer (COO). Crane takes over the leadership of the company from Professor James Watts, who will be stepping down after nine years from his role as CEO. Crane brings almost 50 years of high-level engineering and management expertise to the role, more than 40 of which have been with Flann. With a 69-strong team based in Bodmin, Flann has a 60 year track record of continuous innovation and manufacturing expertise which has seen the company secure a market-leading position in the design and manufacture of precision RF and microwave components.

▲ Donn Mulder

The Board of Directors of **Anritsu Corp.** announced that the global communications leader has named **Donn Mulder** president and CFO of **Anritsu Co.**, the U.S. subsidiary of Anritsu Corp., effective immediately. In his new position, Mulder will oversee the corporate business operations of Anritsu Co., as well as R&D, marketing/field operations and manufacturing operations of Anritsu's Network and Infrastructure Business Unit based in Morgan Hill, Calif. Mulder succeeds Toru Wakinaga who held this position, as well as responsibility for the overall sales operations in the Anritsu Americas Sales Region, since September 2017.

Tektronix Inc. announced that **Tami Newcombe** has been promoted to president of Tektronix. Newcombe joined Tektronix in early 2017 as commercial president and has been responsible for leading global sales and marketing. In her elevated role, Newcombe will report to Pat Byrne, who previously served as president of Tektronix and is currently senior VP at Fortive. Newcombe is an accomplished leader with 25 years of experience at Fortune 500 technology companies. She brought a diverse background to Tektronix when she joined, having held positions in sales leadership, field sales, operations, marketing and engineering.

▲ Tami Newcombe

▲ Daniel Leibholz

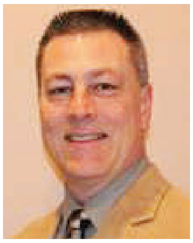
Analog Devices Inc. (ADI) announced that **Daniel Leibholz**, VP of ADI's Communications Business Unit, has been named CTO, effective immediately. As CTO, Leibholz will develop and lead ADI's technology strategy for applications across the company's end markets. In his previous role, Leibholz has overseen a period of tremendous growth as the company has delivered best-in-class offerings for the 5G wireless and wired markets. Leibholz joined ADI in 2008 from Advanced Micro Devices Inc. (AMD), where he had served as an AMD Fellow. Prior to his tenure at AMD, Leibholz was named a Distinguished Engineer at Sun Microsystems Inc.

▲ Rajappan "BG" Balagopal

pSemi Corp., a Murata company, announced that **Rajappan "BG" Balagopal** has been named VP of intellectual property (IP) and licensing. Balagopal will drive strategic development and management of pSemi's patent portfolio. Balagopal brings over 20 years of broad experience in IP management, including strategy, valuation, supply chain management, general legal counseling, business development and transactions. He has supervised interdisciplinary teams of attorneys, technologists and business professionals to solve complex IP problems, generate IP revenues and reduce IP costs and risks for large and small companies.

▲ Sean Mirshafiei

Isola Group announced it has promoted **Sean Mirshafiei**, formerly VP global marketing, to chief sales and marketing officer. Mirshafiei was initially with Isola from 2000 to 2009. He left in 2009 to fill various roles in product management and marketing strategy at Rogers Corp. and MacDermid Enthone. He returned to Isola in 2017 as VP global marketing. Mirshafiei has a B.S. in chemical engineering from the California State Polytechnic University and a M.B.A. from the University of Sout.



▲ Mark Perhacs

RFMW Ltd. announced that **Mark Perhacs** has joined their organization as director of sales for North America, reporting directly to Mike Carroll, VP global sales. Perhacs joins RFMW with more than 25 years of sales and marketing experience and with an extensive background in RF and microwave technology markets. Prior to RFMW,

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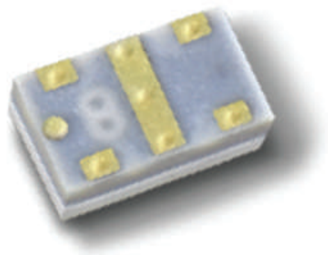

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Perhacs worked with industry-leading companies to deliver state-of-the-art products and services to various key markets. Most recently, Perhacs held the position of key account manager for aerospace and defense at Huber+Suhner. He was also director of sales for 3DGS.

▲ Dr. Ulrich Rohde

Dr. Ulrich Rohde has been selected to receive the 2019 CAS Industrial Pioneer Award. The Industrial Pioneer Award honors the individual(s) with exceptional and pioneering contributions in translating academic and industrial research results into improved industrial applications and/or commercial products. The award is given by **IEEE Circuits and Systems (CAS) Society** and President Yong Lian extended his congratulations and looks forward to honoring Dr. Rohde at their flagship conference, ISCAS 2019. The purpose of the annual IEEE CAS Society Awards is to illuminate the accomplishments of Society members and celebrate their dedication and contributions both within the field and to the Society.

PLACES

Mercury Systems Inc. celebrated the dedication of its expanded Advanced Microelectronics Center (AMC) in Huntsville, Ala. Congressman Mo Brooks; Col. Robert Barrie, Military Deputy, PEO Aviation; Donna McCrary of the Huntsville/Madison County Chamber of Commerce; and Harrison Diamond from the Office of the Mayor joined senior Mercury executives for a ribbon cutting ceremony, reception and facility tour. A state-of-the-art, 24,000 square foot design and assembly facility for RF and digital processing technologies, including 5,000 square feet of lab space with secure production capabilities, the expanded AMC provides redundant and complementary capabilities with the company's existing AMCs located in Hudson, N.H, Phoenix, Ariz. and West Caldwell, N.J.

In a bid to strengthen its R&D efforts for high frequency components, **Infineon** has expanded its manufacturing division in Linz, Austria. The Infineon Austria holding company DICE (Danube Integrated Circuit Engineering) expects to have a new building up and running by the summer of 2020. The building will provide room for about 400 employees—creating the possibility of 220 new jobs, as they currently employ 180 employees in their existing facility. The main focus of this center will be the development of 77 GHz radar chips for driver assistance systems. The Linz site develops solutions for important future markets.

Taoglas has inaugurated a new facility in downtown Minneapolis, Minn. to support the increasing demand for its products and services for development of IoT devices and solutions. The new facility features a state-of-the-art antenna and RF test and design laboratory, including a large 5 m anechoic chamber. It is the latest Taoglas location to receive an upgrade, and the first such facility in the Midwest dedicated to the IoT market.

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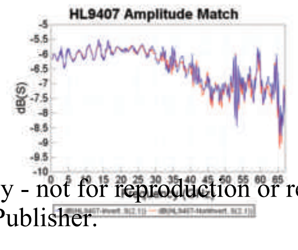

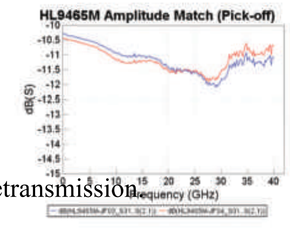

INVITED PAPER

Integrated 140 GHz FMCW Radar for Vital Sign Monitoring and Gesture Recognition

K. Vaesen, A. Visweswaran, S. Sinha, A. Bourdoux, B. van Liempd and Piet Wambacq
imec, Leuven, Belgium

An integrated, high performance, 140 GHz frequency-modulated continuous wave (FMCW) radar system enables the detection of minute motion, offering utility for various applications. Its main features are described in this article, including transceiver characterization and measurements of vital signs using a 2×2 MIMO radar assembly.

Since the introduction of the first radar systems in the early 1930s, radar technology has evolved significantly. During this time, researchers have reduced the size, power consumption and cost dramatically, while increasing resolution and enhancing the algorithmic computational capabilities. Development and advances in IC technology have enabled a class of low-power and short-range mmWave radars with carrier frequencies in the 30 to 300 GHz range (10 to 1 mm wavelength), adding to the mass of wireless applications pervading society. Today, radars are embedded in a number of cars, as parking aids or for safety, detecting pedestrians, other road users and objects at a few meters.

These high frequency radars with small form factors can be integrated almost invisibly in numerous devices, to enable a broad range of smart and intuitive applications, such as building security (e.g., people counting and intruder detection), remote health monitoring of automobile drivers, monitoring the vital signs of patients and gesture recognition for intuitive man-machine interaction. The number of use cases will imminently grow as radar systems offer finer range resolution, smaller footprint, higher energy efficiency and lower cost.

A MULTITUDE OF FLAVORS

Although all radar systems follow the same basic principle, their various implementations determine the cost, size, power consumption and capability. Radars can differ by the frequency of the carrier (e.g., 2.4, 8, 60, 79, 140 GHz), bandwidth, type of carrier modulation (e.g., frequency or phase) and pulsed or continuous wave (CW). By necessity, small radars with high resolution operate at high carrier frequencies with wide bandwidth. As resolution is inversely proportional to bandwidth, radar systems operating above 100 GHz can offer very broadband operation, which enables fine range resolution. A Doppler shift is observed as a change in frequency of the wave reflected from a target, when the source and target are moving closer together or further apart. This shift can be measured more precisely at higher frequencies to provide a more exact determination of a target's velocity.

In time, data from multiple sensors—which may add LiDAR, hyperspectral imagers, infrared cameras and ultrasonic sensors to radar—will be merged on a common platform, each offering advantages and having limitations. Radar technology is an environmentally robust solution and can serve as an alternative to optical image sensors


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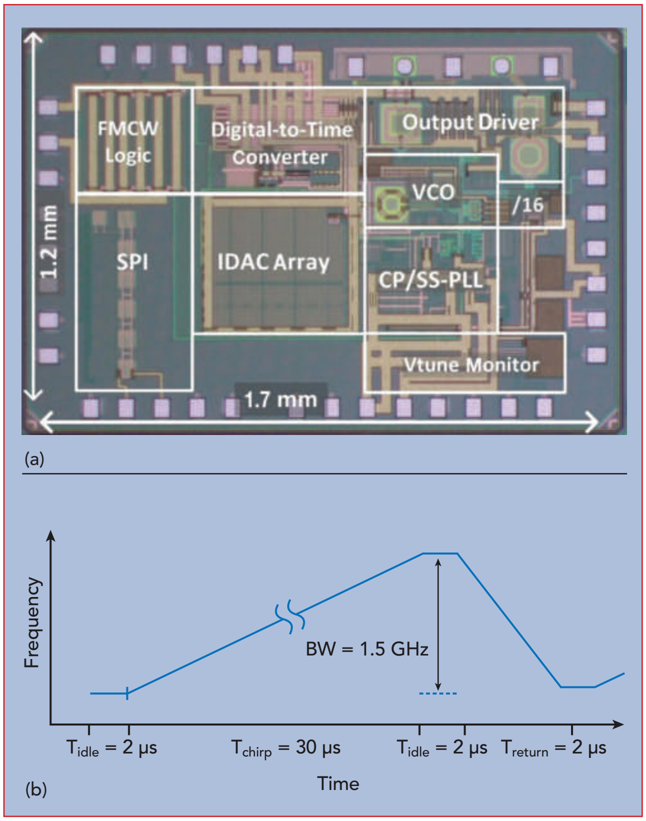


Fig. 1 16 GHz FMCW PLL IC (a) and chirp modulation response (b).

when privacy concerns or regulations prohibit using cameras. Supplementing the development of radar sensor technology, advances in physical pattern recognition are driving advanced machine learning techniques to classify objects or gestures using radar Doppler signatures.

140 GHz FMCW RADAR TRANSCEIVER IC

Targeting vital sign detection and gesture recognition, imec has developed a 140 GHz FMCW radar transceiver with on-chip antennas. The radar operates over a range from 0.15 to 10 m and has 11 mm range resolution, achieved with 13 GHz of RF bandwidth centered at 145 GHz. The transceiver IC is fabricated with a production 28 nm bulk CMOS technology, which enables a low-cost solution.

The main building block of the radar is an integrated transceiver featuring on-chip antennas and a sub-sampling digital phase-locked loop (PLL), which forms the FMCW chirp generator. Antennas integrated on the same chip couple with each other, resulting in leakage between the transmit (Tx) and receive (Rx) paths; however, the radar features on-chip leakage cancellation in the receiver to circumvent this effect, which can result in gain compression and DC offsets. The radar receiver measures the difference between the frequency of the reflected and transmitted RF chirps. This frequency difference is translated into the MHz range, making amplification, filtering and analog-to-digital conversion much easier than with other radar waveforms (e.g., phase-modulated CW).

The PLL generates a frequency modulated CW signal, where the carrier frequency is modulated over a wide bandwidth using a linear sawtooth waveform. The repetition rate of the modulating sawtooth is known as the chirp rate. Imec has developed and characterized a 16 GHz, fast chirping PLL fabricated with a 28 nm bulk CMOS process (see ***Figure 1a***). This PLL can operate both in a classical mode as well as a divider-less sub-sampling mode, offering flexibility and high performance. The PLL achieves a wide chirp bandwidth of 1.5 GHz in only a 30 μs chirp period, allowing fast sawtooth frequency modulation (see ***Figure 1b***).

Multiple transceiver ICs were

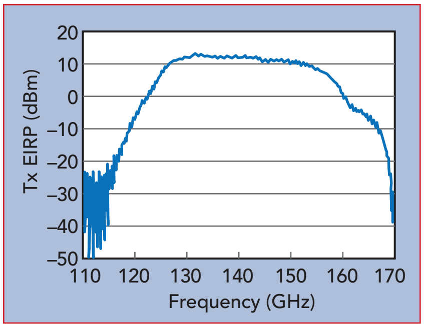
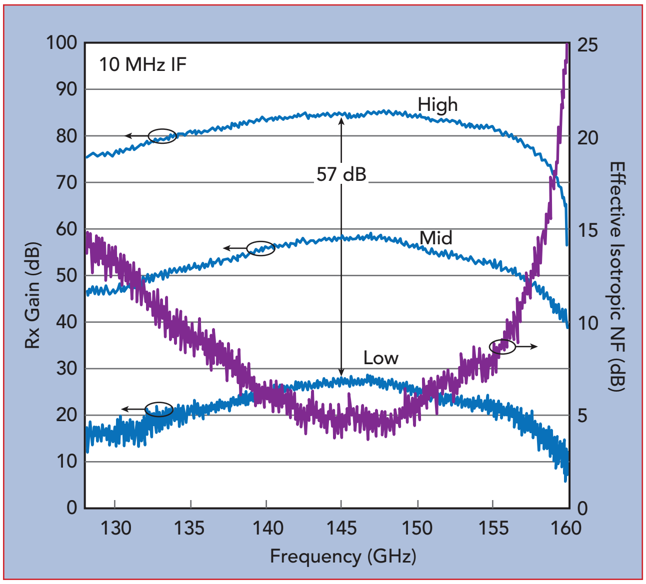


Fig. 2 Transmitter EIRP.

used to create a 2×2 MIMO radar, augmenting the range and speed detection capabilities of a single-input-single-output radar. MIMO increases the azimuth angular resolution, providing additional information to resolve target orientation.

In the MIMO configuration, a central 16 GHz chirp signal is distributed to multiple Tx inputs. The signal is up-converted to 144 GHz using a cascade of two frequency triplers, after which it is amplified and transmitted via the on-chip antennas. The radiated chirp is reflected by targets broadside to the antennas and captured by the on-chip receiver. The reflected signal is amplified in the receiver and compared with a replica of the initial chirp signal, using a mixer. The delay of the received signal, corresponding to the time-of-flight to the target and back, results in an instantaneous frequency offset compared to the reference chirp. The greater the distance to the target, the greater the relative frequency shift and the range of the target is obtained from the frequency of the down-converted signal. The analog output from the receiver is converted to a digital signal, enabling signal processing to extract the range and speed.



▲ Fig. 3 Receiver gain and effective isotropic noise figure.

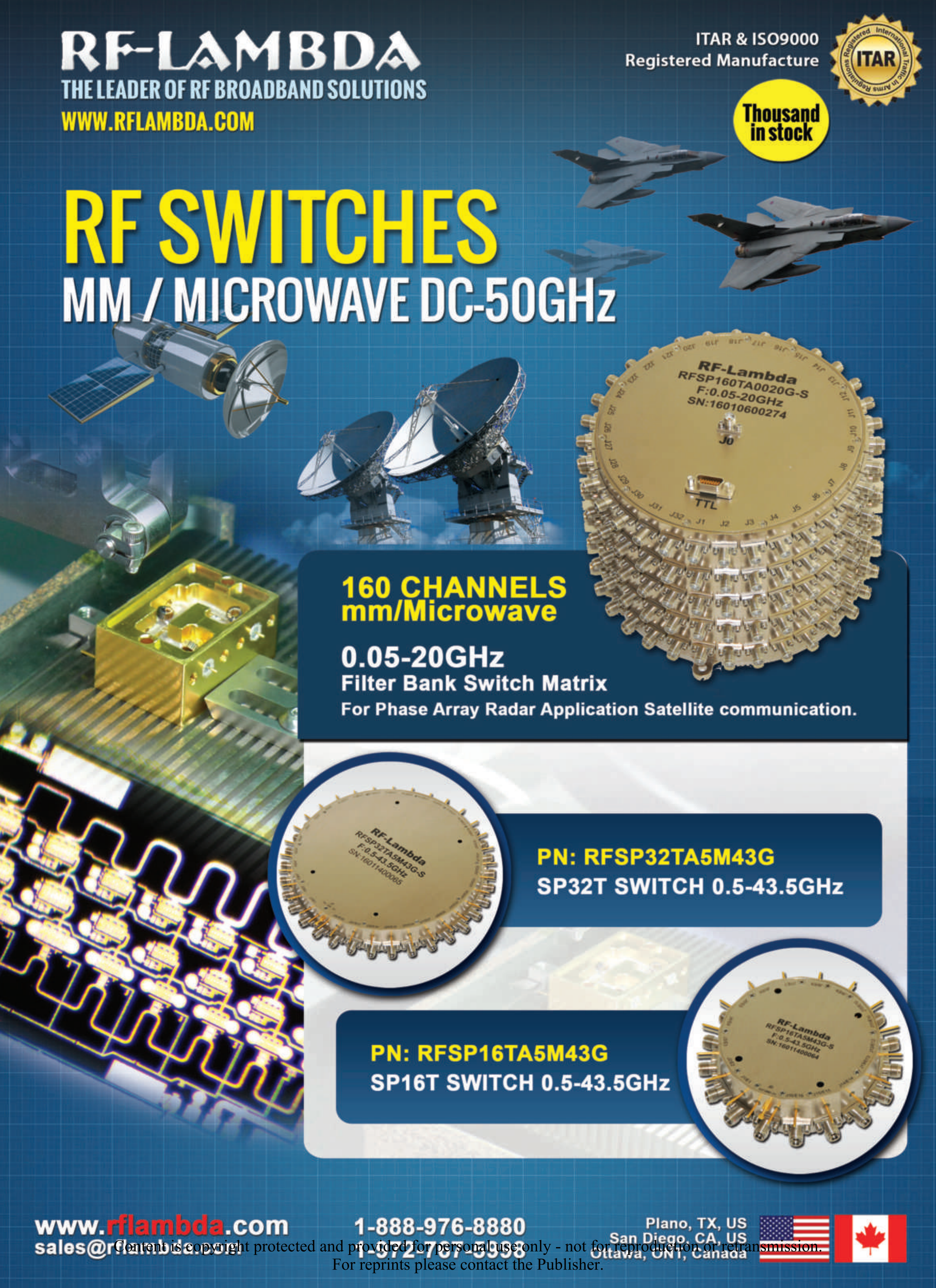
The transmitter is characterized by its effective isotropic radiated power (EIRP). For the integrated 140 GHz prototype, the measured EIRP is as high as 11 dBm and has a 3 dB bandwidth from 127 to 154 GHz (see ***Figure 2***). This is the highest recorded EIRP in D-Band for a single integrated transceiver compared to currently published state-of-the-art ICs (see ***Table 1***). The receiver's performance is characterized by its noise figure and conversion gain: 8 and 84 dB, respectively (see ***Figure 3***). The total power consumption of the radar transceiver IC is less than 500 mW.

TABLE 1

SINGLE CHIP mmWAVE RADAR TRANSCEIVERS

Reference	This Work	Wuppertal, Trans. THz 2016[1]	TI, JSSC 2014[2]	TI, ISSCC 2018[3]	IHP, IMS 2016[4]	I. Nasr, Google, IFX, JSSC 2016
Technology	28 nm CMOS	0.13 µm SiGe	65 nm CMOS	45 nm CMOS	0.13 µm SiGe	0.35 µm SiGe
Radar Type	FMCW	FMCW	Pulsed	FMCW	FMCW	FMCW
Antenna	On Chip	On Chip	In Package	In Package	On Chip	In Package
Frequency (GHz)	145	240	160	79	122	60
RF Bandwidth (GHz)	13	60	7	4	5.8	7
Range Resolution (cm)	1.1	0.3	2.1	3.8	2.6	2.1
Channels	1Tx-1Rx	1Tx-1Rx	4Tx-4Rx	3Tx-4Rx	1Tx-1Rx	2Tx-4Rx
Single Path Tx Power/EIRP (dBm)	11.5 (EIRP)	5	4	10.8	5	4
Rx Gain (dB)	80	10	42.5	NA	NA	19
Noise Figure (dB)	8	21	22.5	18	NA	9.5
IF Bandwidth (MHz)	17	18	100	15	NA	1
Chip Size (mm^2)	6.5	3.2	20	22	10.35	20.2
Power Diss. for All Channels (mW)	500	1800	2200^{+0}	3500^{++}	NA	990^{x}

$^{+}$Includes On-Chip PLL and ADC
$^{++}$Includes On-Chip PLL, ADC and DSP
^{0}Power Dissipation in Pulsed Operation
^{x} RF Front-End Only with On-Chip VCO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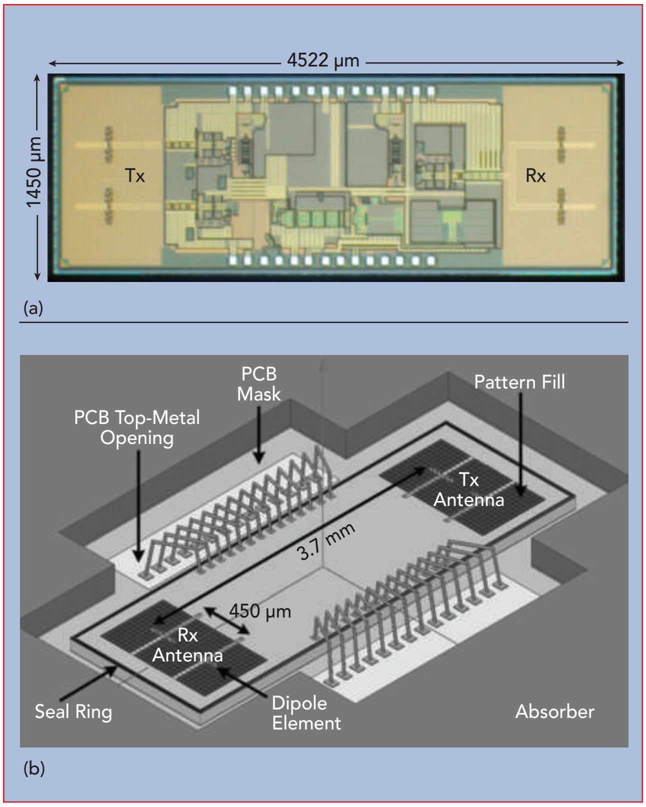

Fig. 4 Transceiver IC (a) and packaging (b), showing the Rx and Tx antennas integrated on opposite sides of the IC.

Radars with frequencies below 100 GHz require large off-chip antennas, which are usually fabricated on high frequency laminates and attached to the IC via flip-chip or wire bond interfaces. Developing and implementing these complex antenna-on-package modules significantly contributes to the cost and size of the final radar system. However, the higher the frequency of the carrier—the smaller its wavelength—the more the size of the antenna element is reduced. For carrier frequencies above 100 GHz, the antenna is sufficiently small that it can be integrated on the radar chip. This antenna-on-chip solution offers clear size and cost advantages compared to off-chip antennas on printed circuit boards (PCB). When integrated on-chip, there is no need for mmWave transitions between the IC and PCB that ultimately degrade bandwidth and signal strength. In this design, the antenna elements were integrated into the passivation layer of the transceiver, with the Tx and Rx antennas 2 mm apart to minimize crosstalk (see ***Figure 4***).

For many applications, including gesture recognition, high angular resolution is needed to capture gestures in three dimensions. This can be accomplished with MIMO radar, as they transmit mutually orthogonal signals from multiple Tx antennas, which are then extracted from each of the Rx antennas. Imec has demonstrated a 1×4 virtual array with three transceiver ICs, including two transmitters and two receivers, resulting in a 2×2 MIMO assembly shown in ***Figure 5***. The configuration is called "1×4 virtual" because the angular resolution corresponds to the resolution obtained by the four elements in a row. In this configuration, the central chirp signal is distributed to the separate transceiver chips on a PCB. Using the super-resolution MUSIC algorithm, a fine angular resolution of 7.5 degrees is achieved with a complete MIMO radar form factor of only a few square centimeters.

VITAL SIGN DETECTION AND GESTURE RECOGNITION

Two main applications are envisioned for the 140 GHz MIMO radar: vital sign detection and gesture recognition.

The feasibility of detecting vital signs in real-time, including monitoring heart rate and breathing, have been demonstrated. The 1×4 MIMO radar captured the 1 and 5 Hz beats of a "reference heart"—a speaker diaphragm with 1 mm displacement—as shown in ***Figure 6a***. In a second experiment, the feasibility of measuring micro-skin motion in real-time, which reflects a person's respiration and heartbeat,

was demonstrated (see ***Figure 6b***). In the future, greater processing capability will enable more accurate distinctions between heartbeat and respiration.

A portable 1×4 MIMO radar demonstrator is currently being built to measure vital signs in real-time. To capture gestures and motion, the radar must have high angular resolution, which is achieved with larger MIMO arrays. A 4×4 virtual MIMO radar, realized by one row and one column of four transceiver ICs each, is currently being developed and will be complemented with additional processing capabilities for micro-Doppler information and machine learning techniques. Machine learning will train the system using classified data to recognize the Doppler signatures of moving objects.

SUMMARY

An extremely compact, fully integrated 140 GHz FMCW radar transceiver in 28 nm CMOS has been demonstrated. Centered at 145 GHz and up-converted from a 16 GHz PLL chirp signal, an RF bandwidth of 13 GHz yields 11 mm range resolution. The IC contains Tx and Rx signal paths and integrated antennas. For the transmitter, a record EIRP of 11 dBm from a single element was measured, while the receiver achieved a noise figure and conversion gain of 8 and 84 dB, respectively. In a 2×2 or 1×4 virtual MIMO configuration, fine angular resolution was achieved. These features enable the radar to detect vital signs and gestures. Imec is currently building portable demonstrators to further show the capability of its 140 GHz MIMO radar systems.

Imec is also developing other compact and low-cost radar sensing solutions for IoT applications, including 8, 60 and 79 GHz CMOS-based radars. The ICs are designed to achieve state-of-the-art performance while avoiding "specialty" semiconductor technologies.■

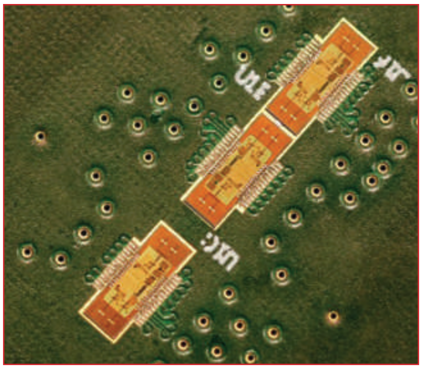

Fig. 5 MIMO radar board with three transceiver ICs.

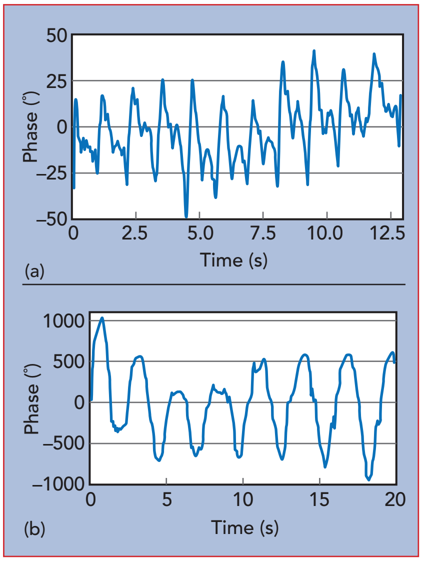

Fig. 6 MIMO radar vital sign measurements: reference heartbeat (a) and skin motion reflecting heartbeat and respiration (b).

ACKNOWLEDGMENT

The authors thank Panasonic and Sony for their support.

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Broadband Power Amplifier Design Using Extended Resistive-Reactive Continuous Class F Modes

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Institute of Microelectronics Chinese Academy of Sciences and University of Chinese Academy of Sciences, Beijing, China

This article describes an approach to extend the bandwidth of power amplifiers (PA) designed using resistive-reactive series of continuous class F modes (SCFM). By introducing third harmonic loads to the resistive-reactive SCFM PA, the overlap between the fundamental and harmonic impedances is solved and the operating bandwidth extended. Using this approach, a 0.5 to 2.3 GHz high efficiency PA was designed, with experimental results achieving 10 W output power and 59 to 79 percent drain efficiency from 0.5 to 2.3 GHz.

With the rapid development of wireless communications technology, next-generation wireless systems need wider bandwidth to achieve higher data rate transmission. As a key transmitter element, PAs are required to work more efficiently, over broader bandwidths and handle multiple standards.

In recent years, much research has explored improving the bandwidth and efficiency of PAs. In 2009, S. C. Cripps proposed the continuous mode PA to solve the bandwidth limitation of traditional switch-mode PAs, by properly introducing reactive second and third harmonic impedances.[1] Continuous class B/J, continuous class F and class F^{-1} modes were subsequently proposed.[2-6] In theory, the maximum bandwidth of continuous class B/J, continuous class F and class F^{-1} PA modes is restricted to an octave due to harmonic impedances at the edge of the Smith chart. Thus, the rigorous requirements of harmonic loads created difficulty realizing multi-octave performance. The resistive-reactive series of continuous modes was proposed by Lu and Chen in 2013[7] to relax the strict demands of harmonic loads, introducing resistive harmonic impedances to the continuous modes.[8-9] With this approach, the bandwidth can exceed an octave by introducing resistive second harmonic loads and a more extensive fundamental impedance space, extending the bandwidth of broadband PAs. The resistive-reactive series of inverse continuous modes PA proposed by Li et al.[9] illustrates similar properties for the design of broadband PAs.

In this article, an extended mathematical formula is applied to the resistive-reactive SCFM. The design space is further extended by introducing third harmonic impedances, providing more freedom when designing high efficiency multi-octave PAs.

EXTENDED RESISTIVE-REACTIVE SCFM

The traditional resistive-reactive SCFM has a half-wave rectified sinusoidal current waveform, $i_{ds}(\theta)$, at the intrinsic current generator plane of the device:

$$i_{ds\_SCFMs} = \frac{1}{\pi} + \frac{1}{2}\cos\theta + \frac{2}{3\pi}\cos 2\theta + L \quad (1)$$

The voltage waveform, $v_{ds}(\theta)$, is no longer rigorously restricted to a square waveform and includes a set of variations dependent on the parameters α and γ:

$$v_{ds}(\theta) = \left(1 - \frac{2}{\sqrt{3}}\cos\theta + \frac{1}{3\sqrt{3}}\cos 3\theta\right)(1-\gamma\sin\theta) \times (1+\alpha\cos\theta) \quad (2)$$

Resistive third harmonic impedances are introduced by multiplying the current waveform of the resistive-reactive SCFM by the factor $(1+\beta\cos\theta)$, while the voltage waveform remains unchanged. The new current waveform is represented by:

$$i_{ds} = \left(\frac{1}{\pi} + \frac{1}{2}\cos\theta + \frac{2}{3\pi}\cos 2\theta\right)(1+\beta\cos\theta) \quad (3)$$

Alternative impedance solutions with resistive second and third harmonic impedances can be obtained. The load impedance to be presented at each harmonic is calculated by dividing the voltage by the current. Here, Z_n is designated as the n^{th}-order harmonic impedance. Thus, the normalized harmonic impedances can be calculated from:

$$Z_1 = 3\sqrt{3}\pi \left(\left(\frac{2}{\sqrt{3}} - \alpha\right) + j\left(1 - \frac{7}{12\sqrt{3}}\alpha\right)\gamma\right) / (6\pi + 16\beta) \quad (4)$$

$$Z_2 = 3\sqrt{3}\pi \left(\frac{5}{6\sqrt{3}}\alpha + j\frac{1}{2}\left(\frac{7}{3\sqrt{3}} - \alpha\right)\gamma\right) / (8 + 3\pi\beta) \quad (5)$$

$$Z_3 = -3\sqrt{3}\pi \left(\frac{1}{3\sqrt{3}} + j\frac{1}{2\sqrt{3}}\alpha\gamma\right) / 4\beta \quad (6)$$

The feasibility of Z_1, Z_2 and Z_3 depends on the conditions

$$0 \le \alpha \le 1 \text{ and } \frac{-8}{3\pi} \le \beta \le 0$$

being fulfilled. ***Figure 1*** illustrates the variation of the fundamental and harmonic impedances vs. α and β. The second harmonic region moves toward the fundamental region with variation of α and β, and the third harmonic region approaches the fundamental region with decreasing β. This characteristic makes solving the overlap between the fundamental and harmonic impedances in a multi-octave design possible.

Drain efficiency can be calculated from Equations 2 and 3 as:

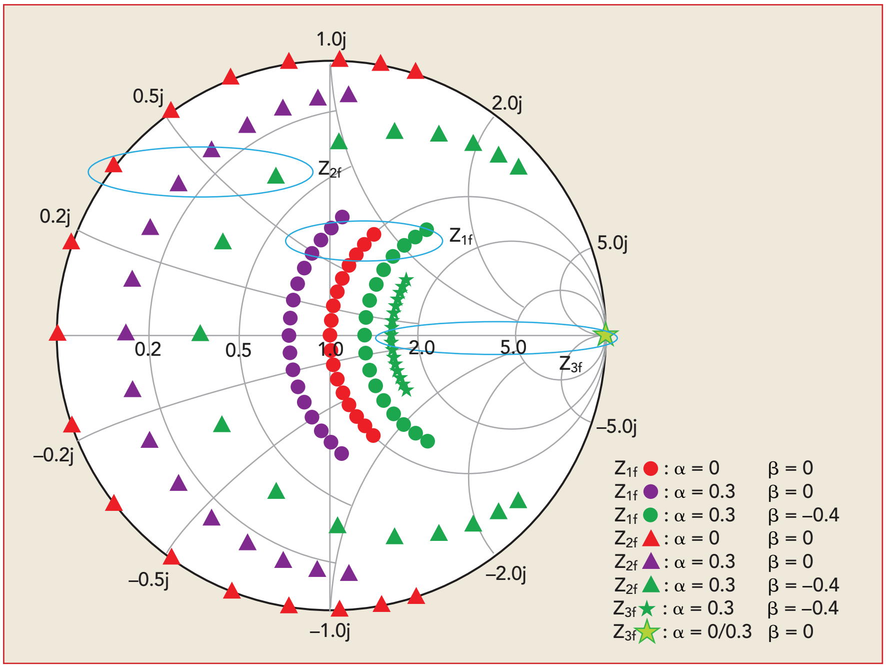


Fig. 1 Fundamental and harmonic impedances vs. α and β.

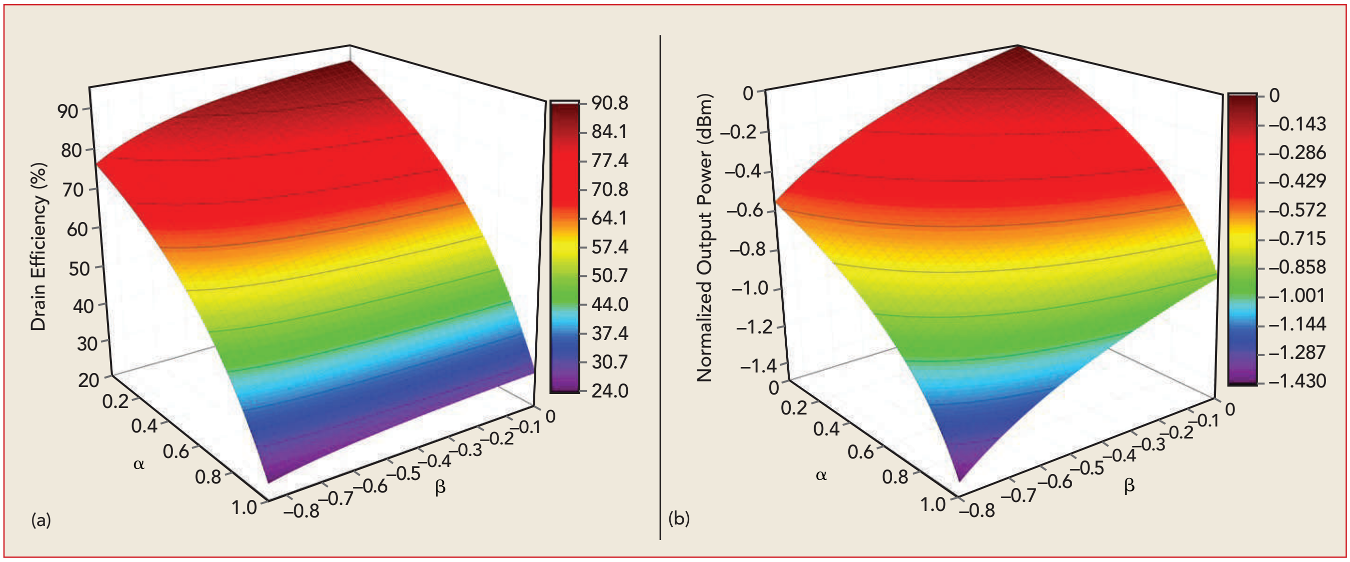


Fig. 2 Drain efficiency (a) and normalized output power (b) vs. α and β.

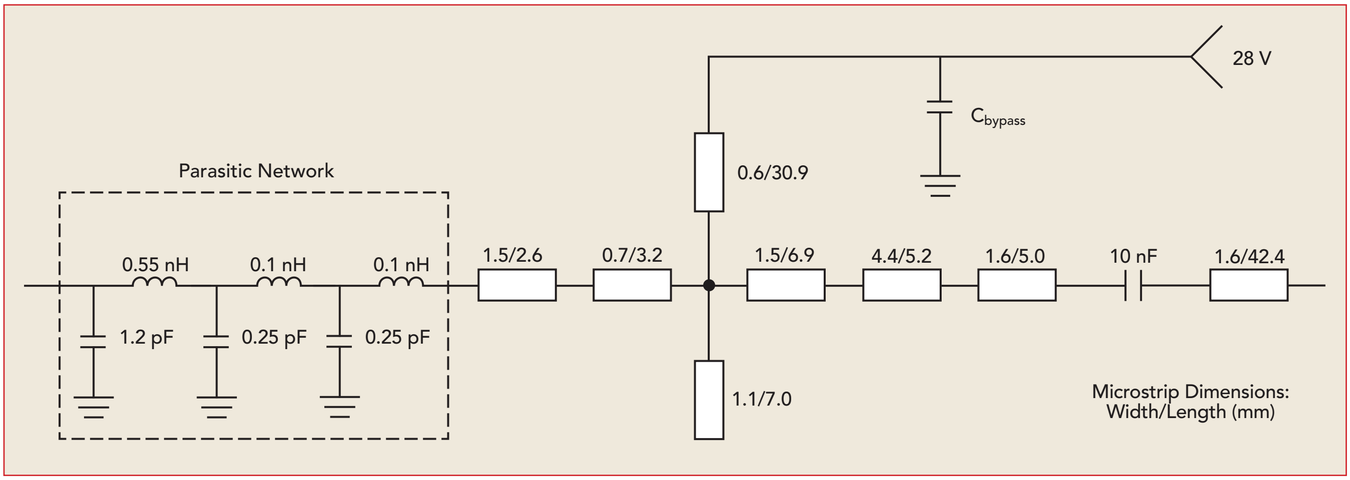
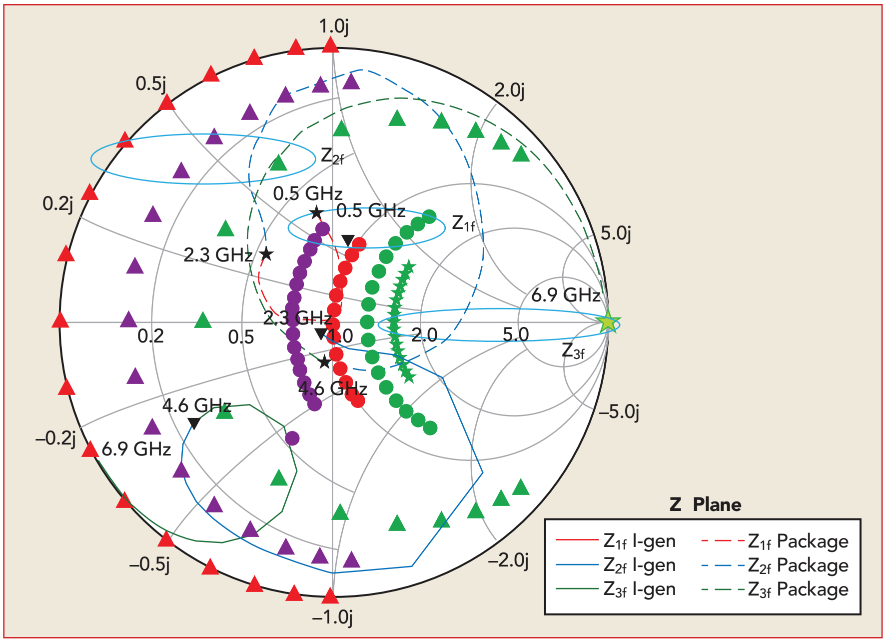


Fig. 3 Output matching network.



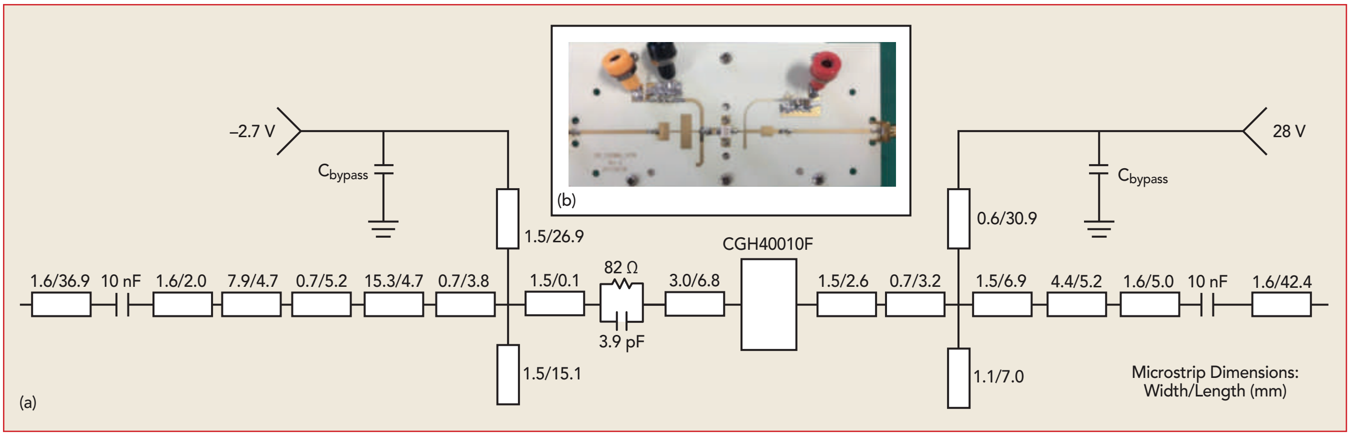
▲ **Fig. 4** Fundamental and harmonic impedances at the I-gen and package planes.

$$DE = \frac{2-\sqrt{3\alpha}}{\sqrt{3-\alpha}} \times \frac{3\pi + 8\beta}{12 + 3\pi\beta} \tag{7}$$

Drain efficiency is a function of α and β. The variation of drain efficiency and output power with respect to α and β are shown in ***Figure 2***. The variation of α and β should be restricted within a limited region to achieve acceptable drain efficiency with a slight degradation of output power. In this work, the conditions of $0 \leq \alpha \leq 0.4$ and $-0.4 \leq \beta \leq 0$ are selected to achieve drain efficiency greater than 65 percent.

SIMULATION AND MEASUREMENT

To verify the effectiveness of this approach, a 0.5 to 2.3 GHz resistive-reactive SCFM PA was designed us-



▲ **Fig. 5** PA schematic (a) and prototype (b).

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APD-2-2G18G-SFF-1W https://www.pmi-rf.com/product-details/apd-2-2g18g-sff-1w	2 - 18 GHz (Operates from 0.1 to 22 GHz)	15	1.0	0.3	3	1.625" x 1.0" x 0.38" 2-Way / SMA (F)
APD-2-218-FD https://www.pmi-rf.com/product-details/apd-2-218-fd	2 - 18 GHz	16	1.5	0.5	2.5	1.58" x 1.00" x 0.40" 2-Way / SMA (F)
APD-4-2G26G-292FF-1W https://www.pmi-rf.com/product-details/apd-4-2g26g-292ff-1w	2 - 26 GHz	15	2.25	0.5	6	3.0" x 2.0" x 0.375" 4-Way / 2.92mm (F)
APD-2-18G40G-20W-292FF https://www.pmi-rf.com/product-details/apd-2-18g40g-20w-292ff	18 - 40 GHz	18	1.5	0.3	4	1.06" x 0.85" x 0.5" 2-Way / 2.92mm (F)
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APD-8-30M6G-SFF https://www.pmi-rf.com/product-details/apd-8-30m6g-sff	30 MHz - 6 GHz	-8 / 32	6.5	+10	+15 V @ 100 mA	4.5" x 4.3" x 0.5" 8-Way / SMA (F)
APD-8-100M-28V https://www.pmi-rf.com/product-details/apd-8-100m-28v	100 MHz	-5.5 / 25	9.0	+13	+28 V @ 750 mA	4.0" x 2.0" x 0.55" 8-Way / SMA (F)


APD-2-18G40G-20W-292FF

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APD-8-30M6G-SFF


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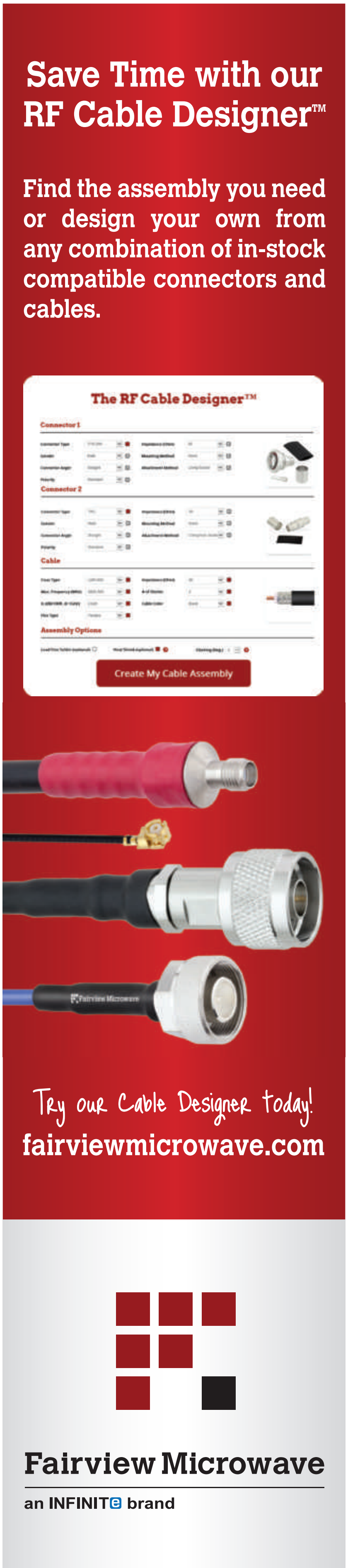


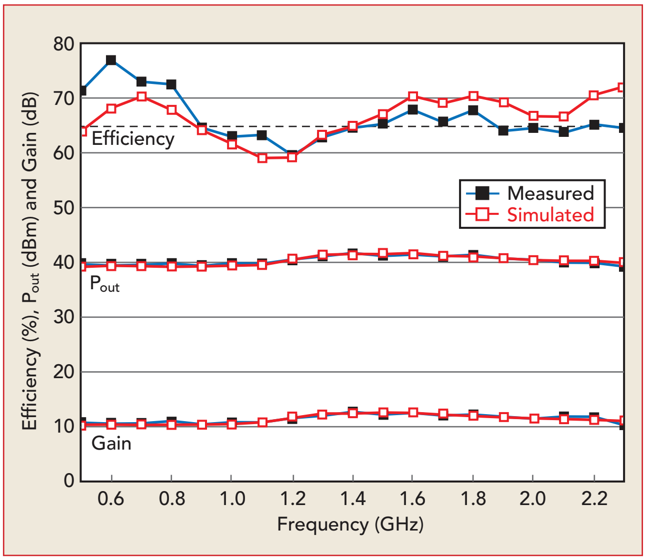
ing a Wolfspeed CGH40010F GaN transistor, operating at a quiescent drain bias of 28 V and of 68 mA, and a 30 mil thick Rogers 4350B substrate (ε_r = 3.66) with a conductor thickness of 35 μm.

The optimum load impedances were obtained by harmonic load-pull simulation using an iterative process from high to low frequency, where the impedance obtained at the high frequency was used to terminate the low frequency harmonic. This was repeated until the optimum load impedances were obtained. The output matching network was designed using the real frequency direct computational technique.[10] ***Figure 3*** shows the broadband output matching network for this design. Due to the small effect of input harmonic impedance on performance,[11] when designing the input matching network, more attention was paid to fundamental matching.

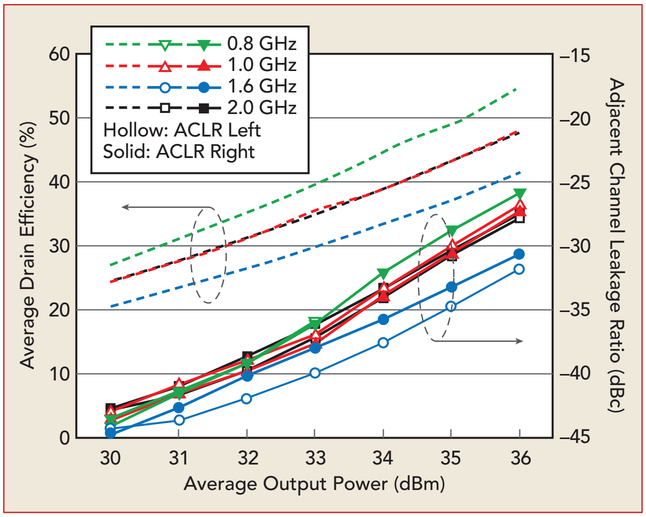
A precise model of the parasitic network for the widely used CGH40010F transistor has been derived and reported by Tasker and Benedikt.[12] Based on this parasitic network model, the impedance trajectories in the Smith chart at I-gen and at the package plane of the output matching network are shown in ***Figure 4***. The derived fundamental impedances at the current plane across the operating band from 0.5 to 2.3 GHz are in or near the theoretic region.

The final design of the resistive-reactive SCFM PA is shown in ***Figure 5***. Simulated and measured results with a CW input power of 29 dBm are shown in ***Figure 6***. A drain efficiency of 59 to 79 percent and saturated output power of 39.4 to 41.6 dBm are achieved across the band from 0.5 to 2.3 GHz. The measured results are consistent with the simulations.

To characterize linearity, a 20 MHz LTE signal with a peak-to-average power ratio of about 7.5 dB was used to drive the PA at 0.8, 1, 1.6 and 2 GHz. As shown in ***Figure 7***, the broadband PA exhibits good linearity at about 5 dB back-off power, where the adjacent channel leakage power ratio (ACLR) is lower than −30 dBc, with 34.1 to 49.1 percent average efficiency. ***Table 1***



▲ Fig. 6 Simulated vs. measured output power, efficiency and gain.



▲ Fig. 7 Measured average drain efficiency and ACLR with 20 MHz LTE signal.

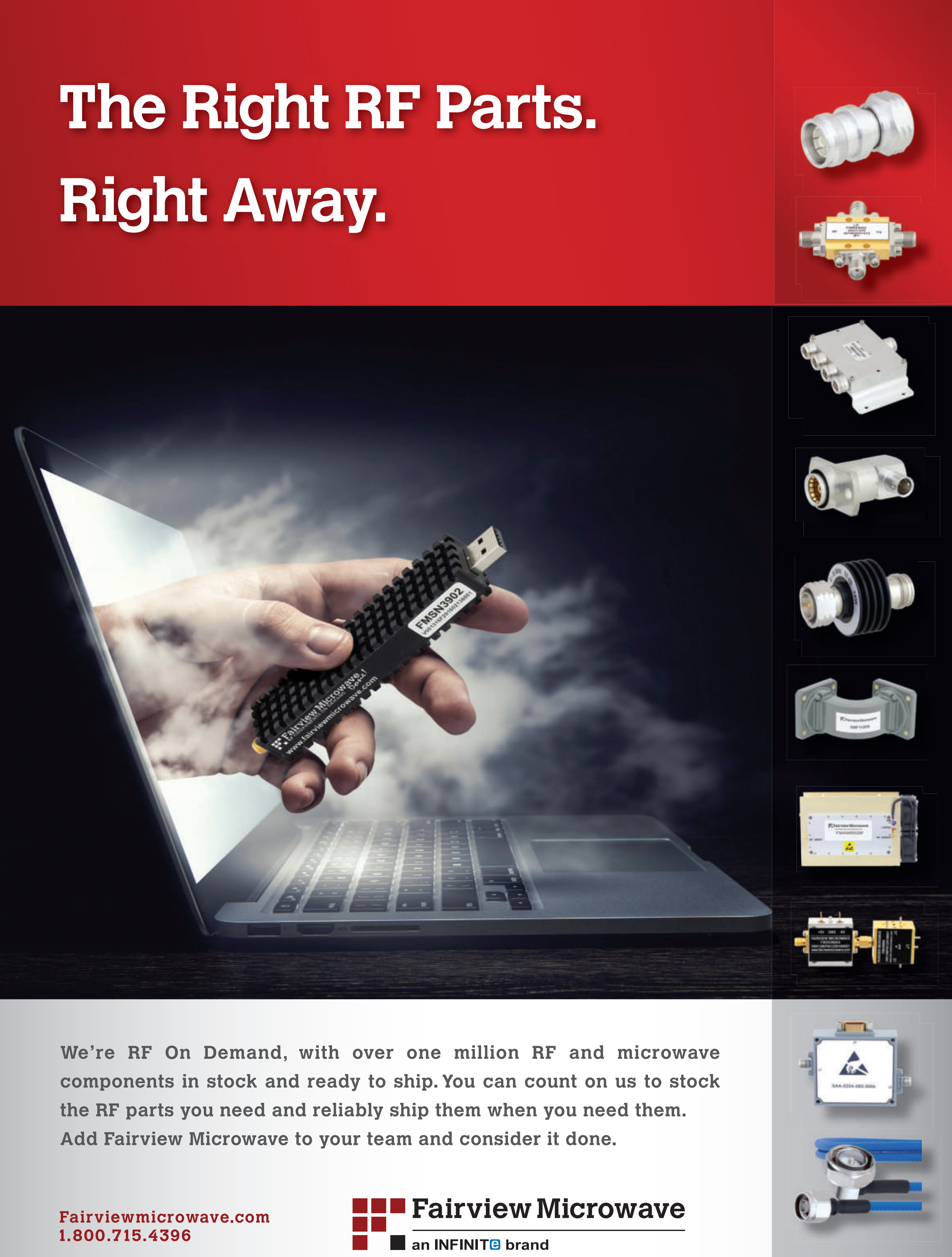

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TABLE 1
PA COMPARISON

Reference	Mode	Bandwidth (GHz) (%)	P_{out} (dBm)	Drain Efficiency (%)
3	SCM	1.6 to 2.8 54.5	39.1 to 41.5	67 to 82
6	SCIM	2.4 to 3.9 47.6	39.9 to 41.3	62.2 to 75
8	Res.-Rea. SCM	0.5 to 1.3 88.9	39.0 to 41.4	70 to 87
9	Res.-Rea. SCIM	2.4 to 3.75 44	40.8 to 42.2	66 to 71
This Work	Res.-Rea. SCFM	0.5 to 2.3 129	39.4 to 41.6	59 to 79

compares the performance of this PA with other similar state-of-the-art broadband PAs.

CONCLUSION

The resistive-reactive SCFM design space was extended by introducing the third harmonic impedance. Using this methodology, the overlap between the fundamental and harmonic impedances was effectively solved, and a broadband high efficiency PA was designed, built and tested. The agreement between simulation and measurement demonstrates the validity of this approach for a multi-octave, high efficiency PA. Driven by 20 MHz LTE signals, the ACLR of the proposed PA is lower than −30 dBc at approximately 35 dBm output power, with average drain efficiency higher than 34 percent.■

ACKNOWLEDGMENTS

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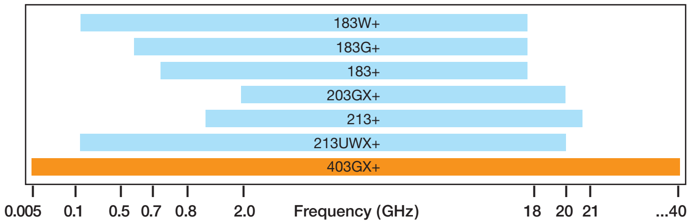
Wideband Performance



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INVITED PAPER

Adopting the 64 to 71 GHz Band for Fixed Wireless Applications

Sivers IMA
Kista, Sweden

The 60 GHz band (57 to 64 GHz) has long been recognized as ideal for dense urban data networks because of its large capacity combined with excellent spectrum reuse, due to oxygen absorption. The use of phased array antenna technology enables novel mesh network architectures and significantly reduces the size and cost of equipment, compared to conventional fixed antenna technology, but its reduced range limits some applications. Recent regulatory decisions have opened up additional spectrum from 64 to 71 GHz. This article explores the absorption characteristics across the newly widened band and discusses the applications enabled by commercial transceiver RFICs covering the expanded frequency range from 57 to 71 GHz.

National regulators, responsible for allocating spectrum to different users, must balance competing commercial and government interests. The frequency allocations that the regulators make are determined by the type of application and its needs, such as bandwidth and propagation. The historic use of the band must also be considered. As spectrum needs are common among nations, and spectrum usage has spillover effects across borders, spectrum allocation is necessarily harmonized at the supra-national level by organizations such as the European Conference of Postal and Telecommunications Administrations (CEPT) and the International Telecommunication Union (ITU).

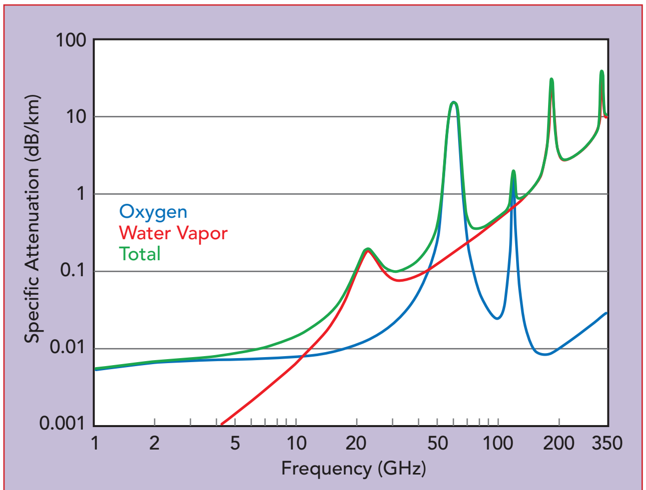

Fig. 1 Specific attenuation vs. frequency from 1 to 350 GHz.

Bands with impairments—such as high attenuation due to water or oxygen absorption—are typically less useful for traditional communications applications. Therefore, regulators have opened them with the intent to enable new applications. The results are often unexpected and transformational: think of cordless phones in the 900 MHz band and Wi-Fi at 2.4 and 5 GHz. Regulators evaluated the same considerations when they allocated the 60 GHz band for unlicensed use.

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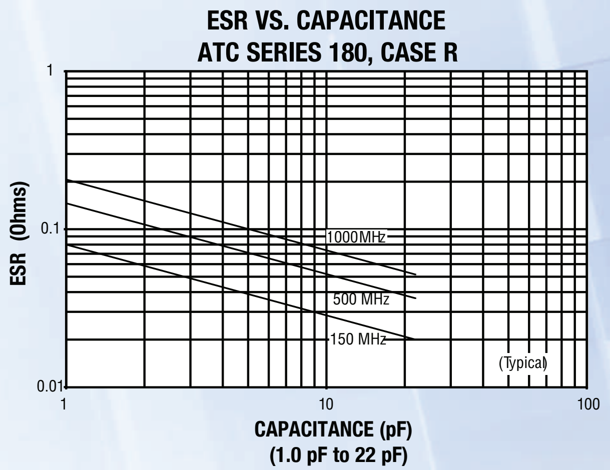

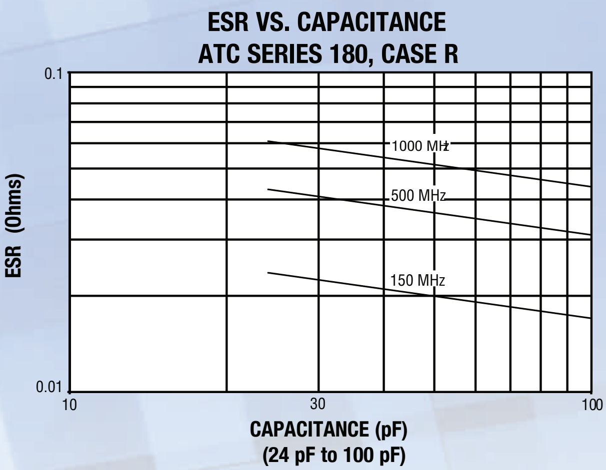

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To assist with spectrum allocation, the ITU has published ITU-R P.676-11, "Attenuation by Atmospheric Gases," which estimates the attenuation due to oxygen and water vapor under different conditions and across the frequency range from 1 to 350 GHz (see ***Figure 1***). Annex 2 of the recommendation provides a simplified approximate method to estimate gaseous attenuation applicable to the full frequency range. The 57 to 64 GHz band coincides with an oxygen absorption peak, which reaches a maximum of approximately 15 dB/km at 60 GHz (see ***Figure 2***, which shows more detail). The attenuation in this band is substantially greater than observed for other bands in the low mmWave part of the spectrum, which makes it ideal for short-range applications.

The Federal Communications Commission (FCC) allocated the band from 59 to 64 GHz for unlicensed use in 1995. In 2001, the FCC added spectrum from 57 to 59 GHz, providing a total of 7 GHz for unlicensed use. In 2009, CEPT/ECC/Recommendation (09)01, "Use of the 57 to 64 GHz Frequency Band for Point-to-Point Fixed Wireless Systems," allocated the same band for unlicensed use, subject to implementation by the national regulators of the 48 CEPT member states.

CHARACTERISTICS OF THE 57 TO 64 GHz BAND

Allocating a substantial contiguous band enables it to be divided into multiple wide channels, which provides for very high data capacity. For example, by using the IEEE 802.11ad channelization, which divides the band into channels of 2.16 GHz with an occupied bandwidth of 1.76 GHz, bit rates up to 4.62 Gbps using 16-QAM single carrier modulation and 8.085 Gbps using 64-QAM single carrier modulation can be achieved. As noted, the 57 to 64 GHz band coincides with the oxygen absorption peak, with a maximum of approximately 15 dB per kilometer at 60 GHz. ***Figure 3*** overlays the atmospheric attenuation for 802.11ad channels 1 through 3, showing the attenuation peaks in channel 2. Channels 1 and 3 experience similar attenuation, meaning the impact on link range is broadly the same for all three channels.

The maximum distance for a radio link to be reliably operated is defined as the point where the system gain—the transmit power measured as EIRP minus the nominal receiver sensitivity—equals the loss from atmospheric attenuation plus effects such as the absorption by

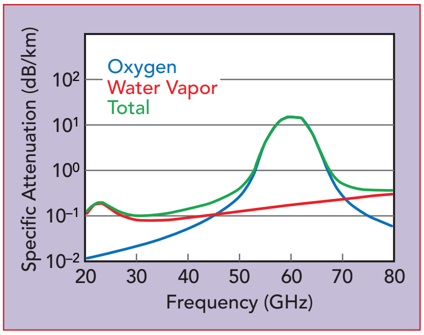


Fig. 2 Specific attenuation from 20 to 80 GHz.

TABLE 1

LINK DISTANCE FOR A 16 Tx, 16 Rx TRANSCEIVER ON IEEE 802.11ad CHANNEL 2

		Modulation and Coding		
	Units	MCS 8 QPSK	MCS 12 16-QAM	MCS 12.3 64-QAM
Maximum Average EIRP	dBm	40	40	37
Nominal Sensitivity	dBm	–89	–82	–77
System Gain	dB	129	122	114
Distance (Ch 2)	m	400	260	135
Distance (Ch 2), No Rain	m	460	290	150

rain or reflections from the ground, buildings or other objects. For this analysis, assume rain losses for rain zone K (e.g., Chicago, Beijing or New Delhi) and availability of 99.9 percent, per ITU recommendation ITU-R PN.837-1, "Characteristics of Precipitation for Propagation Modeling."

For phased array implementations, the maximum average EIRP is typically limited by regulation to 40 dBm. The receiver's sensitivity is derived from the per-element sensitivity and the gain of the antenna array. In this example, an array of 16 receive (Rx) elements is modeled, using the performance of a commercially available transceiver RFIC (see ***Sidebar***, pg. 82) connected to antennas with a per-element gain of 11 dBi. In principle, RF transceiver ICs can be tiled for greater performance; however, as the transmit power often reaches the regulatory cap, the benefit of tiling is mainly in receiver sensitivity. For a link operating in channel 2, the maximum link distance with a single transceiver using various modulation and coding schemes (MCS) is shown in ***Table 1***. The high specific attenuation in these channels yields relatively short link distances, especially at the higher bit rates requiring higher order modulation.

The range of the link corresponds to one or two city blocks, ideal for dense networks in urban areas where nodes are closely spaced in point-to-multipoint (PTMP) or mesh architectures. With careful channel allocation, these links can reuse the spectrum across an urban area without self-interference or causing interference to other networks. This capability enables a variety of use cases:

- Fixed wireless broadband, both backhaul and access.
- Outdoor Wi-Fi backhaul.
- Small cell backhaul.
- Video surveillance backhaul.
- Smart city IoT backhaul.

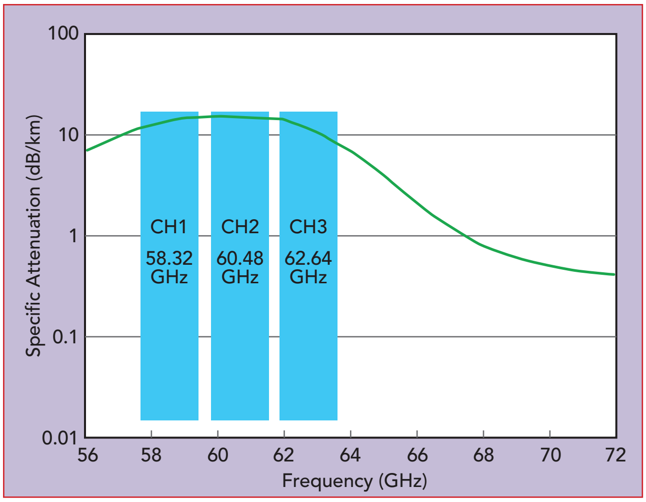
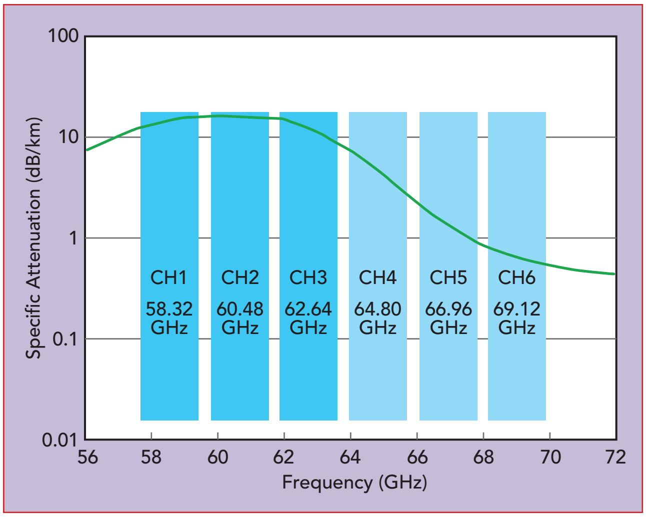


Fig. 3 Specific attenuation in IEEE 802.11ad channels 1 to 3.

EXTENDING LINK DISTANCE

Previously, longer links could only be established using conventional point-to-point radio equipment with fixed, high gain antennas and the attendant high equipment, installation and alignment costs. Unfortunately, these conventional links are impracti-



▲ Fig. 4 **Specific attenuation of the newer 64 to 71 GHz band, comparing 802.11ad channels 1 to 6.**

cal for most fixed networks of any size and impossible for transportation networks. Alternatively, using spectrum with lower specific atmospheric attenuation enables longer-range PTMP and mesh networks using lower cost, more flexible phased array antenna systems.

In its "Spectrum Frontiers Report and Order," released on July 14, 2016 (FCC 16-89), the FCC opened the 64 to 71 GHz band for use by unlicensed devices, adopting the same technical standards set for the 57 to 64 GHz band, defined in section 15.255 of the FCC rules. The FCC noted the agency's action created a 14 GHz segment of contiguous spectrum to "encourage the development of new and innovative unlicensed applications and promote next-generation, high speed wireless links with higher connectivity and throughput, while alleviating spectrum congestion from carrier networks by enabling mobile data off-loading through Wi-Fi and other unlicensed connections."

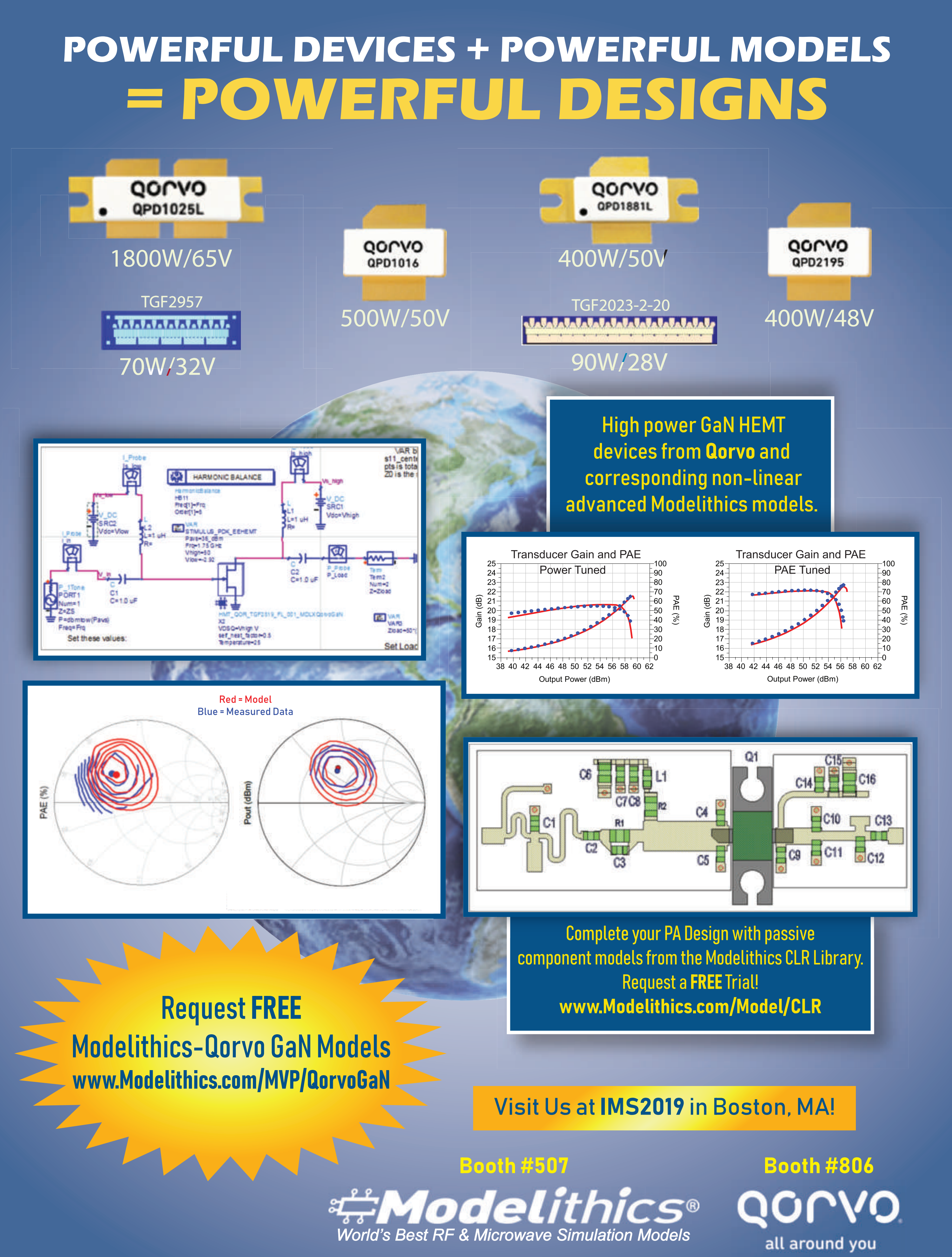
Ofcom, the U.K. regulator, conducted a "Fixed Wireless Spectrum Strategy" consultation in early 2018, resulting in a decision in July 2018 making the 64 to 66 GHz band unlicensed (it was previously coordinated by Ofcom) and opening the 66 to 71 GHz band for unlicensed use for 5G-like fixed wireless and mobile use cases. The Ofcom decision makes the U.K.'s spectrum allocation aligned with the U.S. allocation. The Ofcom decision and submissions from other parties are currently being reviewed by CEPT ECC, with the possible adoption of the same spectrum allocations more broadly through revisions to the ECC recommendations.

Using the same 802.11ad channel configuration, ***Figure 4*** shows the atmospheric attenuation for the newly unlicensed spectrum and compared to channels 1 through 3. The attenuation in channels 4 through 6 is substantially lower than in the original unlicensed band, with the attenuation in channel 6 approaching 0.6 dB/km. Using the same system parameters described above, significantly longer link dis-

TABLE 2

LINK DISTANCE FOR A 16 Tx, 16 Rx TRANSCEIVER ON IEEE CHANNELS 2 AND 6

		Modulation and Coding		
	Units	**MCS 8 QPSK**	**MCS 12 16-QAM**	**MCS 12.3 64-QAM**
Maximum Average EIRP	dBm	40	40	37
Nominal Sensitivity	dBm	–89	–82	–77
System Gain	dB	129	122	114
Distance (Ch 2)	m	400	260	135
Distance (Ch 2), No Rain	m	460	290	150
Distance (Ch 6)	m	600	330	150
Distance (Ch 6), No Rain	m	> 700	420	170



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tances can be achieved. ***Table 2*** compares the estimated link distances between channels 2 and 6, showing from a 50 percent increase for QPSK modulation to 11 percent for 64-QAM. The ability to support longer link distances of 300 to 400 m using channel 6 enhances the performance of existing applications and opens up new use cases:

- Use in suburban and lower density urban areas.
- Lower density small cell deployments.
- Long-range video surveillance.
- Wide area smart city IoT deployments.
- Transportation (e.g., trackside to train, roadside to bus, V2X).

A network operator can now deploy a less dense network in the upper part of the unlicensed band, increasing density over time by adding new links at lower frequencies.

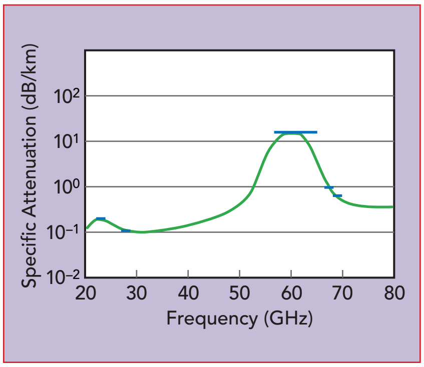

Fig. 5 **Specific attenuation of the 24 and 28 GHz 5G bands vs. the extended 60 GHz band.**

This potential can significantly improve the economics of a fixed network, and transportation applications, which require support for mobility over relatively long distances, become practical.

Interestingly, the specific attenuation in channels 5 and 6 of the newly allocated spectrum is comparable to that of the 5G licensed bands at 26 and 28 GHz (see ***Figure 5***). While higher output power is permitted in the licensed bands, overall system performance is limited by the narrower channels and the higher order modulation required. The 66 to 71 GHz unlicensed band may be an equivalent alternative to the licensed bands for fixed wireless applications.

CONCLUSION

The availability of wide channels in the unlicensed 57 to 64 GHz band with the development of products using phased array antenna technology has made the development of dense, high capacity urban networks using novel mesh architectures practical. The addition of 64 to 71 GHz to the unlicensed band, with its lower atmospheric attenuation, enhances the scope of existing applications and offers new possibilities, especially in the transportation sector. Silicon process nodes with mmWave performance enable companies such as the Sivers IMA to develop transceivers covering the full 57 to 71 GHz band. This capability allows network operators and other service providers to exploit the potential of the unlicensed band.

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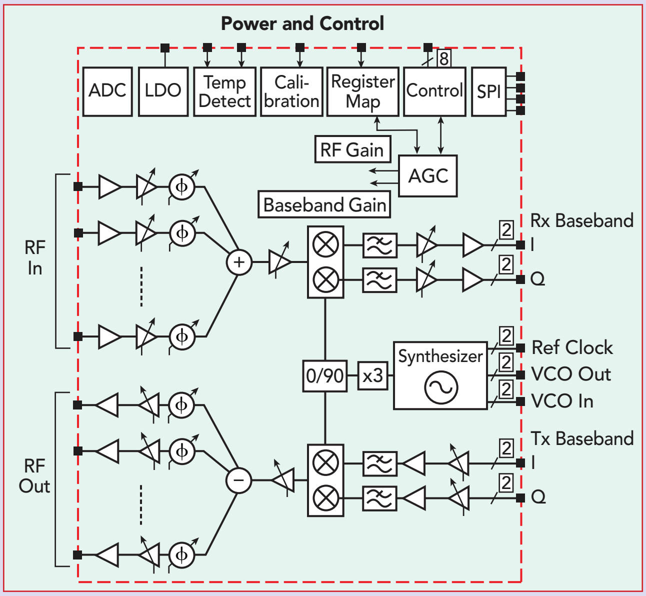
Sidebar: Highly Integrated Silicon RFICs Enabling 57 to 71 GHz Phased Arrays

To use the abundant mmWave spectrum being allocated by regulators, operators must field compact and affordable base stations. Phased array architectures offer the best performance and flexibility for many use cases, yet the number of elements in the array, with transceivers at each element, demands seemingly conflicting transceiver requirements for high integration and low cost. Fortunately, the extension of silicon's economies of scale to mmWave frequencies over the last decade has created the technology platform enabling the development of these RFICs by companies such as Sivers IMA.

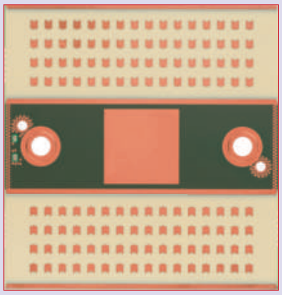
Sivers IMA's TRX BF01 is a highly integrated phased array RF transceiver developed for dynamic wireless communications infrastructure, such as mesh networks. It operates across 57 to 71 GHz and meets the IEEE 802.11ad specification, supporting channels 1 through 6, with center frequencies from 58.32 to 69.12 GHz. The transceiver integrates 16 Tx and 16 Rx signal paths and can be tiled into larger arrays (see ***SB Figure 1***). The transceiver uses a direct conversion architecture for both Tx and Rx, connecting from the baseband modem to 60 GHz patch antennas via a low loss stripline connection.

The transmit path includes integrated linear power amplifiers, providing a combined output power of greater than 22 dBm. The receive path includes low noise amplifiers with 7 dB noise figure, providing excellent receiver sensitivity, and analog channel filtering to suppress out-of-band interference, making the transceiver robust in a noisy RF environment and tolerant of out-of-band interferers. The transceiver includes a fully autonomous AGC, optimizing the receive gain based on the wanted and out-of-band signal levels, and provides autonomous DC offset and support for LO leakage and I/Q calibration. The error vector magnitude of –27 dB in both the transmit and receive modes supports modulation up to 64-QAM. High resolution phase shifters and signal path amplitude control enable accurate beamforming and reduced side lobes. The transceiver also contains a low noise VCO and fixed-N synthesizer and includes an auxiliary analog-to-digital converter to support various external functions, such as power and temperature measurements. With this level of integration, a complete transceiver system requires very few external components.



SB Fig. 1 TRX BF01 transceiver block diagram.

To address a range of use cases, the transceiver may be paired with various antenna array configurations. One common use is a distribution link for wireless mesh networks, which requires a link distance of several hundred meters combined with wide azimuth steering to address the different nodes in the mesh. In this scenario, the typical antenna design provides a horizontal steering range of 90 degrees with a fixed vertical beam. The corresponding half power beamwidth is 90 degrees horizontally, 20 degrees vertically. The antenna array can be implemented using a low loss laminate material, such as Megtron 6 or Rogers 3003, and standard printed circuit board fabrication. These materials are robust and proven and are cost-effective for high volume mmWave applications, such as wireless communications and automotive radar. Each antenna element has a gain of 10 dBi with flat frequency response from channels 1 through 6. The combination of the patch elements in a typical antenna array configuration with a single RF transceiver produces 16 Tx and 16 Rx antenna elements, providing 22 dB minimum gain on boresight (see ***SB Figure 2***).



SB Fig. 2 The BFM06010 module integrates the transceiver RFIC and antenna array into 16 Rx and 16 Tx beamforming channels.

Combining the RF antenna module with a suitable baseband device, such as IDT's Rapidwave™ RWM6050, provides a complete 60 GHz communications subsystem, which is integrated with a network processor to create a wireless mesh network node. ***SB Table 1*** provides a system gain analysis, illustrating how the twin goals of wide steering range and long distance can be accomplished for a wireless mesh distribution network.

SB TABLE 1

BEAMFORMING MODULE PERFORMANCE IN CHANNEL 6 (69.12 GHz)

		Modulation and Coding			
	Units	MCS 4 BPSK	MCS 8 QPSK	MCS 12 16-QAM	MCS 12.3 64-QAM
PHY Rate	Mbps	1155	2310	4620	6757
Conducted Power	dBm	22.5	21	17	
Antenna Array Gain	dBi	23			
EIRP	dBm	45.5	44	40	37
Constrained EIRP	dBm	40	40	40	37
Element Sensitivity	dBm	–69	–66	–59	–54
Antenna Array Gain	dBi	23			
Receiver Sensitivity	dBm	–92	–89	–82	–77
System Gain	dB	132	129	122	114
Link Distance	m	750	600	330	150

All-Digital Antennas for mmWave Systems

Mike Kappes
IQ-Analog Corporation, San Diego, Calif.

To realize high performance mmWave communications, beamforming antenna systems will need to be smarter, faster, smaller, lower power, cost less, have lower latency and be easier to integrate than current technologies. Much like with previous telecommunication systems, integrating important processing and signal conditioning functions will enable more cost-effective and compact mmWave beamforming antennas. The development of complex mmWave RF and analog hardware for 5G and tactical communications will initiate an inevitable evolutionary trend in digital communications, with digital processing eventually supplanting analog. The recent emergence of an all-digital antenna approach leveraging antenna processing units (APU) and ASICs could accelerate this trend, further reducing the time-to-market for highly anticipated multi-data path mmWave 5G and tactical communications.

The limited bandwidth and abundant congestion of sub-6 GHz spectrum has spurred extensive investigation into additional swaths of spectrum from 20 GHz to over 100 GHz (i.e., mmWave) for next-generation wireless communication systems. Originally sought after by industrial and commercial organizations for 5G, interest in the mmWave spectrum has expanded to encompass military and aerospace applications, such as tactical communications.[1–3] Beyond a manifold increase in the available bandwidth, compared to the sub-6 GHz spectrum, mmWave frequencies present a variety of benefits, as well as a range of design and operational challenges.

The size of antennas and transmission lines at mmWave frequencies are smaller than those at sub-6 GHz, owing to the shorter physical wavelength, with the smaller size enabling much more compact hardware. Moreover, the beamwidths of mmWave antennas are much narrower, hence more spatially selective than lower frequency antennas. These benefits come with the tradeoff of higher RF path loss and less efficient transmission. Additionally, the atmospheric attenuation at mmWave frequencies is much higher than in the sub-6 GHz bands. The reduced signal dispersion limits interference, jamming and potential snooping to roughly line-of-sight, offering benefits for tactical communications.

To overcome the greater RF path loss and atmospheric attenuation, it is widely accepted that the use of beamforming antenna technologies is one of the most viable solutions.[4–11] Certain beamforming designs also enable active antenna features, such as active electronically scanned arrays (AESA), which have been instrumental in jamming, anti-jamming, SATCOM and aerospace communications systems.

Many research, industry and military organizations are investigating and developing mmWave active antenna technologies that can be deployed in a reliable and cost-effective manner. Cost, size and complexity are significant factors for mmWave communications systems, especially for 5G, as the range and coverage provided by small cells is intrinsically less than the prior generation macro cells, meaning operators need to deploy many more 5G small cells in denser environments. This R&D involves the development of analog, hybrid and digital beamforming systems and their relative feasibility. This article discusses these methods and concludes an all-digital antenna approach leveraging digital beamforming is the best and inevitable architecture.

BEAMFORMING AND MIMO

Beamforming is the manipulation of an antenna pattern to control the mainlobe and sidelobe responses. A variety of methods can be used to accomplish this, though the dominant method discussed in this article is with multi-element antennas with phase control or delay. At a certain carrier frequency and with a properly designed multi-element antenna, a phase shift calculated for each antenna element can change or "steer" the antenna pattern. Beam steering with phase shifts can be used with linear antenna arrays to change the azimuth antenna pattern, and 2D antenna arrays can control the pattern in both azimuth and elevation.

Beamforming benefits mmWave communications since mmWave antenna systems typically have narrow antenna patterns with high attenuation, and multi-element antennas with active beamforming can increase the gain of the aperture and steer the beam toward a desired target to achieve the maximum signal quality. With sufficiently sophisticated beam steering technology, active beam steering enables a mmWave communications link to have a longer range and greater throughput.

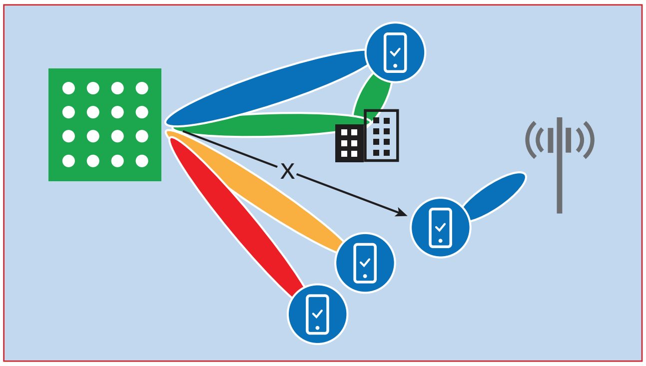


Fig. 1 MIMO can increase capacity and coverage in dense urban and in-building environments by pointing beams and creating nulls. Source: Ericsson.[12]

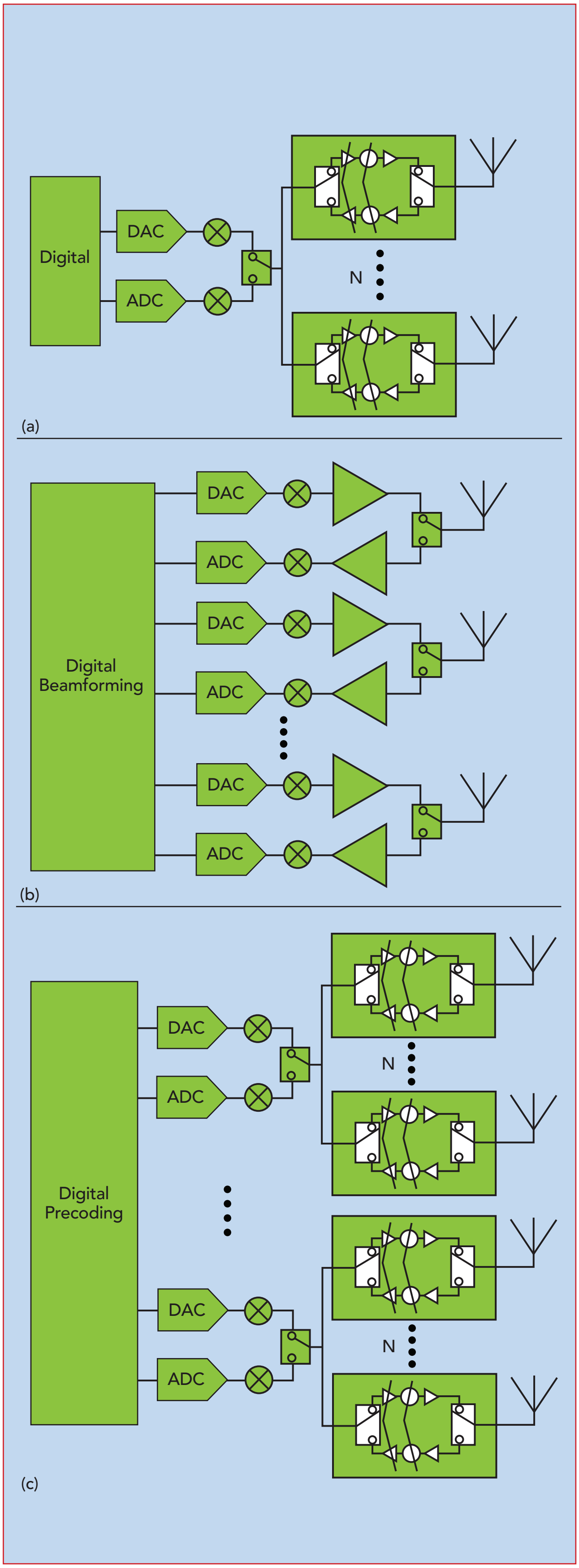


Fig. 2 Simplified block diagrams of analog (a), digital (b) and hybrid beamforming (c). Source: Analog Devices.[8]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A related topic is using spatial diversity with multi-element antennas to create more than one signal path from a given antenna array to the user, a method known as MIMO (see ***Figure 1***). The ability to transmit and receive multiple spatial streams allows for additional communication to occur simultaneously, either augmenting the throughput to a single user (SU-MIMO) or multiple users (MU-MIMO). Employing MIMO technology is another method to enhance the throughput of 5G communications and connect larger numbers of users simultaneously, without deploying additional cells. These techniques generally best serve dense urban environments and require multiple radio channels. In the case of mmWave, extremely narrow beamwidths, high atmospheric attenuation and the likelihood that multipath and reflections will suffer from high attenuation limit the potential gains for MIMO technology.

BEAMFORMING TYPES

The original analog beamforming antenna systems used fixed delays created by phase shifters at each antenna element to create a static beam pattern designed for a single frequency. Advancements of this approach added switches to select among several fixed phase shifters, creating a set of pre-designated antenna patterns. Further advancements adopted adjustable phase shifters at each antenna element, enabling a flexible, actively controlled phased array antenna, i.e., AESAs. With these beamforming antennas, the digital signals are usually created at baseband using digital-to-analog converters (DAC), converted to RF via frequency conversion and split to feed the transmit/receive (T/R) modules with phase shifters at each element. The received signal follows the reverse path; after down-conversion, the RF is digitized with an analog-to-digital converter (ADC) for processing. The T/R module contains the phase shifter, amplitude control and power and low noise amplifiers. This architecture, known as analog beamforming, requires a separate control signal for each phase shifter at each of the antenna elements and is limited to steering a single spatial beam (see ***Figure 2a***).

A more recent approach uses DACs and ADCs directly connected to each T/R module. This method, known as elemental digital beamforming, enables the beamforming algorithms and digital baseband processing to be entirely implemented with robust digital hardware, eliminating the need for sensitive analog RF phase shifters used with analog beamforming. Digital processing is capable of creating multiple spatial streams simultaneously, such that a single antenna array can dynamically create MIMO data streams and beams optimized in real-time for the user and load requirements (see ***Figure 2b***).

The biggest challenge for digital beamforming is power consumption. Analog beamforming requires lower DC power. However, since each analog beamformer only supports a single beam—and a digital beamformer enables multiple concurrent beams—digital beamforming is favored in high density environments demanding low latency and uncongested communication. Digital beamforming is particularly attractive for infrastructure networks supporting mobile users.

As the data conversion requirements of elemental digital beamforming systems are the bottleneck for provisioning digital beamforming solutions, cost and power considerations for mmWave antenna arrays have led to an interim approach using hybrid beamforming. Although there are various methods, hybrid beamforming generally combines the analog beamforming phase shifting topology for a subset of the antenna elements—with RF phase shifters, attenuators, low noise and power amplifiers, switching and circulators/isolators still used—and each subarray is driven by data converters with some level of digital precoding (see ***Figure 2c***). With this approach, the processing load on the digital electronics and

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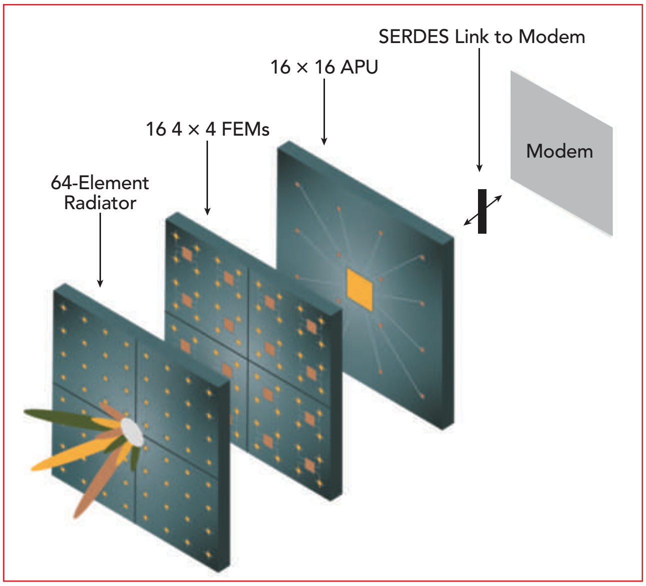

Fig. 3 mmWave all-digital antenna.

power consumption are less than with elemental digital beamforming. Hybrid beamforming typologies can be designed to allow for multiple spatial streams, although it is less flexible than elemental digital beamforming since the number of beams is limited to the number of hybrid subsets.

To realize elemental digital beamforming for mmWave multi-element antennas, the electronics must be capable of processing Gbps of throughput in real-time, while minimizing latency. 5G, for example, requires signal bandwidths up to 400 MHz. Elemental or all-digital beamforming requires that modulation, demodulation, conversion, spatial processing and beamforming processing occur in real-time, or at least fast enough to track a mobile user. Therefore, more intelligence is required with all-digital beamforming antennas than just baseband processing and beamforming, and these added digital functions are energy expensive. If realized as a discrete module, they add significant complexity to the physical layout, increasing size and, likely, cost. This is especially true if software-defined logic, such as FPGAs, is used. At this point, thermal management and power management become significant design considerations and high density and high throughput board-to-board and cable-to-board interconnects may be required. To avoid this complexity, a fully integrated ASIC with multi-channel wide bandwidth data conversion and efficient FinFET CMOS digital processing is required to meet the promise of digital beamforming. IQ-Analog has defined a family of APUs to service this emerging market need.

While an analog beamforming antenna system is less complicated and is generally more power efficient than comparable hybrid or digital beamforming antennas, the size and cost of discrete analog components and interconnects pose complexity issues as the antenna array grows beyond a small size. For antenna arrays greater than 4 × 4 or 8 × 8, hybrid beamforming or digital beamforming offer size, weight and cost advantages. Operators typically desire minimal changes to the form factor and power of their equipment, to keep leasing and operational costs down. While 5G mobile handsets can operate with roughly the same data and power efficiency as with 4G, 5G mmWave antenna infrastructure must be deployed at roughly 10× greater density and deliver 10× greater data capacity, which demands the most efficient multi-beam digital antenna processors. The unique digital antenna processing needs of mmWave antennas must be addressed using the most highly integrated and streamlined methods possible, meaning a unique ASIC composed of high channel count data converters, digital antenna processing and high speed digital I/O systems.

ALL-DIGITAL ANTENNAS

With greater component integration, the hybrid and digital topologies become more feasible, enabling mmWave beamforming and MIMO antennas to have a greater number of antenna elements. This


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shift enables more capable and flexible antenna systems that can provide higher gain with SU-MIMO or MU-MIMO operation. The promise of these architectures hinges on the performance of the digital and conversion electronics, i.e., the ability of the direct RF sampling and direct digital synthesis to address the full capacity of the mmWave spectrum. Otherwise, additional frequency translation hardware will be required, increasing complexity and reducing flexibility.

These trade-offs materialize as modem and beamforming technologies designed strictly for a single application, which may be infeasible for commercial and military manufacturers who want more flexible and capable solutions to support complex licensing and geographic restrictions. Direct RF sampling enables more flexible use of spectrum and does not limit a mmWave antenna to set 28 or 39 GHz frequency bands; any spectrum within the capability of the RF sampling hardware is accessible. Direct RF sampling is ideal when paired with software-defined radios (SDR); however, it presents a challenge for the data converters to meet the performance requirements.

With the specifications for mmWave 5G and tactical communications not fully defined and likely to change, the trend is for modem suppliers to provide SDR solutions rather than fixed modems. As the mmWave standards evolve, the SDR can be reprogrammed to meet the updated standard, whether for 5G or military applications. Modular scalability at the antenna elements and beamforming hardware is desirable for mmWave 5G base stations, to provide the flexibility to be upgraded without complete and costly hardware replacement. This is critical for operators, as the number of 5G mmWave base stations will be roughly 10× the number of 4G base stations to provide similar coverage. The number of 5G mmWave base stations may actually reach the same order of magnitude as mobile 5G handsets.

To take full advantage of SDR technology, full spectrum conversion and digital beamforming APUs are needed, an architecture dubbed all-digital antennas. The all-digital antenna, a digital beamforming phased array that supports several wide bandwidth MIMO beams, integrates an antenna array, RF front-end (RFFE) SoC and multi-chip module containing an APU and modem using a high speed converter interface, such as JESD204B (see ***Figure 3***).[13] The APU contains digital down-conversion with decimation and up-conversion with interpolation. Ideally, the all-digital antenna beamforming function is an ASIC rather than an FPGA or FPGA-ASIC hybrid. Though feasible in each configuration, building an FPGA-based all-digital antenna requires a greater footprint and significantly higher power consumption, with greater latency and likely higher cost. The best configuration would be a monolithic FinFET ASIC, with the most efficient data converter and digital processing.

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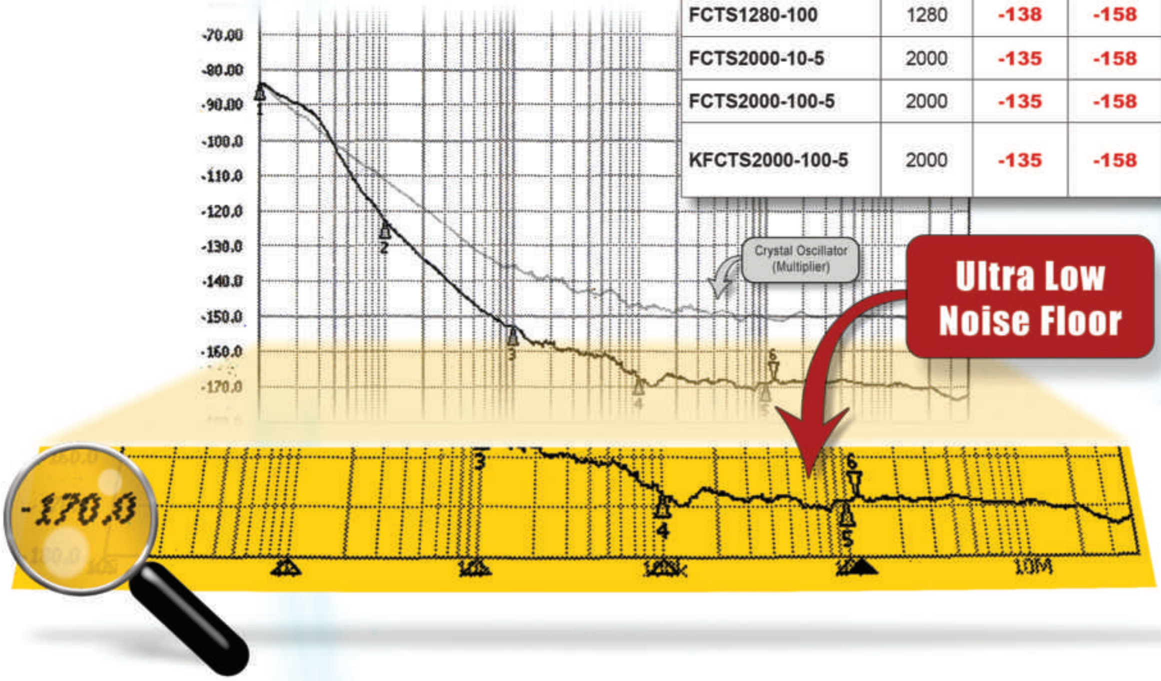
Model	Frequency (MHz)	Phase Noise (dBc/Hz) [Typ.] @10 kHz	Phase Noise (dBc/Hz) [Typ.] @100 kHz	Package
VFCTS128-10	128	-155	-160	
FCTS800-10-5	800	-144	-158	
KFCTS800-10-5	800	-144	-158	
FSA1000-100	1000	-145	-160	
KFSA1000-100	1000	-145	-160	
FXLNS-1000	1000	-149	-154	
KFXLNS-1000	1000	-149	-154	
FCTS1000-10-5	1000	-141	-158	
KFCTS1000-10-5	1000	-141	-158	
FCTS1000-100-5	1000	-141	-158	
FCTS1000-100-5H	1000	-144	-160	
FCTS1040-10-5	1040	-140	-158	
FCTS1280-100	1280	-138	-158	
FCTS2000-10-5	2000	-135	-158	
FCTS2000-100-5	2000	-135	-158	
KFCTS2000-100-5	2000	-135	-158	



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CONCLUSION

Though the trend toward integration and all-in-one ICs was a slow process for prior generations of wireless communications (i.e., 2G, 3G, 4G and Wi-Fi), the path toward ASIC-based APUs and a more efficient all-digital antenna for 5G will be accelerated by 5G's tremendous market demand. High performance full spectrum conversion APUs have already been fabricated in FinFET CMOS, and the underlying technology exists to realize multi-channel APU derivatives capable of the several GHz of addressable signal bandwidth needed for 5G. Designed with flexibility and programmability, these APUs can be readily adapted to a range of mmWave applications, such as 5G, tactical communications, autonomous vehicle radar and V2X and LEO SATCOM.■

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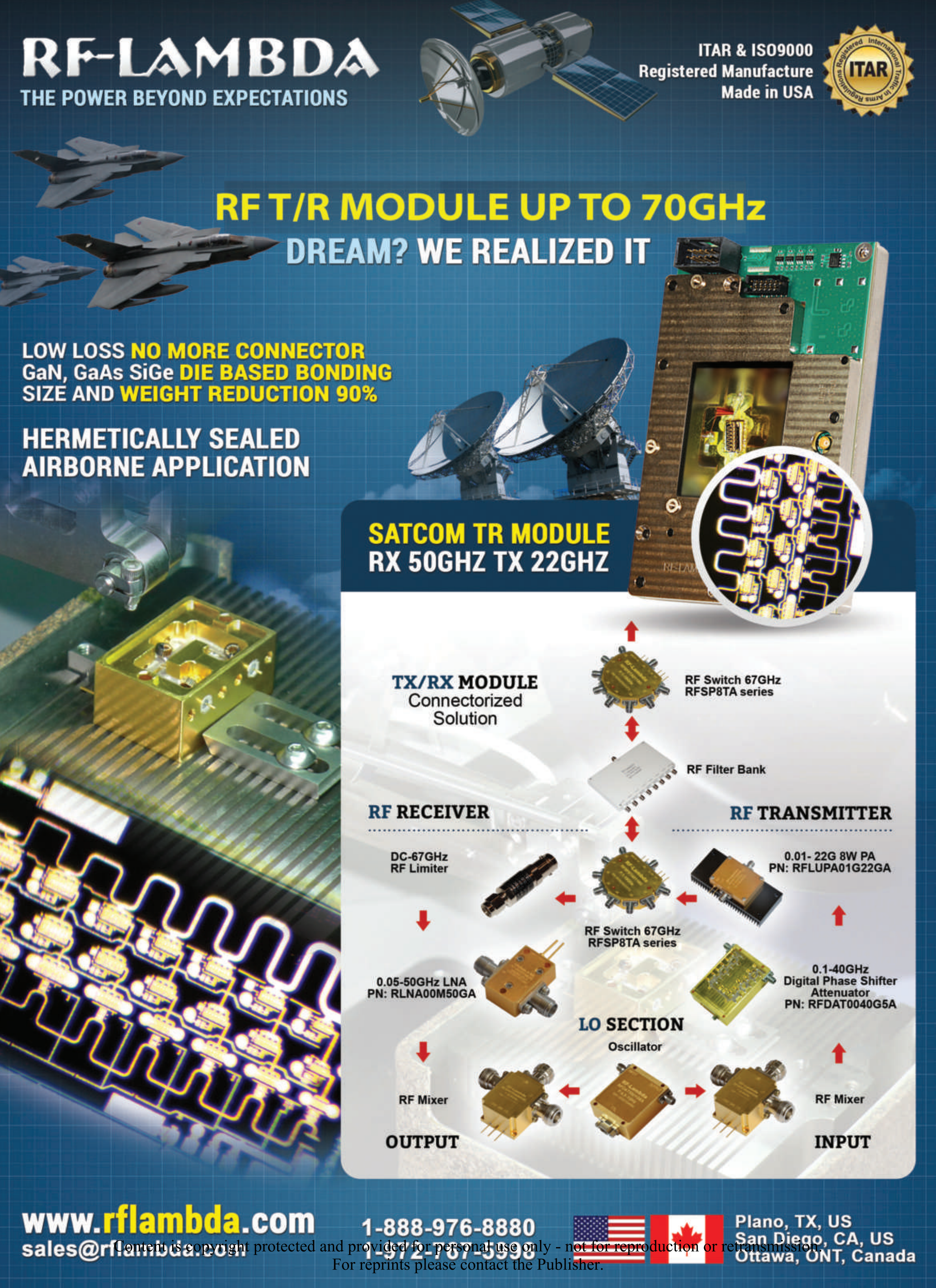
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AWGs Crunch Size, Deliver Performance

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Grosshansdorf, Germany

The latest family of Spectrum Instrumentation arbitrary waveform generators (AWG) provides exceptional signal quality, size, channel density and cost. The M2p.65xx series adds eight new models, packaged as single half-size PCIe cards, offering users the choice of one, two, four or eight generator channels. The small card size enables installation in almost any PC, turning it into a highly flexible, multi-channel signal source. Using the latest high-resolution, 16-bit digital-to-analog converter (DAC) technology, the cards can generate test signals with very low distortion, exceptional dynamic range and high signal-to-noise ratio.

The new AWGs offer sampling rates of 40, 80 or 125 MSPS, and every channel has its own DAC and output stage. The outputs are designed for accuracy and flexibility, incorporating four switchable filter paths to optimize signal quality and output swings to ±6 V into a high impedance load (1 MΩ) or ±3 V into 50 Ω.

VERSATILE WAVEFORM GENERATION

For generating long and complex waveforms, the cards are equipped with a generous 512 MS on-board memory. The memory can be segmented and waveforms created by looping on and switching between different memory segments. A first-in, first-out (FIFO) streaming capability enables new waveform data to be transferred over the fast PCIe x4 bus at rates up to 700 Mbps while stored information is being replayed. This makes FIFO streaming ideal for creating ultra-long single-shot waveforms or constantly changing burst type signals, commonly found in radar, ultrasound, LiDAR or sonar systems. The signal generation possibilities are virtually limitless.

For applications requiring the connection of AWGs and digitizers, for stimulus-response or closed-loop test systems, Spectrum's Star-Hub piggyback module can synchronize up to 16 M2p-class products. The new M2p.65xx AWGs match perfectly with the M2p.59xx 16-bit digitizers, which were released in 2018 (see ***Figure 1***). The M2p.59xx digitizers offer one to eight channels with sampling rates between 20 and 125 MSPS. With Star-Hub distributing a common clock and trigger signal to each channel, it is simple to build systems with up to 128 fully synchronous channels—perfect for situations where multiple test points or arrays of sensors need to be stimulated by different test signals at the same time.

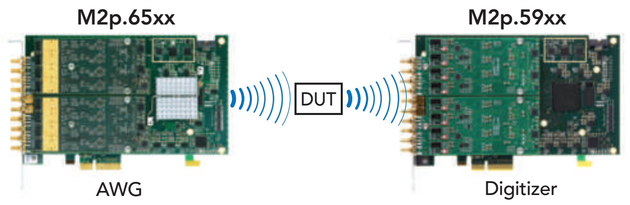

Fig. 1 **The new AWGs match with Spectrum's digitizers for stimulus-response and closed-loop testing.**

SIMPLE GENERATION AND CONTROL

The AWG cards are fully programmable, shipped with drivers and working examples free of charge. Most popular software languages are supported (e.g., C++, VB.NET, C#, J#, Delphi, Java, Python), as well as tools like LabVIEW and MATLAB.

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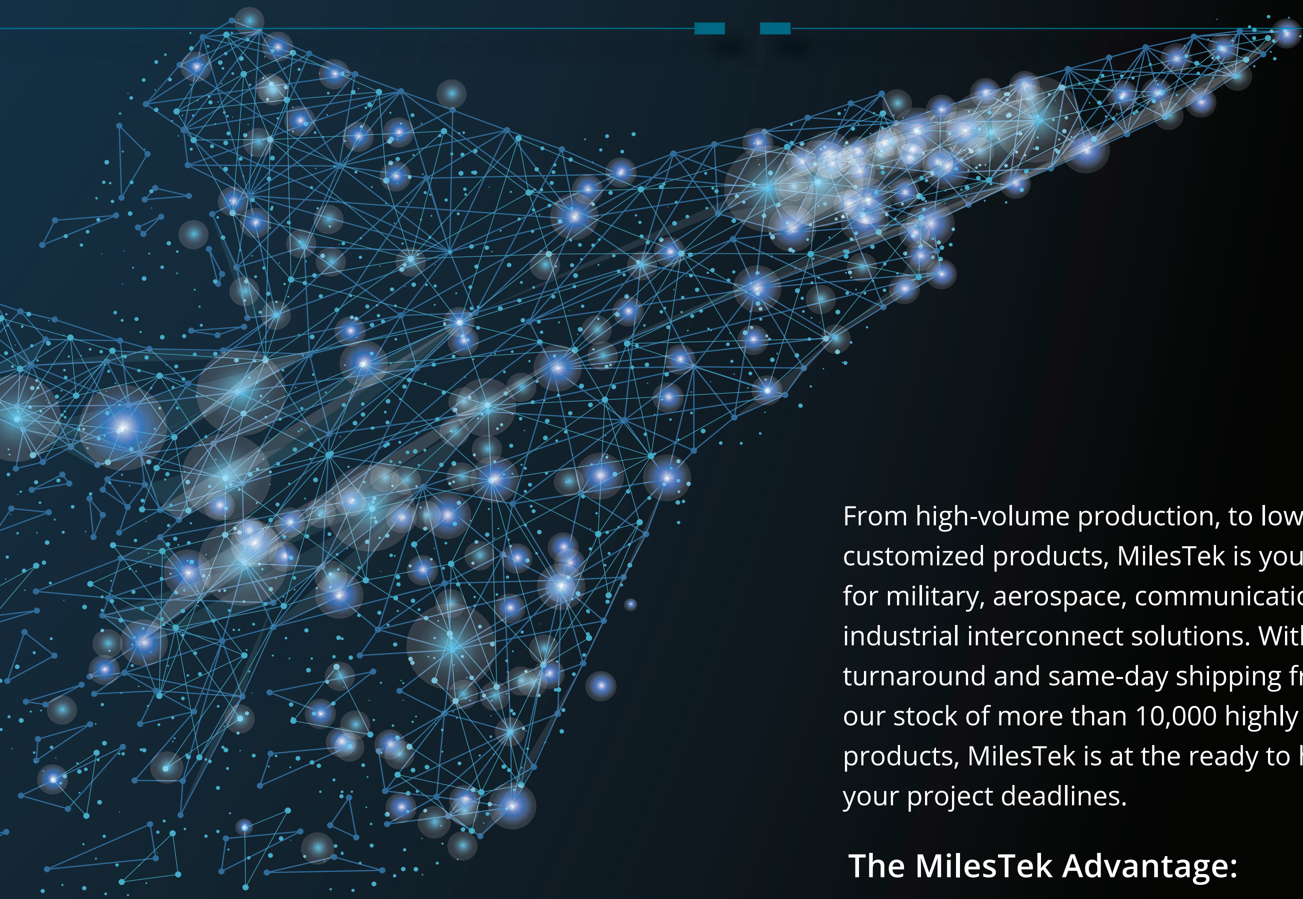

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Spectrum also offers its own software, SBench 6 Professional, which controls all card modes and settings using a simple graphical user interface. It supports multi-channel operation, waveform display, signal generation, data analysis and documentation. A built-in EasyGenerator function can be used to produce waveforms like sine, triangle or rectangle, with selectable frequency, amplitude and phase. More complex signals can be created using mathematical equations or imported data from other programs or devices, such as digitizers or oscilloscopes, using binary, ASCII or wave formats.

To allow fast integration into almost any automated test system, the cards come with a high level of connectivity (see ***Figure 2***). The clock and trigger inputs and signal outputs are provided via SMB connectors on the front panel, which also hosts four MMCX connectors (one multi-function output and three multi-function I/O lines). These can be used for tasks such as additional synchronous digital output channels, clock, trigger or status output, as well as asynchronous I/O lines.

Fig. 2 **The front panel contains clock and trigger inputs and signal outputs, as well as four MMCX connectors, offering flexible options for using the AWG.**

Switching the multi-purpose I/O lines to digital outputs adds another four synchronous output channels to the AWG, making it possible for a single AWG card to generate up to eight analog outputs and four digital outputs in parallel at full speed. It is a helpful feature when interfacing with other equipment for controlling experiments or OEM projects.

FIVE-YEAR WARRANTY

The new M2p.65xx series AWGs are available for immediate delivery. All cards are shipped factory tested and include software drivers, working examples and a base version of Spectrum's SBench 6 software for initial testing. The cards are backed with an industry-leading five-year warranty with software and firmware updates, free of charge, for the lifetime of the product.

VENDORVIEW

Spectrum Instrumentation GmbH
Grosshansdorf, Germany
www.spectrum-instrumentation.com

Economical Spectrum Analysis for 5G mmWave

OML Inc.
Morgan Hill, Calif.

We have been hearing about the arrival of 5G for several years now: how 5G's real-time speed, real-time interactivity and real-time connectivity will change the way we work, live and play. This year, 5G finally becomes a reality, building out official wireless carrier announcements inaugurating 5G services. Beginning in select areas in a few major metropolitan cities, 5G is expected to gain momentum as services are deployed from now into 2020. This build-out is creating the demand for cost-effective test equipment to support 5G installation and maintenance. The spectrum/signal analyzer is the most crucial item for field use, providing a view of the RF spectrum and measuring wireless metrics, important parameters to assure quality of service and avoid interference.

Leading test equipment manufacturers have developed portable handheld signal analyzers that rival their benchtop models. With frequency coverage from Hz to various upper frequencies (i.e., 6, 9, 14, 18, 20, 26.5, 32, 44, 50 and 54 GHz), portable handheld signal analyzers can support a wide range of applications, including 5G, wireless backhaul, satellite, radar, aerospace and defense. These portable handheld signal analyzers have similar performance to the benchtop signal analyzers at a slightly lower cost.

The initial 5G rollout adds new frequency bands below 6 GHz and between 24 and 40 GHz, so a signal analyzer needs to have an upper frequency of 40 GHz to support 5G deployment and maintenance. However, continuous coverage to 40 GHz is not usually necessary, and 40 GHz signal analyzers can be expensive. OML offers a lower cost alternative, an economical solution for 5G. The M28H6ADC is a high performance yet economical block converter for the 26, 28 and 39 GHz 5G bands. Used with a 6 GHz signal analyzer with a tracking generator, the M28H6ADC enables the sub-6 GHz signal analyzer to add the 24 to 40 GHz 5G bands. This innovative solution costs much, much less than a 40 GHz signal analyzer and achieves the needed performance.

The 6 GHz signal analyzer itself will measure the sub-6 GHz 5G bands. Connecting the M28H6ADC to the signal analyzer enables the analyzer to cover the 24 to 40 GHz spectrum. Configuring the unit is simple: first connect the M28H6ADC LO input and IF output ports to the 6 GHz signal analyzer tracking generator output and RF input ports, respectively. Then, attach a WR28 horn antenna to the M28H6ADC input port,

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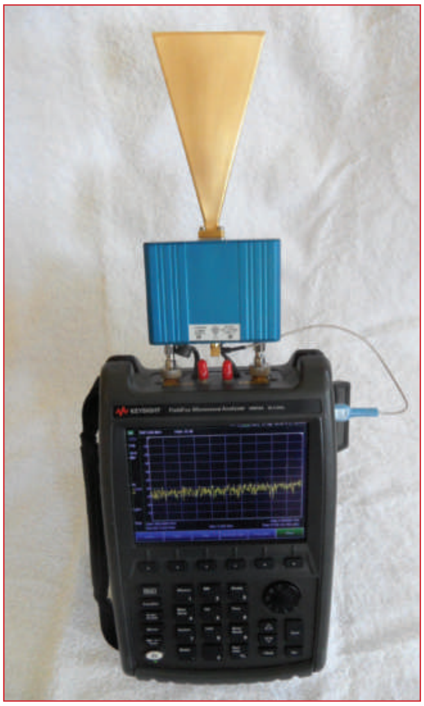

Fig. 1 **5G field test system comprised of a WR28 horn antenna, M28H6ADC down-converter and Keysight FieldFox analyzer.**

enabling over-the-air measurements (see ***Figure 1***). The mixer's IF output feeds the 6 GHz signal analyzer RF input, and the signal analyzer displays the captured 24 to 40 GHz spectrum on the LCD screen, showing the down-converted IF frequencies. The signal can be analyzed further by connecting the M28H6ADC IF output port to other test equipment.

The compact M28H6ADC has an IF bandwidth of 6.5 GHz and 10 dB typical conversion loss, which translates to a noise floor (i.e., minimum discernable signal) of −164 dBm at 1 Hz bandwidth. The 6.5 GHz IF bandwidth is sufficiently broad to capture the 26, 28 and 39 GHz 5G bands: 24.25 to 27.5, 27.5 to 28.35, 37 to 38.6 and 38.6 to 40 GHz. The key to transforming the 6 GHz signal analyzer into a mmWave signal analyzer is the ability of the M28H6ADC to tune the built-in tracking generator's CW signal to the appropriate LO frequency and amplitude to drive the M28H6ADC's down-converter. DC power for the M28H6ADC is provided from the signal analyzer's USB port or a separate USB power pack.

Comparing the performance of a high performance 44 GHz analyzer to the M28H6ADC with a 6 GHz signal analyzer, ***Figure 2a*** shows a measurement of the 28 GHz 5G band (i.e., 27.5 to 28.35 GHz) using Keysight's EXA N9010A 44 GHz signal analyzer. ***Figure 2b*** shows the same signal measured with the M28H6ADC, which down-converts the band to a 0.5 to 1.35 GHz IF signal and drives a Keysight FieldFox analyzer. Figure 2b has no correction for the conversion loss of the M28H6ADC or the in-line WR28 waveguide to coaxial adapter. ***Figure 3*** overlays the two measurements and accounts for the conversion loss of the M28H6ADC. For reference, the signal measured with a Keysight 8487A power sensor is also plotted.

With the M28H6ADC added to the MxxHxADC product family, OML now offers the most comprehensive and flexible portable down-converter portfolio for mmWave applications, covering 24 to 110 GHz.

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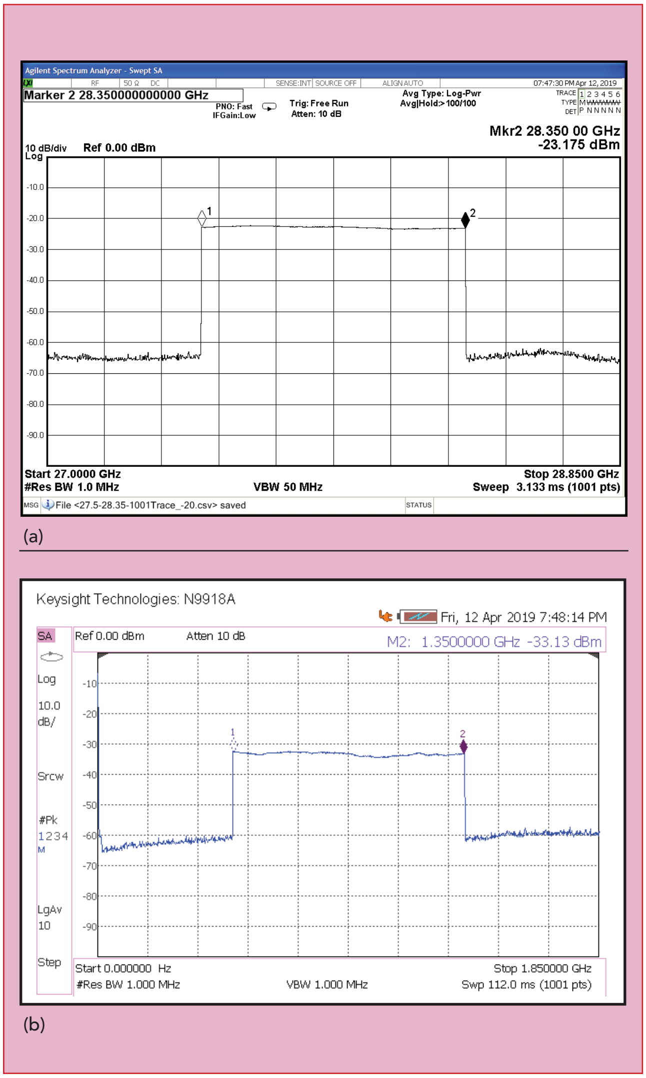


Fig. 2 **The 27.5 to 28.35 GHz 5G band measured with Keysight's EXA N9010A 44 GHz signal analyzer (a) and the M28H6ADC down-converter feeding a 6 GHz Keysight FieldFox analyzer (b).**

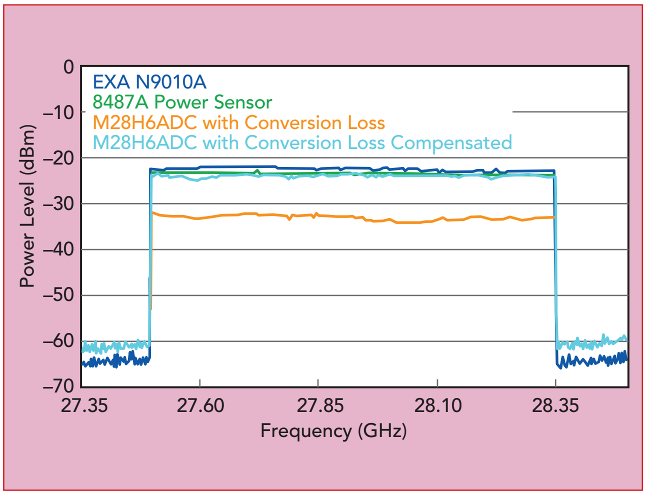
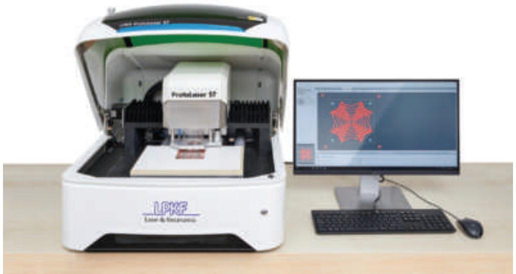


Fig. 3 **Comparison of the 27.5 to 28.35 GHz measurements using the Keysight EXA N9010A, M28H6ADC/FieldFox combination and a Keysight 8487A power sensor.**



Fabricate PCBs at Your Desk

LPKF Laser & Electronics AG
Garbsen, Germany

The RF market is developing faster than ever. Wireless communication is present everywhere—home, office, factory and vehicle, with new applications developing at high speed. Without wiring and bulky connectors, miniaturization and simplicity are easier to achieve with new designs. Making this possible and inexpensive, RF antennas and circuitry are often moved to the printed circuit board (PCB); hence, fast prototyping is essential to prove circuit layouts and quickly release these new products to the market. To help designers fabricate prototype boards quickly, the first tabletop LPKF laser etching system, ProtoLaser ST, offers excellent performance using popular high frequency substrates from Rogers and other manufacturers.

GEOMETRIC PRECISION

Using LPKF CircuitPro PL 3.3, with predefined laser tool parameters from the supplied materials library, LPKF evaluated the performance using a wideband antenna design as a test vehicle, comparing the geometry of the design with physically measured results on fabricated samples. The demonstration evaluated the copper wall quality, surface damage and processing time.

A planar logarithmic periodic wideband antenna, measuring 60 mm × 60 mm, was fabricated with the ProtoLaser ST, using LPKF's "hatching" algorithm, where larger areas of conductive material are removed by slicing it into smaller pieces and then delaminating it from the board. After processing, the boards were cleaned with the LPKF cleaner and a soft brush. ***Figure 1*** shows samples using Rogers RO3003, RO4003 and RT5880, with substrate thicknesses of 510, 410 and 254 μm, respectively, and a common Cu thickness of 18 μm on both sides. For a direct comparison, the same geometry was used for each board, despite the different RF properties of the substrates. The ProtoLaser ST's ultra-flat ceramic vacuum table holds the thinnest and most sensitive materials in place, stress-free: in this case, the 10 mil thick and very soft RT5880.

The primary concern with any fabrication technique is geometric precision. The logarithmic periodic antenna has a complicated geometry, a good test vehicle to demonstrate the capabilities of the laser etching process. The layout at the center of the antenna, at the electrical connection point, provides a

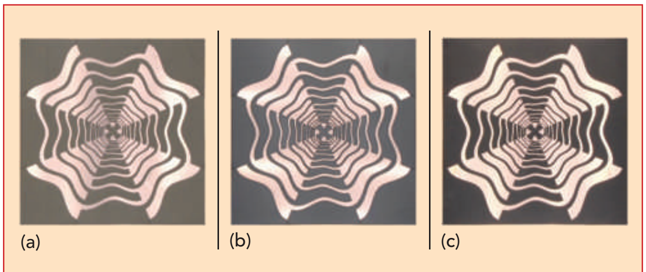


Fig. 1 **Logarithmic periodic antenna fabricated on RO3003 (a), RO4003 (b) and RT5880 (c) substrates with the ProtoLaser ST.**

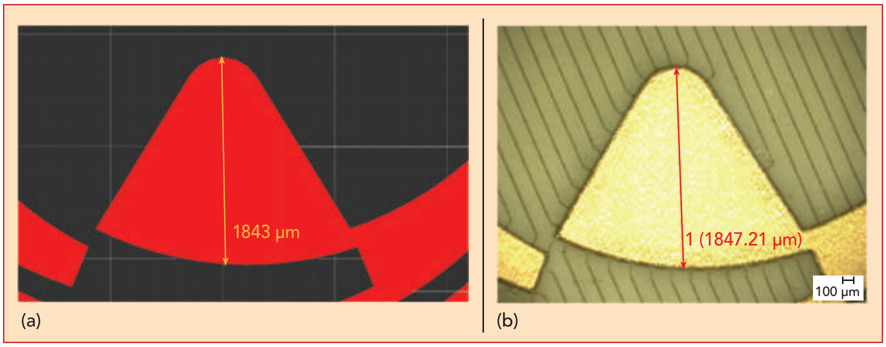


Fig. 2 **CAD design (a) vs. fabricated sample on RO4003 (b).**

good assessment of the laser's ability to achieve the track and gap widths and curved features (see ***Figure 2***). All measurements were performed at the same position, with the same approach and using a Keyence VHX-1000 digital microscope. The design values, measured data and calculated deviations are shown in ***Table 1***. These largely minor dimensional differences can be improved by optimizing the parameters for the material and compensating the design dimensions after measuring the performance.

TABLE 1

DESIGN VS. MEASURED DIMENSIONS

	Design (µm)	Measured (µm)	Deviation (%)
RO3003	217	209	3.7
	387	389	0.5
	1843	1846	0.1
RO4003	217	210	3.2
	387	390	0.8
	1843	1847	0.2
RT5880	217	211	2.8
	387	389	0.5
	1843	1842	0.05

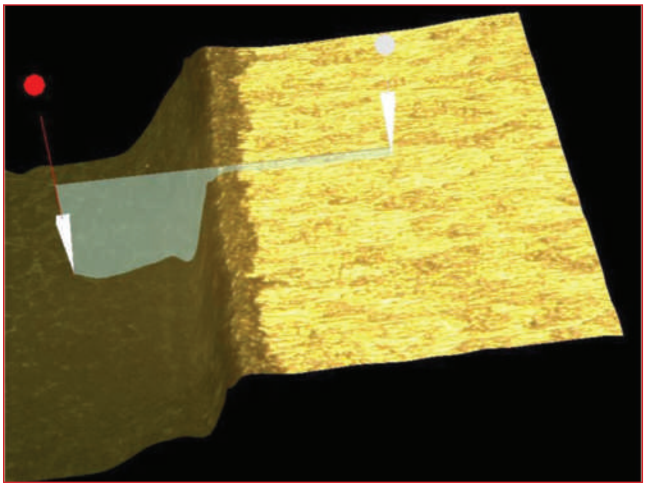


Fig. 3 **Profile of a laser-cut side wall on RO5880.**

SURFACE, WALLS AND SPEED

LPKF has patented a method for removing large areas of copper from the substrate: first cutting these areas into thinner tracks—called hatching—then using laser heat to delaminate the material. After cutting through the copper, depending on the substrate composition, minor scribe lines on the substrate surface may be seen using a microscope, as seen in Figure 2b. The laser cut is straight and smooth, yielding near-perfect walls. The walls may be inclined a few degrees outward (see ***Figure 3***), a slight chamfer which is opposite to the under etching with wet technology.

The size of the sample used for this evaluation was 60 mm × 60 mm, 36 cm^2, and the average processing time with the three Rogers samples was 212 seconds each, a processing speed of 10 cm^2/minute. Processing a reasonably sized 100 cm^2 board (10 cm × 10 cm) will take approximately 10 minutes—probably less time than required to solder a pair of RF connectors to a board to measure the performance.

FLEXIBILITY

A new granite base and perfectly flat vacuum table enable thin flexible materials and foils to be positioned freely and held precisely. The LPKF ProtoLaser ST is compact and economical, the first high-end tabletop laser etching system requiring only a single-phase power socket and compressed air to operate. As with all LPKF ProtoLaser systems, the ST has a large laser safety window for monitoring the process and laser class 1 qualification to ensure operator safety and convenience.

Design data from RF simulation software can be imported into LPKF CircuitPro with a few clicks via DXF or a vector format. Intuitive software guides the user, beginning with selecting the material and laser tool through the steps to fabricate a finished PCB. Libraries of proven materials and tools enable a quick start for prototyping, and users can add custom tools to the library for unique materials.

Offering fast processing and compatible with a wide range of materials, the LPKF ProtoLaser ST enables efficient prototyping of complex digital, analog and RF/microwave circuit boards. It supports single or double sided boards and multiple technologies on the same substrate. The laser system achieves exact geometries on almost any material, fabricating complex geometries such as antennas, filters and other applications where precise, steep sidewalls are required.

With additional equipment, the LPKF ProtoLaser ST can produce multilayer boards. The latest generation of the powerful CAM and machine software, LPKF CircuitPro, handles data preparation and system control in a single package. CircuitPro is optimally designed to process substrates prepared with an LPKF ProtoMat. Together with the integrated camera system, the software enables the exact positioning of pre-drilled and cut-out PCBs. CircuitPro guides users through the production steps for multilayer boards, simplifying the process for the user.

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EUROPEAN MICROWAVE WEEK 2019
THE CONFERENCES

Don't miss Europe's premier microwave conference event. The 2019 week consists of three conferences and associated workshops:

- European Microwave Integrated Circuits Conference (EuMIC) 29th September - 2nd October 2019
- European Microwave Conference (EuMC) 1st - 3rd October 2019
- European Radar Conference (EuRAD) 2nd - 4th October 2019
- Plus Workshops and Short Courses (From 29th September 2019)
- In addition, EuMW 2019 will include, for the 10th year, the Defence, Security and Space Forum on 2nd October 2019 and for the first time the Automotive Forum on 30th September 2019.

The three conferences specifically target ground breaking innovation in microwave research. The presentations cover the latest trends in the field, driven by industry roadmaps. The result is three superb conferences created from the very best papers submitted. For the full conference programme including a detailed description of the conferences, workshops and short Courses, please visit **www.eumweek.com**. There you will also find details of our Partner Programme and other Social Events during the week.

FAST TRACK BADGE RETRIEVAL

Register online and print out your badge in seconds onsite at the Fast Track Check In Desk

CONFERENCE PRICES

There are TWO different rates available for the EuMW conferences:

- **ADVANCE DISCOUNTED RATE** – for all registrations up to and including 30th August 2019
- **STANDARD RATE** – for all registrations made after 30th August 2019

Please see the Conference Registration Rates table on the back page for complete pricing information.
All payments must be in Euro – cards will be debited in Euro.

Online registration is open now, up to and during the event until 4th October 2019

DELEGATES

Registering for the Conference

- Register online at **www.eumweek.com**
- Receive an email receipt with barcode
- Bring your email, barcode and photo ID with you to the event
- Go to the Fast Track Check In Desk and print out your delegate badge
- Alternatively, you can register onsite at the self service terminals during the registration opening times below:

  - Saturday 28th September (16:00 - 19:00)
  - Sunday 29th September - Thursday 3rd October (08:00 - 17:00)
  - Friday 4th October (08:00 - 10.00)

Once you have collected your badge, you can collect the conference proceedings on USB stick and delegate bag for the conferences from the specified delegate bag area by scanning your badge.

CONFERENCE REGISTRATION INFORMATION

EUROPEAN MICROWAVE WEEK 2019, 29th September - 4th October, Paris, France

Register Online at www.eumweek.com

ALL FEES ARE INCLUSIVE OF FRENCH VAT @ 20%

ONLINE registration is open from 28th May 2019 up to and during the event until 4th October 2019.

ONSITE registration is open from 16:00 on 28th September 2019.

ADVANCE DISCOUNTED RATE (up to and including 30th August) STANDARD RATE (from 31st August & Onsite).

Reduced rates are offered if you have society membership to any of the following*: Eu*MA*, GAAS, IET or IEEE.

Eu*MA* membership fees: Professional € 25/year, Student € 15/year.

If you register for membership through the EuMW registration system, you will automatically be entitled to discounted member rates.

Reduced Rates for the conferences are also offered if you are a Student/Senior (Full-time students 30 years or younger and Seniors 65 or older as of 4th October 2019). The fees shown below are invoiced in the name and on behalf of the European Microwave Association. Eu*MA*'s supplies of attendance fees in respect of the European Microwave Week 2019 are inclusive of French VAT.

ADVANCE REGISTRATION CONFERENCE FEES (UP TO AND INCLUDING 30TH AUG.)

CONFERENCE FEES	ADVANCE DISCOUNTED RATE			
	Society Member (*any of above)		Non Member	
1 Conference	Standard	Student/Sr.	Standard	Student/Sr.
EuMC	€ 470	€ 130	€ 660	€ 190
EuMIC	€ 360	€ 120	€ 510	€ 170
EuRAD	€ 320	€ 110	€ 450	€ 160
2 Conferences				
EuMC + EuMIC	€ 670	€ 250	€ 940	€ 360
EuMC + EuRAD	€ 640	€ 240	€ 890	€ 350
EuMIC + EuRAD	€ 550	€ 230	€ 770	€ 330
3 Conferences				
EuMC + EuMIC + EuRAD	€ 810	€ 360	€ 1140	€ 520

STANDARD REGISTRATION CONFERENCE FEES (FROM 31ST AUG. AND ONSITE)

CONFERENCE FEES	STANDARD RATE			
	Society Member (*any of above)		Non Member	
1 Conference	Standard	Student/Sr.	Standard	Student/Sr.
EuMC	€ 660	€ 190	€ 930	€ 270
EuMIC	€ 510	€ 170	€ 720	€ 240
EuRAD	€ 450	€ 160	€ 630	€ 230
2 Conferences				
EuMC + EuMIC	€ 940	€ 360	€ 1320	€ 510
EuMC + EuRAD	€ 890	€ 350	€ 1250	€ 500
EuMIC + EuRAD	€ 770	€ 330	€ 1080	€ 470
3 Conferences				
EuMC + EuMIC + EuRAD	€ 1140	€ 520	€ 1600	€ 740

WORKSHOP AND SHORT COURSE FEES (ONE STANDARD RATE THROUGHOUT)

FEES	STANDARD RATE			
	Society Member (*any of above)		Non Member	
	Standard	Student/Sr.	Standard	Student/Sr.
Half day WITH Conference registration	€ 100	€ 80	€ 130	€ 100
Half day WITHOUT Conference registration	€ 130	€ 100	€ 170	€ 130
Full day WITH Conference registration	€ 140	€ 110	€ 180	€ 130
Full day WITHOUT Conference registration	€ 180	€ 140	€ 240	€ 170

EUROPEAN MICROWAVE WEEK WORKSHOPS & SHORT COURSES

SUNDAY 29th September		
Full Day	WS-01	EuMC/EuMIC
Full Day	WS-02	EuMC/EuMIC
Full Day	WS-03	EuMC
Full Day	WS-04	EuMC
Full Day	WS-05	EuMC/EuMIC
Half Day AM	WS-06	EuMC
Half Day PM	WS-07	EuMC
Full Day	WS-08	EuMC/EuMIC
Full Day	WS-09	EuMC
Full Day	SS-01	EuMC
Half Day AM	SS-02	EuMC/EuMIC

MONDAY 30th September		
Half Day AM	WM-01	EuMC/EuMIC
Half Day PM	WM-02	EuMC
Full Day	WM-03	EuMC
Full Day	WM-04	EuMC/EuMIC
Full Day	WM-05	EuMC
Full Day	WM-06	EuMC
Half Day AM	WM-07	EuMC
Half Day PM	WM-08	EuMC
Half Day AM	WM-09	EuMC/EuMIC
Half Day PM	SM-01	EuMC

TUESDAY 1st October		
Half Day AM	STu-01	EuMC

WEDNESDAY 2nd October		
Full Day	WW-01	EuMC/EuRAD
Full Day	WW-02	EuMC/EuRAD

THURSDAY 3rd October		
Half Day AM	WTh-01	EuRAD
Full Day	WTh-02	EuMC/EuRAD
Half Day PM	STh-01	EuRAD

FRIDAY 4th October		
Half Day AM	WF-01	EuRAD
Full Day	WF-02	EuMC

SPECIAL FORUM FEES

	ADVANCED RATE (UP TO & INCL 30TH AUG)	
Automotive Forum Monday 30th September	€ 260 For Delegates (those registered for EuMC, EuMIC or EuRAD)	€ 360 For All Others (those not registered for a conference)
	STANDARD RATE (FROM 31ST AUG & ONSITE)	
	€ 320 For Delegates (those registered for EuMC, EuMIC or EuRAD)	€ 420 For All Others (those not registered for a conference)
	ONE STANDARD RATE THROUGHOUT	
Defence, Security and Space Forum Wednesday 2nd October	€ 20 For Delegates (those registered for EuMC, EuMIC or EuRAD)	€ 60 For All Others (those not registered for a conference)

OTHER ITEMS

Proceedings on USB Stick

All papers published for presentation at each conference will be on a USB stick, given out FREE with the delegate bags to those attending conferences. The cost for an additional USB stick is € 50.

Partner Programme and Social Events

Full details and contacts for the Partner Programme and other Social Events can be obtained via the EuMW website www.eumweek.com.

SPECIAL SESSIONS

Date	Time	Title	Location	No. of Days	Fee
Tuesday 1st October and Wednesday 2nd October	08:30 - 17:50	European Microwave Student School	Room 746 - Tuesday Booth by Reg. Desk - Wednesday	1 full day & 2 half-days	€ 40
Tuesday 1st October and Wednesday 2nd October	13:50 - 17:50 Tuesday 09:00 - 17:50 Wednesday	European Microwave Doctoral School	Room 741BC - Tuesday Booth by Reg. Desk - Wednesday	1 half-day & 2 half-days	€ 80

10 dB Directional Coupler Covers 10 to 110 GHz

KRYTAR Inc. has developed a directional coupler covering 10 to 110 GHz with an exceptionally flat 10 dB coupling across the full bandwidth. The model 1100110010 achieves coupling of 10 ±1.5 dB from 10 to 90 GHz and 10 ±1.8 dB from 90 to 110 GHz. Frequency sensitivity (amplitude flatness) is typically ±1.25 dB from 10 to 90 GHz and ±1.80 dB from 90 to 110 GHz. Directivity is ≥ 10 dB from 10 to 55 GHz and ≥ 7 dB—typically 10 dB—from 55 to 110 GHz.

This stripline design with standard 1 mm SMA female connectors has an insertion loss of 5.5 dB maximum across the band, including the coupled power. At any port, the maximum VSWR is 1.8:1 from 10 to 50 GHz and 2.5:1 from 50 to 110 GHz. For applications requiring multiple couplers on multiple channels, such as antenna beamforming, the unit-to-unit coupling tolerance is within ±1.50 dB across the full 10 to 110 GHz.

This new directional coupler is extremely compact, measuring 1.55 in. × 0.38 in. × 0.80 in., and weighs 1.2 ounces. It will withstand an input power of 20 W average and 3 kW peak. The operating temperature range is from −54°C to +85°C.

The 1100110010 is well-suited for wireless designs and test and measurement systems for the emerging mmWave and 5G markets, antenna beamforming and electromagnetic compatibility (EMC) testing. The coupler can be manufactured to meet military specifications, for use in electronic warfare (EW) and other military systems.

Founded in 1975 and privately owned, KRYTAR develops broadband microwave components and test equipment for commercial and military applications. Products include directional couplers, detectors, hybrids, power dividers/combiners, terminations, coaxial adapters and a power meter and power sensors.

VENDORVIEW

KRYTAR Inc.
Sunnyvale, Calif.
www.krytar.com

New Landing Page for 50th Anniversary

VENDORVIEW

In conjunction with their 50th Anniversary, AR has unveiled a new corporate landing page. The page highlights the four divisions that make up the AR family of companies—AR RF/Microwave Instrumentation, AR Modular RF, SunAR RF Motion, AR Europe—and serves as a launching page to each of the four companies. AR RF/Microwave Instrumentation is a world-class source for broadband high-power, solid-state, RF amplifiers and microwave amplifiers; TWT amplifiers; log periodic antennas and high-gain horn antennas; and EMC test equipment.

AR RF/Microwave Instrumentation

www.arworld.us

The Conference Comes to Your Screen

EDI CON Online will take place September 10-12, 2019, bringing much needed technical training and information directly to engineers' desktops and mobile devices. Featuring three days of keynotes, technical sessions, workshops and product demonstrations, with video, traditional webinar and screen sharing formats. Covering topics such as 5G, IoT, signal integrity, power integrity and EMC/EMI. Attendees select their sessions for EDI CON Online in a single sign-on registration portal. Content is available online for free to attendees live (with Q&A) or to watch later on-demand.

EDI CON Online

www.edicononline.com

New Merged Website

Electronic Products has completed their merger with Semiconductor Enclosures Inc., and are operating as Electronic Products Inc. (EPI). EPI is now your single-source for a wide range of high-quality hermetic glass-to-metal seal components as well as a fully integrated HTCC precision ceramics manufacturer providing ceramic tape systems, ceramic substrates, multilayer ceramic substrates, metallization services, metal to ceramic assemblies and microelectronic ceramic packaging. With this merger, EPI provides ceramic based products and services to customers in the RF/microwave, AlN power, Hi-Rel, military, communications, aerospace, medical, optical and industrial markets.

Electronic Products Inc. (EPI)

www.elecprodinc.com/

New Website Update

K&L Microwave's website provides information and tools, such as the Filter Wizard® web application, to speed the identification of custom design solutions from a full range of company products. The latest web update features a new look, mobile device support and social media links. Research capabilities, access data sheets, submit quote requests, read the latest news and download K&L's new Product Catalog and new Space Brochure.

K&L Microwave

www.klmicrowave.com

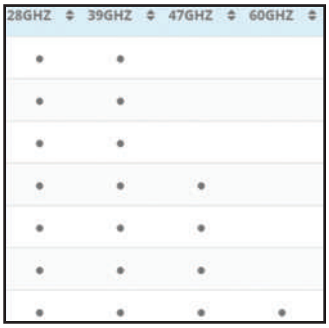
New Website Update

KRATOS General Microwave, one of the largest suppliers of microwave products to the defense and non-defense markets, has updated its website to better reflect the company's various capabilities and product lines. Each product line page provides easy access to the various COTS microwave products in each category. To help their customers better utilize their microwave products, the company added a link to White Papers that provide greater detail about some of their product lines. KRATOS General Microwave website also now includes archived GMC product catalogs.

KRATOS General Microwave

http://gmcatalog.kratosmed.com/Kratos-General-Microwave-Product-Catalog

5G & mmWave Landing Page



At Marki Microwave, the company designs their components to achieve the highest performance over the widest bandwidths to enable new designs and simplify testing. To highlight their multi-octave mmWave products, the company has created a useful 5G & mmWave landing page. Every Marki component that supports 28 GHz and above, up to 85 GHz currently, is listed and is sortable based on frequency band and package. Marki updates this list monthly with exciting new product releases.

Marki Microwave

www.markimicrowave.com

DIY Vector Network Analyzer Kit

VENDORVIEW

The first of the Univeristy Project kits, UVNA-63, includes all the elements students need to build a fully functioning vector network analyzer, develop S-parameter algorithms and perform real-time measurements of 2-port RF devices. The kit comprises Vayyar's high performance transceiver chip with a variety of RF components from Mini-Circuits, along with control software and a development environment for Python and MATLAB®.

Mini-Circuits

www.minicircuits.com/WebStore/uvna_63.html

Free Tools Page

VENDORVIEW

Modelithics® offers multiple free tools for RF and microwave design in the Free Tools area of the website. Designers can download the Modelithics SELECT+ Library for multiple supported simulators. SELECT+ is a sample collection of Modelithics models for various types of components. Free model library trial requests are also available for many Modelithics Vendor Partners (MVP). In addition to the models, the free tools area includes downloadable S-parameter files, example projects for multiple simulators, an ROI calculator, a mixer spur table and information about the Modelithics University Program.

Modelithics

www.modelithics.com/freetools

New Website

Quest Manufacturing is proud to announce the launch of their new website. The new website is mobile-friendly and offers live chat support. Product Search allows you to lookup products by keywords or SKU#, and, without having to login, you can check for available stock on any item. With Distributor Locator integrated with Google Maps, you can see all businesses and sites supplying Quest products in your area. The new website also features latest catalogs, detailed product spec drawings and informative product videos.

Quest Manufacturing

www.questmanufacturing.net

GaN & SiC for Power Electronics Tech Hub

Richardson RFPD Inc. announced the launch of the GaN & SiC for Power Electronics Tech Hub, a microsite featuring the latest news on GaN and SiC innovations, news and product releases. The new GaN & SiC for Power Electronics Tech Hub offers a robust library of GaN and SiC new product features and technical resources, including white papers and videos, as well as links to online purchasing and the option to sign-up for product updates via email. It is the latest in Richardson RFPD's selection of Tech Hubs.

Richardson RFPD Inc.

http://gan-sic-power.richardsonrfpd.com/

Updated Website

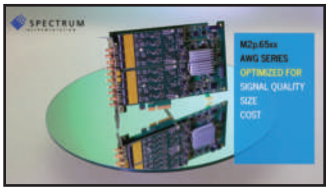
Spectrum Elektrotechnik, supplier for state-of-the-art RF and microwave products to the defense and space market amongst others, has launched its new website to give customers a better insight over their manufacturing capabilities and their extensive product lines, like RF adapters and connectors, RF cable assemblies, phase shifters, etc. Cable assemblies and waveguide-to-coax adapters can be configured online; easy filter functionality helps finding the right product for your application, for all product lines a quick and easy quote request is available.

Spectrum Elektrotechnik GmbH

www.spectrum-et.com

New Video

VENDORVIEW



Spectrum presents: 16-bit AWGs with eight channels per card. Having eight AWG-channels on a single PCIe-card with only 168 mm in length offers great new opportunities for very compact and affordable test systems. Spectrum Instrumentation added two new 8-channel-cards to their latest "65" series of PCIe arbitrary waveform generators, with 40 or 80 MS/s on all eight channels. Using Spectrum's "Star-Hub" synchronization-module additionally, up to 80 channels can be fully synchronized in a single PC. Get all the facts in their new video.

Spectrum Instrumentation

www.spectrum-instrumentation.com/en/news

Web&VideoUpdate

New "Single Source" Website

Teledyne Defense Electronics (TDE), an innovative new Teledyne brand representing the combined capabilities of 11 Teledyne companies, unveiled a new website that provides a "single source" on the web for accessing its comprehensive high tech offerings for global markets. TDE serves as a joint supplier for numerous distinguished Teledyne brands. Visitors to the new TDE website will find access to over 100 product lines by whichever method they choose: by market, by technology type or by simple alphabetical listings.

Teledyne Defense Electronics

www.teledynedefenseelectronics.com/

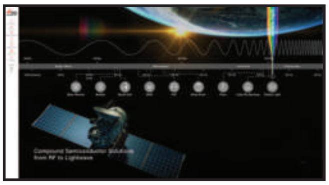
New Video

Telegaertner introduces the Cell IQ Series, a product family comprised of three connector series: the field-proven 4.3-10 series standard, the compact and robust 2.2-5 series solution and the 1.5-3.5 series which already helps you take the next step into the future of connection technology. These products cover the complete spectrum of MCO requirements and deliver maximum power in any size. The video takes a closer look at the company's newest product family, highlights its technical features and demonstrates application range.

Telegaertner

www.telegaertner.com/go/mco

Updated Homepage



Established in 1999, WIN Semiconductors is a global provider of pure-play GaAs and GaN wafer foundry services for the wireless, infrastructure and networking markets. With three advanced wafer fabs located in Taiwan, WIN provides customers a diverse portfolio of Hetero-junction Bipolar Transistor, Pseudomorphic High Electron Mobility Transistor, GaN HEMT, PIN Diode and Optical Device solutions for leading edge products used in smartphones, wireless infrastructure, optical networks, 3-D sensing, satellite, aerospace and defense and automotive markets.

WIN Semiconductors Corp.

www.winfoundry.com/

Asia-Pacific Microwave Conference

APMC 2019

10 - 13 DECEMBER 2019 SINGAPORE

Sands Expo and Convention Centre www.apmc2019.org

Microwaves bridging Smart Cities

SCAN ME

Call for Papers

2019 Asia-Pacific Microwave Conference (APMC) and Technical Exhibition in Singapore

Active Devices and Circuits

Low-noise devices and circuits, high-power devices and circuits, wide band-gap devices, microwave tubes, control circuits (mixer, oscillator, switch, etc.), MMICs, RFICs, millimeter and THz wave devices and circuits, graphene devices, and other relevant topics.

Passive Components

Multiband, broadband, tunable, and reconfigurable filters, resonators, directional couplers and hybrids, waveguides and transmission lines, ferrite and SAW devices, RF MEMS, LTCC devices, packaging, metamaterials and EBG structures, plasmonic and optical components, nanomaterials, and other relevant topics.

Systems

5G systems, high-speed and broadband millimeter and THz wave systems, MIMO systems, microwave photonics, radar and sensor systems, IoT/M2M/RFID systems, wearable devices and systems, security and health monitoring systems, wireless power transfer systems, energy harvesting devices and systems, microwave medical and biomedical applications systems, whitespace systems, software defined/ cognitive/smart radio systems, satellite systems, near/far field measurement, EMC/ EMI, SI/PI, microwave heating and chemistry, and other relevant topics.

Antennas and Propagation

EM field theory, EM wave propagation, wave scattering and inverse scattering, DOA estimation, localization, antenna theory and design, millimeter-wave/THz and optical antennas, small antennas, broadband and multi-band antennas, MIMO antennas, active adaptive and smart antennas, reconfigurable antennas, body channel modelling, and other relevant topics.

Emerging Areas

Nano-electromagnetics, artificial intelligence, machine learning and deep learning for microwave and wireless applications, electromagnetic-acoustics, and other relevant topics.

All accepted and presented papers will be included and published in IEEE Xplore.

Technical Exhibition

The Technical Exhibition on RF/microwave/EMC components, devices, materials, measurements, instrumentation and software will be the major accompanying event of the Asia-Pacific Microwave Week.

This exhibition will provide a diverse array of opportunities to showcase and network with tech companies in an exciting venue hosting major manufacturers and distributors of RF/microwave-related equipment, software, and tools.

Important Dates

Proposals for special sessions & workshops and tutorials	**June 10, 2019**
Preliminary paper submission (3 pages in PDF format)	**June 30, 2019**
Notification of acceptance	**August 30, 2019**
Final paper submission	**September 20, 2019**

MTT-S · EMC SOCIETY · IEEE SINGAPORE SECTION · NUS · NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE · IEEE Advancing Technology for Humanity · EuMA

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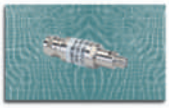
NEW PRODUCTS

FOR MORE NEW PRODUCTS, VISIT WWW.MWJOURNAL.COM/BUYERSGUIDE
FEATURING VENDORVIEW STOREFRONTS

COMPONENTS

Impedance Matching Pads Preserve Signal Integrity



Eliminate impedance discontinuity (mismatches) without introducing reflection to the circuit. Model 851-879-FM4 is a 50 to 75 Ω impedance matching pad that operates from DC to 4 GHz. This 1 W unit offers nominal insertion loss of 5.7 dB and VSWR of 1.5:1 with SMA female/F male connectors. Custom units are available in a variety of impedance and connector types from DC to 4 GHz. BroadWave Technologies impedance matching pads preserve signal integrity by matching virtually any transmission line.

BroadWave Technologies Inc.
www.broadwavetechnologies.com

Digital Phase Shifter

Kratos General Microwave manufactures a complete line of broadband fast switching phase shifters. Model 7929 offers a full tuning range of 360° covering a frequency range of 18 to 40 GHz. Excellent phase accuracy and PM/AM performance are achieved by utilizing double balanced bi-phase linear amplitude modulators. Standard unit designed to operate over −54°C to +95°C. Its small size and high-reliability make it ideal for use in demanding shipboard/airborne environmental conditions. Optional optimized performance is available over a narrower frequency range.

General Microwave Corp.
www.kratosmed.com

18 to 40 GHz, 10 dB Directional Couplers

VENDORVIEW

MECA expanded offering of 5G mmWave products. Featuring 10 dB couplers covering 18 to 40 GHz with 2.92 mm interfaces. Typical specifications of 1.6:1 VSWR, 13 dB directivity, 1 dB insertion loss and 0.5 dB frequency sensitivity. Also available are attenuators, terminations, bias tees, DC blocks and adapters. Additionally octave and mulit-octave models covering up to 50 GHz built by J-Standard certified assemblers and technicians. Made in U.S. with 36 month warranty.

MECA Electronics Inc.
www.e-MECA.com

Directional Coupler

VENDORVIEW

Mini-Circuits' EDC10-183+ is a 10 dB directional coupler that operates from 6 to 18 GHz packaged in MCLP 4 × 4 mm, 24-lead package. It provides excellent coupling flatness over a broad bandwidth and good return loss. This coupler also provides a quadrature phase shift between the signal at the through port and coupler port. Manufacturing using GaAs technology, this model results in relatively high repeatability in performance.

Mini-Circuits
www.minicircuits.com

Ceramic Capacitors

Passive Plus Inc. (PPI) has the 01005BB104 broadband 100 nF multilayer ceramic capacitors. The industry's smallest 100 nF broadband part characterized for RF performance. PPI is a manufacturer of high performance RF/microwave passive components for the medical, semiconductor, military, broadcast and telecommunications industries. PPI specializes in high-Q, low ESR/ESL capacitors, broadband capacitors, single layer capacitors, non-magnetic resistors (high-power and thin film) and trimmer capacitors. PPI is ISO9001:2015 certified.

Passive Plus Inc.
www.passiveplus.com

Absorptive Switch

VENDORVIEW

PMI Model No. P16T-100M50G-100-T-DEC is a single pole, 16 throw, solid-state absorptive switch operating over the frequency range of 0.1 to 50 GHz. This model offers a typical insertion loss of 16 dB, while maintaining a typical isolation of 70 dB. It has a max input power of 20 dBm CW and a max switching speed of 100 ns. This switch is outfitted with 2.4 mm female connectors in a housing measuring 8 × 3 × 0.65 in.

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

GX Series-Coaxial DC Pass RF Surge Protection

The GX Series of surge arrestors are engineered for RF coaxial applications where DC current is needed on the coaxial line. The GX Series can be used on GPS and other active antenna systems that operate in the range from DC to 2700 MHz. The GX Series is available online with same-day shipping.

PolyPhaser
www.polyphaser.com

Terminated (Absorptive) SPDT Switch

RLC Electronics announced the addition of a miniature terminated (absorptive) SPDT switch. The switch provides proven reliability, long-life and excellent electrical performance. It features extremely low insertion loss (< 0.3 dB at 18 GHz) and VSWR (1.5:1 max at 18 GHz) while maintaining high isolation (> 60 dB at 18 GHz). This miniature Terminated SPDT switch measures 1.2 × 2.09 × 0.52 in. (standard unit is 2.25 × 2.25 in.). The standard model is DC to 18 GHz, but versions are available up to 50 GHz.

RLC Electronics Inc.
www.rlcelectronics.com

Power Frequency Tripler

Spacek Labs Model A390-3X14-20K is a single input, four output power frequency tripler designed for operation at 39.3 GHz output frequency. This unit contains all the necessary amplification stages and internal filtering to boost the 14 dBm input power to 17 dBm min./19 dBm typical output power for all ports with undesired harmonics suppressed by at least 50 dB. The multiple output frequency multiplier design is available in frequency bands ranging from 18 to 65 GHz.

Spacek Labs
www.spaceklabs.com

CABLES & CONNECTORS

High Speed End Launch Connectors

Fairview Microwave Inc. has introduced a new extended series of mmWave, remov-

able, end launch, PCB connectors that are ideal for SERDES applications like cloud servers, supercomputing and high speed networking. Fairview's new line of high speed, end launch, PCB connectors consists of 16 models operating in a wide bandwidth that supports high data rates and VSWR as low as 1.1:1. They are offered with four end launch connector interface options: 1 mm (110 GHz), 1.85 mm (67 GHz), 2.92 mm (40 GHz) and 2.4 mm (50 GHz).

Fairview Microwave Inc.
www.fairviewmicrowave.com

Latching USB 2.0 Cable Assemblies

MilesTek's latching USB 2.0 cable assemblies are ideal for military/aerospace applications where vibration is an issue, because unlike standard USB connectors, which rely on a friction fit, the latching USB Type-A connectors on these assemblies provide lock-down mating retention with any USB Type-A jack. Additionally, these cables feature low-smoke, zero-halogen (LSZH) cable jackets. LSZH reduces the amount of toxic and corrosive gases emitted during combustion.
MilesTek
www.milestek.com

Custom Low-PIM Coaxial Cable Assemblies

VENDORVIEW

Pasternack's line of low-PIM coaxial cable assemblies now consists of 160 standard configurations that boast PIM levels of < –160 dBc. These high performance, low-PIM cable assemblies are constructed with flexible, lightweight, UL910, plenum-rated, SPP-250-LLPL, RF coaxial cable which can operate in temperatures from –55°C to +125°C. These high quality cables deliver low insertion loss and excellent VSWR, are 100 percent RF and PIM tested and ship with the PIM test results marked on the cables.
Pasternack
www.pasternack.com

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Times Microwave introduces its new Clarity Series of 18, 26.5 and 40 GHz coax test cables. Clarity boasts steel torque, crush and overbend protection with abrasion resistance yet does not compromise flexibility. The cable is ultra stable through 40 GHz with exceptionally low attenuation. An industry first includes an ergonomically designed, injection molded strain relief and Times' new, SureGrip™ coupling nut to significantly improve the user's everyday experience. Clarity is appropriate for use as VNA test port extension, R&D lab, production test and even system interconnect cables.

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AMPLIFIERS

TWT Amplifier

The Model 477Ka provides 700 W peak power at duty cycles up to 8 percent from 33 to 36 GHz. Particular emphasis has been placed on the generation of the output RF pulse shape. The RF output pulse width tracks the input 5 V video pulse. Internal power supplies are DC-DC converter designs operating at 50 kHz with fast loop response times so that output level variations are minimal for any PRF including a non-periodic or burst type PRF.
Applied Systems Engineering Inc.
www.applsys.com

10 kHz to 1000 MHz U Series Amplifier

VENDORVIEW

AR's new family of "U" (Universal) Series RF solid-state Class A power amplifiers now includes a 250 W model that covers the 100 kHz to 1000 MHz frequency range. These amplifiers are ideal for EMC, laboratory use, antenna and component testing, Watt meter calibration, medical/physics research and more. This compact, high performance and affordable amplifier joins a family of products available in 1, 2.5, 10, 25 and 50 W output levels that covers 10 kHz to 1000 MHz.
AR RF/Microwave Instrumentation
www.arworld.us/USeries

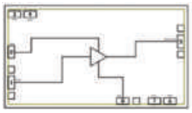
GaN Solid-State Power Amplifiers

COMTECH PST introduced its latest addition to its GaN solid-state power amplifier product line. Comtech's latest development continues to expand on its integrated RF GaN Power Amplifier designs by offering a small form factor (SFF) module. Consistent with its planned technology development roadmap, Comtech proudly introduces the latest in GaN-based 6 to 18 GHz RF amplifier for TWT/MPM replacement. This highly integrated design is ideal for use in communication, EW and radar transmitter systems where space, cooling and power are limited.
COMTECH PST
www.comtechpst.com

Driver Amplifier

VENDORVIEW

Custom MMIC has just released the CMD292, a new wideband Distributed Driver Amplifier MMIC. CMD292 delivers 13 dB of gain with a corresponding output 1 dB compression point of +27 dBm and output IP3 of +33 dBm at 15 GHz. The CMD292 features a positive gain slope over frequency, easing broadband designs when flat gain profile is desired. The CMD292 is a pad-compatible replacement for the Analog Device product, HMC994.



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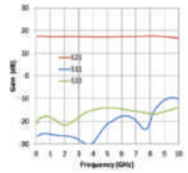
DC to 8 GHz, 1 W GaAs Power Amplifier



Richardson RFPD Inc. announced the availability and full design support capabilities for a new power amplifier from Microsemi Corp., a Microchip company. The MMA053AA is a GaAs MMIC PHEMT distributed power amplifier die that operates between DC and 8 GHz. The amplifier provides 17 dB of gain, +43 dBm output IP3 and +31 dBm of output power at 3 dB compression, while requiring only 410 mA from an 11 V supply.
Richardson RFPD
www.richardsonrfpd.com

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The LC5545DX programmable oscillator from Pletronics features LVDS logic, superior jitter performance and a low operating supply voltage at 1.8 V. This product is ideal for use in storage area networking, optical transceivers and other high performance applications. The part utilizes the latest state-of-the-art programmable technology and is available as either factory programmed or field programmable. The LC5545DEX is based on an AT cut crystal and is a single chip solution allowing the part to be programmed in frequencies up to 1 GHz.
Pletronics
www.pletronics.com

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The FCTS2000-10-5 is a new, 2000 MHz phase locked frequency source featuring excellent phase noise performance, making it ideal for use as a stable local oscillator or frequency reference. Typical phase noise at 100 Hz offset is –80 dBc/Hz at 1 kHz offset is –105 dBc/Hz and at 100 kHz offset is –158 dBc/Hz. The external reference input requirements are 10 MHz at a voltage range between +1 to +3.3 V peak-to-peak with phase noise better than –138 dBc/Hz at 50 Hz offset to achieve published specifica-

MICRO-ADS

tions. Spurious products are suppressed by 80 dB typical and output power is +5 dBm min. Power supply requirements are +5 V at 125 mA and +12 V at 10 mA max. This frequency source is available in a small, RoHS compliant surface mount package measuring 1.25 × 1 × 0.23 in. Operating temperature is –40°C to +85°C.

Synergy Microwave Corp.
www.synergymwave.com

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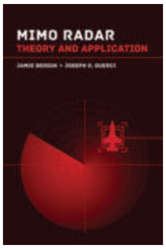

MIMO Radar: Theory and Application

Jamie Bergin and Joseph R. Guerci

This comprehensive resource provides in-depth and timely coverage of the underpinnings and latest advances of MIMO radar. It provides a comprehensive introduction to MIMO radar and demonstrates its utility in real-world applications, then culminates with the latest advances in optimal and adaptive MIMO radar for enhanced detection and target ID in challenging environments. Signal processing prerequisites are explained, including radar signals, orthogonal waveforms, matched filtering, multi-channel beamforming and Doppler processing. This book discusses MIMO radar signal model, antenna properties, system modeling and waveform alternatives. MIMO implantation challenges are covered, including computational complexity, adaptive clutter mitigation, calibration and equalization and hardware constraints.

Applications for GMTI radar, OTH radar, maritime radar and automotive radar are explained. The book offers an introduction to optimum MIMO radar and includes details about detection, clutter and target ID. Insight into adaptive MIMO radar and MIMO channel estimation is presented and techniques and illustrative examples are given. Readers find exclusive flight testing data from DARPA. The breadth of coverage in this all-inclusive resource makes it suitable for both practicing engineers and advanced researchers. The book concludes with discussions on areas for future research.

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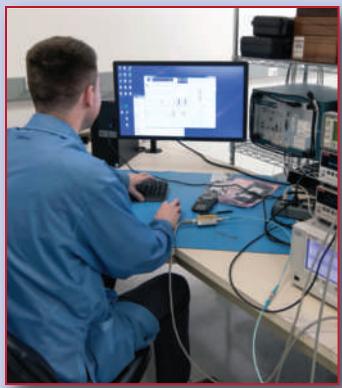


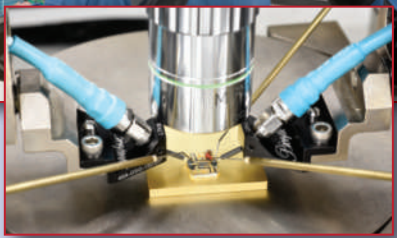

When Paul Blount worked for a fabless semiconductor company, he would come home complaining about what they were doing—or not doing. Paul's wife eventually challenged him to start his own company, since he thought he could do it better. So he did, launching Custom MMIC on May 5, 2006 from the basement of his home. Thirteen years later, the rapidly growing firm has just completed a second office and lab expansion—now at 20,000 square feet—to house the continuing arrival of new staff and test equipment.

Custom MMIC's standard products catalog has grown to 165 products spanning DC to 67 GHz, packaged and die, and reflecting most every RF function: amplifiers, voltage variable and digital attenuators, switches, mixers, phase shifters and multipliers. Custom MMIC did not begin as a standard products company. Initially, Paul offered design services, developing his reputation largely through Small Business Innovation Research (SBIR) programs. The first one tasked him to design LNA MMICs consuming very little power, for X- and Ku-Band phased arrays. His design used only 30 mW, significant for an array with thousands of T/R modules. These innovative designs started the catalog, which now contributes some 85 percent of the company's revenue.

As GaAs MMIC suppliers have consolidated and rationalized their portfolios, Custom MMIC has stepped into that void, finding abundant opportunities by taking on the most challenging requirements and supporting long-lived programs, particularly for military and space systems. Without an internal fab, Custom MMIC designers can choose the best process from an array of global foundries, using it to create an innovative design. As one example, amplifier phase noise is often overlooked as an important limitation on system performance. Seeing this, Custom MMIC pioneered low phase noise amplifiers and now offers a family of products in this area.

Custom MMIC believes the data sheet is the primary tool for assessing and choosing MMICs for a new design. So the applications team is always adding more characterization data, particularly second-tier parameters that may prove important, such as second harmonic and IP2 performance. Better to identify a possible problem from the data sheet before finding it when testing a prototype.

Recognizing the challenge companies face when their suppliers obsolete products, Custom MMIC is implementing an innovative plan to source key Custom MMIC products from two different foundries. Should one fab discontinue a process, Custom MMIC can offer customers a second product "off the shelf." While it may need to be qualified in the system, the customer will not have to embark on a long and costly MMIC design.

Growth and many customer awards are the obvious signs of Custom MMIC's success. Yet they are just the outcome of what makes the company successful: its core values. Paul is proud that not a single employee has resigned in 13 years. He fosters a culture that respects spending time with family and he is passionate about the "Women in Engineering" scholarship, which awards substantial financial support to young women pursuing undergraduate engineering degrees. When you have created a culture of respect and kindness, recruited a talented team, empowered them and treat your customers as members of the team, success follows. QED.

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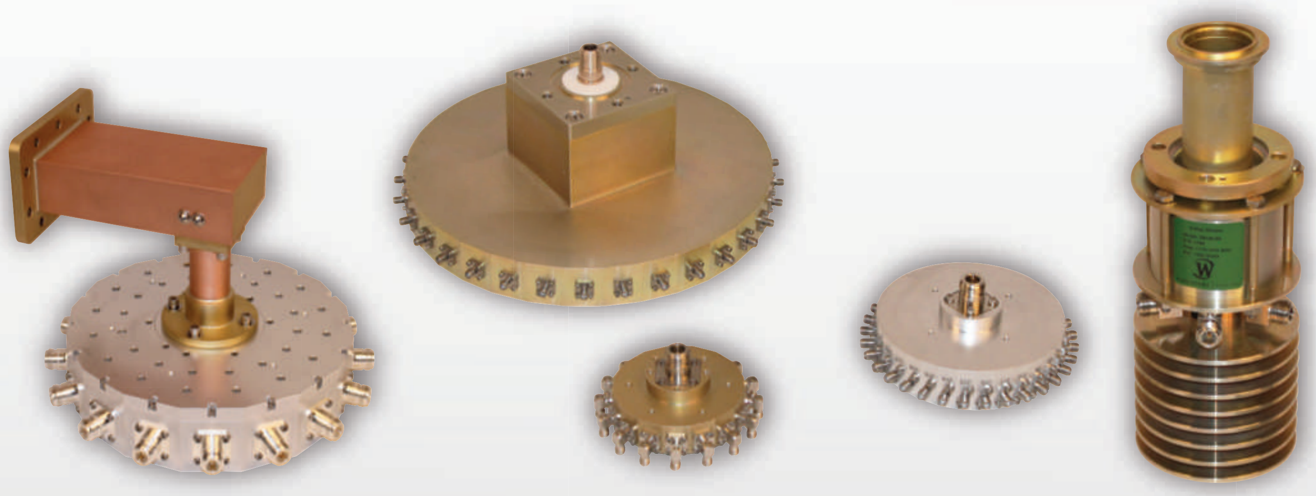
D8454	8-Way	370-450	10,000	0.25	5	1.30	3 1/8" EIA, N-F
D9816	8-Way	330-530	10,000	0.25	5	1.30	3 1/8" EIA, N-F
D9710	8-Way	1000-2500	2,000	0.3	5	1.40	1 5/8" EIA, N-F
D9529	8-Way	2305-2360	1,000	0.2	5	1.15	7/16-Female, N-F
D9528	8-Way	2305-2360	2,000	0.2	5	1.15	7/8" EIA, N-F
D10851	8-Way	2400-2500	8,000	0.2	5	1.25	WR340, 7/16-F
D5320	12-Way	470-860	500	0.3	5	1.30	All N-Female
D11028	16-Way	2305-2360	2,000	0.2	5	1.15	1 5/8" EIA, N-F
D6083	16-Way	2310-2350	2,000	0.2	5	1.15	7/8" EIA, SMA
D11433	16-Way	2700-3500	2,000	0.3	3	1.35	WR284, N-F
D11815	16-Way	2700-3750	6,000	0.3	3	1.35	WR284, N-F
D9582	16-Way	3100-3500	2,000	0.25	6	1.50	WR284, N-F
D11839	16-Way	5300-5900	10,000	0.15	5	1.40	WR159, QD 7/16-M
D6857	32-Way	1200-1400	4,000	0.5	5	1.35	1 5/8" EIA, N-F
D10795	32-Way	900-930	25,000	0.25	3	1.30	WR975, 4.3-10-F



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An Adaptable GaN Power Amplifier for S-Band Radar

INVITED PAPER

Robert Smith and Liam Devlin
Plextek RFI, Great Chesterford, Saffron Walden U.K.
Kim Tran and Richard Martin
Qorvo Inc., Richardson, Texas

S-Band active aperture phased array radars require multiple power amplifiers (PA) producing sufficient RF output power with high power-added efficiency (PAE). GaN technology is now the preferred choice for many of these applications. This article describes the design, realization and evaluation of a PA for S-Band radar using a GaN power transistor from Qorvo. The QPD1020 has hybrid input matching, i.e., a GaN transistor with an internal passive input matching network fabricated on a cost-effective GaAs process. It offers the cost advantages and flexibility of a discrete transistor with many of the space and development time savings of a MMIC solution. The input of the device is internally matched to 50 Ω across 2.7 to 3.5 GHz. As most S-Band radars will only use a portion of this band, the PA output match may be optimized for either output power or PAE across the intended operating band. PAs have been designed to optimize performance across 2.7 to 3.1 or 3.1 to 3.5 GHz by changing only the component values of the RF matching networks. This approach shortens development time compared to a discrete power bar solution.

Active aperture phased array radars require high efficiency solid-state PAs capable of output power of 10s of W. In recent years, GaN on SiC technology has fulfilled this need at L-, S- and X-Band. However, the RF radar engineer still has to select an appropriate form factor for the PA based on specific radar requirements, including adaptability and cost.

This article first reviews the advantages of phased array radar and discusses the passive and active aperture architectures. The requirements of the solid-state PA in an active aperture phased array radar are outlined, showing how a hybrid input matched transistor helps address these. The design of two PAs—"upper" and "lower" band variants—is discussed, including the measured results. The lower band PA was tuned for 2.7 to 3.1 GHz, the upper band for 3.1 to 3.5 GHz. The transistor used for both bands is the same: the Qorvo QPD1020, with an internal input match covering 2.7 to 3.5 GHz.

PHASED ARRAY RADAR

Compared to the historic radar with a rotating antenna, a phased array enables electronic beam steering, meaning the direction of the beam is steered without mechanically positioning the antenna. The beam is positioned much more rapidly using electronic rather than mechanical steering; as such, the radar can quickly switch between multiple targets and generate multiple independent beams.[1] Although the phased array radar has significant technical benefits, it is more expensive and requires a longer development time compared to the historic mechanical radar.

A phased array radar can be implemented as a passive or active aperture (see ***Figure 1***). For simplicity, only the transmit (Tx) path is considered. In a passive aperture, one high-power transmitter is used with a power distribution network feeding the individual elements. The phase at each element is controlled by a phase shifter placed before each antenna. In an active aperture phased array, each element has its own, lower power PA.

When phased array radars were first developed, the passive aperture architecture was preferred, as high-power, high efficiency vacuum tube amplifiers were available that could feed all the antenna elements. In contrast, the solid-state amplifiers used in active aperture radars had relatively low power and efficiency. However, the passive aperture architecture has a number of disadvantages. Phase shifters capable of handling high-power are required, and the loss of the distribution network degrades the overall transmitter efficiency.

In an active aperture topology, the phase shifter is placed before the amplifier, reducing the power handling requirement of the phase shifter. A power distribution network is still required for the active aperture array; however, it only handles relatively modest power levels and does not affect the output efficiency of the PA. The active aperture architecture also offers better redundancy than the passive aperture. If the passive aperture amplifier—typically a vacuum tube—fails, the entire array becomes non-functional. In comparison, if a single PA fails in an active aperture array with hundreds or thousands of elements, the radar continues to function, almost unaffected by the PA failure.

The main limitation of the active aperture array—the relatively low-power and efficiency of solid-state amplifiers

—has been largely addressed by GaN technology. This wide bandgap semiconductor operates at higher voltages, hence can achieve higher power density and efficiency than, for example, GaAs at S-Band.

Active phased array radars place many challenging requirements on the PA. When determining the specifications for a GaN PA used in an active aperture phased array radar, the requirements of the system must be carefully considered:

- Printed circuit board (PCB) area can be very limited in a phased array radar, where the radiating elements are spaced one-half wavelength apart.
- The frequency of operation may vary, depending on the particular radar. For example, at S-Band it may not be necessary to operate across the full 2.7 to 3.5 GHz, which provides the opportunity to optimize performance for a particular portion of the frequency band.
- The available DC power for a radar system also varies depending on application. For example, power and cooling will be relatively unconstrained for a fixed ground radar compared to a vehicle-mounted system. In the former case, it may be preferable to optimize the PA for output power to increase range at the expense of DC power consumption and a more complicated cooling system. In the latter case, the PA could be optimized for PAE to minimize power consumption and simplify cooling requirements.
- Another important consideration is in-band stability. In some applications, it may be desirable to add more stability margin, if the PA is expected to operate at very low temperatures or if the impedances seen by the PA are undefined or unpredictable. In other applications, the terminating impedances may be well defined and the K-factor can be reduced to increase gain.

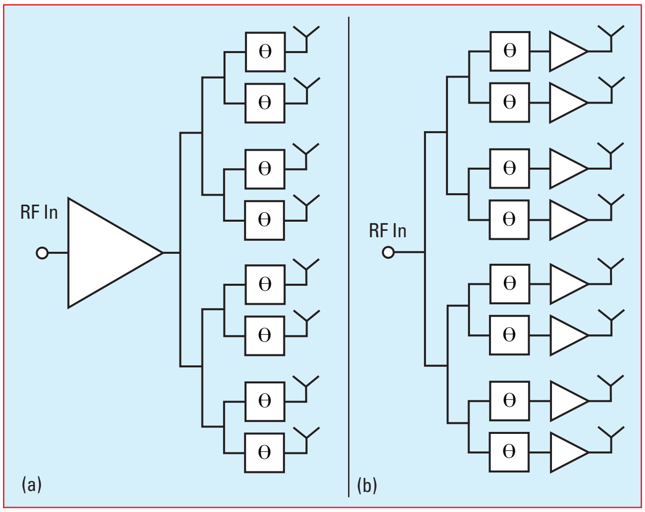

Fig. 1 Passive (a) and active (b) aperture phased arrays.

For a radar system developer, it is desirable to optimize each individual radar to the set of requirements; however, this requires a lot of engineering effort and increases the development time and cost. The ability to tune a specific transistor to address particular radar requirements provides the designer with flexibility without requiring new components to be procured and qualified.

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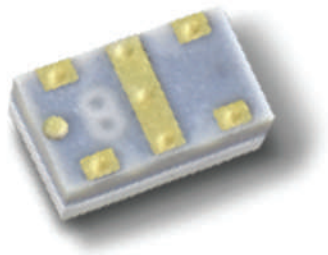

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PA DESIGN

A MMIC provides high levels of performance and only requires a small PCB area. A MMIC also requires minimal design effort from the radar designer: once a suitable MMIC is chosen, it is only necessary to provide the appropriate low frequency decoupling and ensure the package attachment to the PCB provides a reliable electrical ground and thermally conductive path. However, the frequency range and output match of the MMIC is fixed, offering no ability to quickly retune for different requirements. At the other end, a PA based on discrete power bars and surface-mount (SMT) matching components offers high flexibility, at the expense of PCB area, increased development time and increased assembly cost.

A hybrid input matched transistor is a good compromise: more compact than a discrete PCB solution with greater design flexibility than a MMIC. It is also less expensive than a GaN MMIC while providing the performance required by

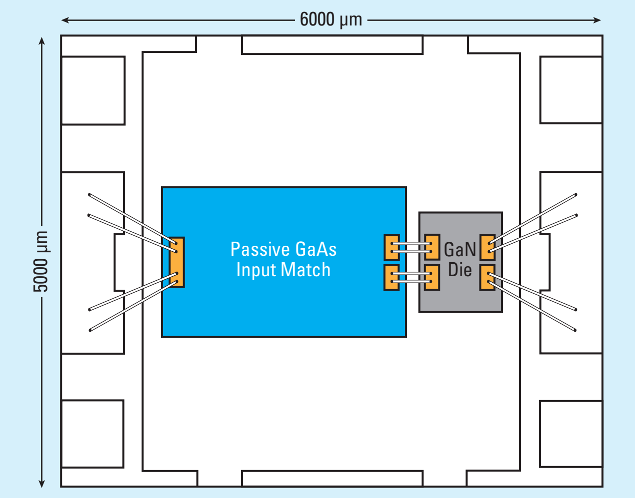


Fig. 2 Internal layout of the QPD1020 GaN transistor with hybrid input matching.

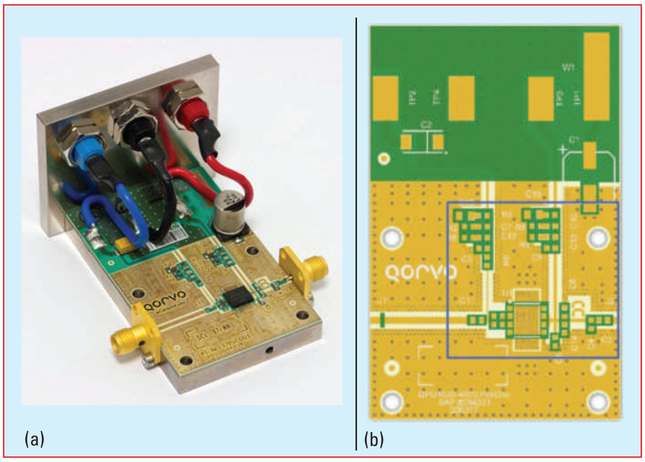
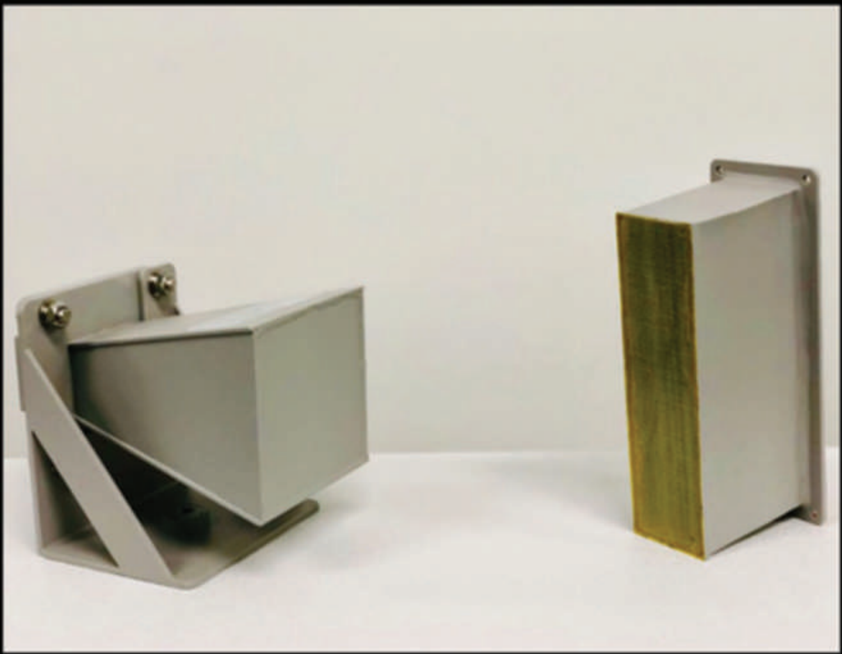
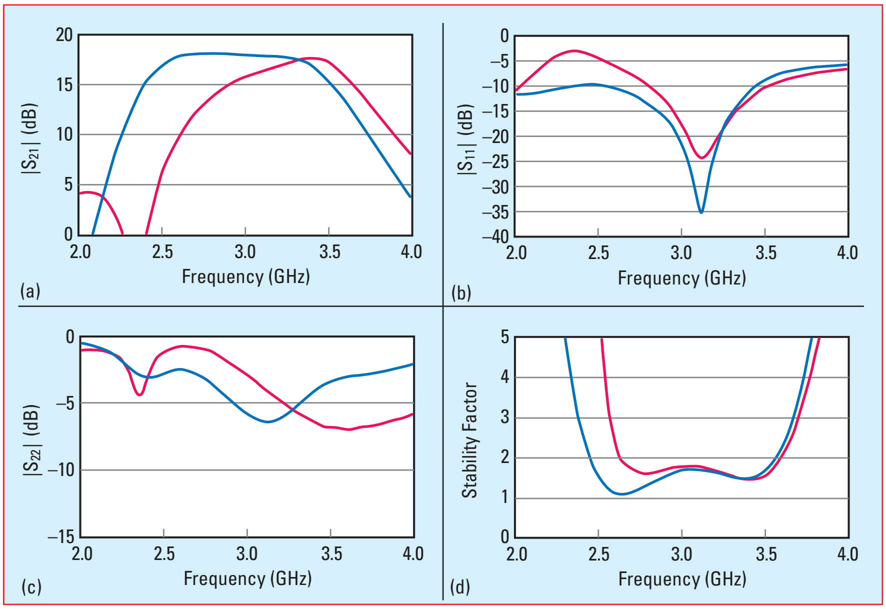


Fig. 3 PA evaluation board (a) and PCB layout (b). The design includes both upper and lower band variants; the main circuit area is outlined in blue.



a modern active aperture phased array radar. The radar designer's job is simplified by only having to retune the PA using SMT component changes. ***Figure 2*** shows the internal layout of the Qorvo QPD1020 transistor. The GaN on SiC power transistor is fabricated on a 0.25 µm, high voltage GaN process, which can be operated at drain bias up to 50 V. The passive input matching circuit die, fabricated on a Qorvo GaAs process, is designed to cover 2.7 to 3.5 GHz and provide some in-band stability. Assembled in a plastic overmold package reduces cost, compared to an air cavity or metal-ceramic package, an important consideration when the transistors will be used in high volume.

Figure 3 shows the PA test fixture and evaluation board. The PCB was constructed from Rogers 4350B laminate with a thickness of 20 mils and was bonded to an aluminum carrier, with an aluminum sidewall with banana plugs added for testing and evaluation. The same PCB layout was used for both the lower and upper band PAs. The SMT components that tune the frequency include a parallel RC network on the input and several shunt capacitors on the output. While designing and fabricating a new PCB layout with modified SMT component positions offers the maximum control over performance, it is considerably more expensive and time consuming.



▲ Fig. 4 Measured small-signal gain (a), $|S_{11}|$ (b), $|S_{22}|$ (c) and stability factor (d) across the lower (blue) and upper (red) bands.

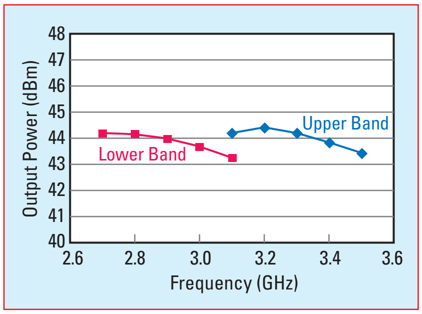
The PCB measures 40.1 mm × 63 mm; however, the area for RF matching and low frequency decoupling measures only 26.7 mm × 24.1 mm. Copper-filled vias in the PCB provide a good electrical ground and thermal path for the transistor. High quality 0603-sized capacitors are used to reduce unit-to-unit variation. With the 50 V supply voltage, the capacitors must have a suitable breakdown voltage.

The PA shown in Figure 3 was originally designed for the 2.7 to 3.1 GHz band,[2] using transistor load-pull data and S-parameters and an EM simulation of the PCB layout. The same PA was subsequently retuned to cover 3.1 to 3.5 GHz. For optimum performance, a small shift in position of the first decoupling capacitors helped shift the response up in frequency. To demonstrate the adaptability of the hybrid input matched approach, the lower band PA was tuned for PAE and the upper band PA for output power.

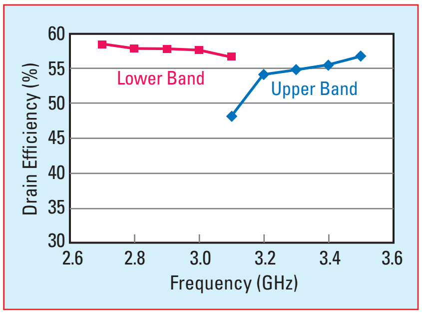
MEASURED PERFORMANCE

All measurements include the losses from the PCB and 3.5 mm connectors.

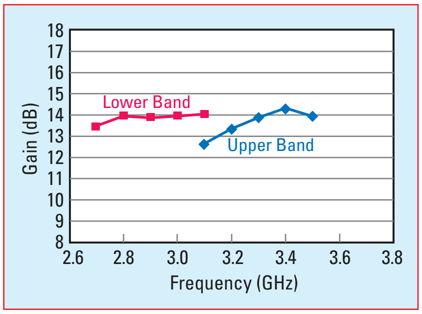
Figure 4 shows the measured small-signal performance of the two PA variants. The lower band was tuned to 2.7 to 3.1 GHz, the upper band to 3.1 to 3.5 GHz. The upper band PA has a positive gain slope, which can be desirable in some applications, as it reduces the need for a gain equalizer. As the input return loss is largely determined by the GaAs passive die within the package, the input return losses of the two variants are similar. The output return loss is set by the PCB output matching network; there is a considerable shift between the variants, corresponding to



▲ Fig. 5 PA output power at P_{3dB}, including evaluation board losses.



▲ Fig. 6 PA drain efficiency at P_{3dB}, including evaluation board losses.



▲ Fig. 7 PA gain at P_{3dB}, including evaluation board losses.

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TABLE 1 MEASURED PERFORMANCE			
Parameter	**Condition**	**Low Band**	**High Band**
		2.7 to 3.1 GHz	3.1 to 3.5 GHz
$P_{3\,dB}$ (dBm)	Typical	43.8	44.0
η at $P_{3\,dB}$	Typical	57%	55%
Mid-Band Small-Signal Gain (dB)	Typical	18.0	17.4
Input Return Loss (dB)	Minimum	11.7	10.3
Output Return Loss (dB)	Minimum	2.8	3.9
Stability Factor	Minimum	1.12	1.45

the desired frequency bands. The stability factor is higher for the upper band PA than the lower band PA. These measurements show how stability factor can be traded for small-signal gain. As discussed, the required stability factor depends on the operating environment of the radar.

The two PAs were measured under pulsed large-signal conditions using a 128 µs pulse-width signal with a 10 percent duty cycle. ***Figure 5*** shows the output power at 3 dB compression (P_{3dB}) for both PAs. Both produce greater than 43 dBm (20 W) output power within their target frequency bands, with a typical P_{3dB} of 44 dBm for the upper band PA. ***Figure 6*** shows the respective PAE at 3 dB compression, including the output losses of the device package, PCB matching networks and SMA connectors. As noted, the lower band PA was tuned for optimum PAE and the upper band PA for P_{3dB}. For comparison, the estimated drain efficiency of the GaN transistor is 64 percent. The efficiency of the upper band PA rolls off at 3.1 GHz; further tuning may improve it. The gain at 3 dB compression is plotted in ***Figure 7***. As with the small-signal gain, the upper band PA shows a positive gain slope, while the gain of the lower band variant is almost flat across the operating band.

CONCLUSION

Active aperture phased array radars have many technical advantages over the passive aperture architecture; however, they require high-power and high efficiency PAs. The hybrid input matched transistor offers an adaptable and cost-effective solution which reduces development time and PCB area compared to a discrete power bar approach, yet allows the RF radar engineer to retune performance to meet the specific needs of the radar system. Two example PAs using the QPD1020 GaN transistor were designed and measured, achieving good performance (see ***Table 1***). The same transistor and power amplifier layout can be retuned for a different frequency band, with the output match designed to optimize output power, PAE or a trade between the two.■

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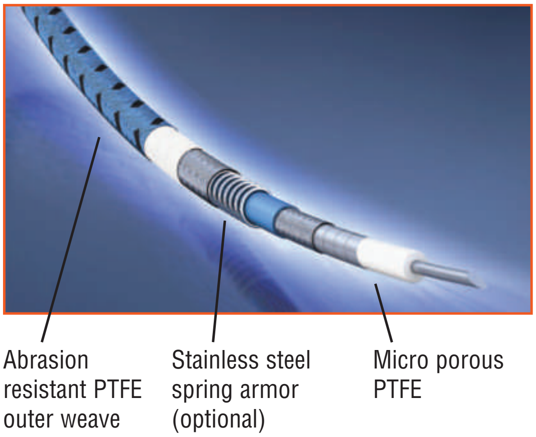

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ARROW

Mil-Spec Coax Cable Assemblies: The Shift from Custom Proprietary to COTS

Pasternack
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Historically, high-reliability (hi-rel) components involved custom and often proprietary processes and were used almost exclusively by the military and space industries. This trend of build-to-print interconnects has shifted in many ways, where it is now more feasible for military and aerospace systems to leverage high-rel commercial off-the-shelf (COTS) components, simply because they often satisfy the electrical performance and physical durability requirements of these systems, frequently with the added benefit of interoperability. This article provides an overview of the trends in high-rel COTS coaxial assemblies, as well as covering the general construction of high-rel cables.

The last decade has seen growing demand for COTS devices across almost all civil and defense-related platforms (e.g., radar, EW, UAV). This is attributed to the increasing need for multi-platform open architectures to replace legacy systems and newer, rapidly evolving systems. The Government Accountability Office (GAO)—an organization that actively audits, evaluates and investigates federal programs for Congress—has identified large government agencies such as the Department of Defense (DoD), Department of Energy and NASA as high risk organizations, largely due to their "inefficient contracting approaches."[1] The implementation of massive, long-term contracts is no longer desirable, due to the potentially compromising position of excessive spending and long contracts. The military's buying power is now finding ways to leverage small business and increase competition, in turn enabling more rapid development and highly efficient, robust systems. Notably, overall contract obligations have decreased dramatically in both the defense and civilian sectors: Federal agencies procured 24 percent less in products and services in the 2015 fiscal year compared to 2011.

To reduce the total cost of ownership for the DoD, programs have shifted from massive, long-term contracts for custom built, complex systems to acquisition strategies that involve flexible

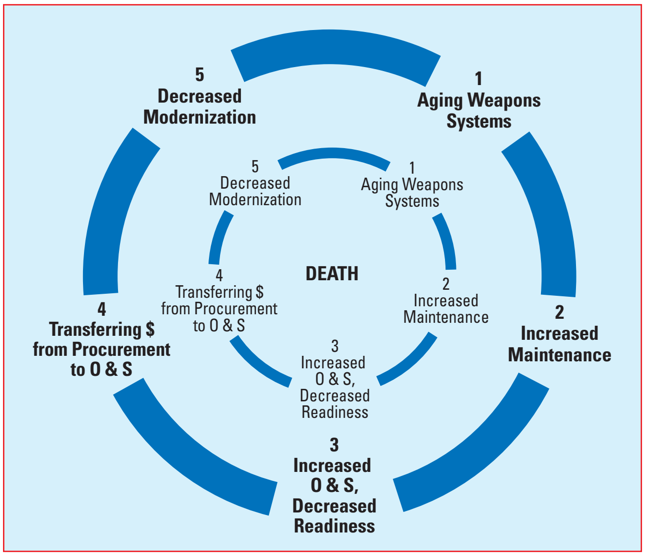
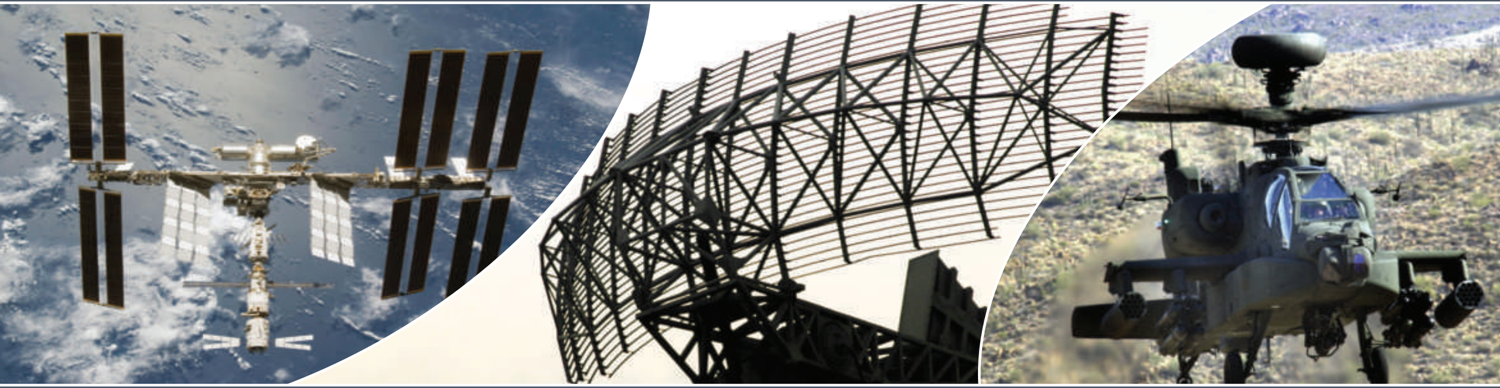


Fig. 1 "Death cycle" of aging military systems, leading to decreased modernization and, ultimately, obsolescence.[3]



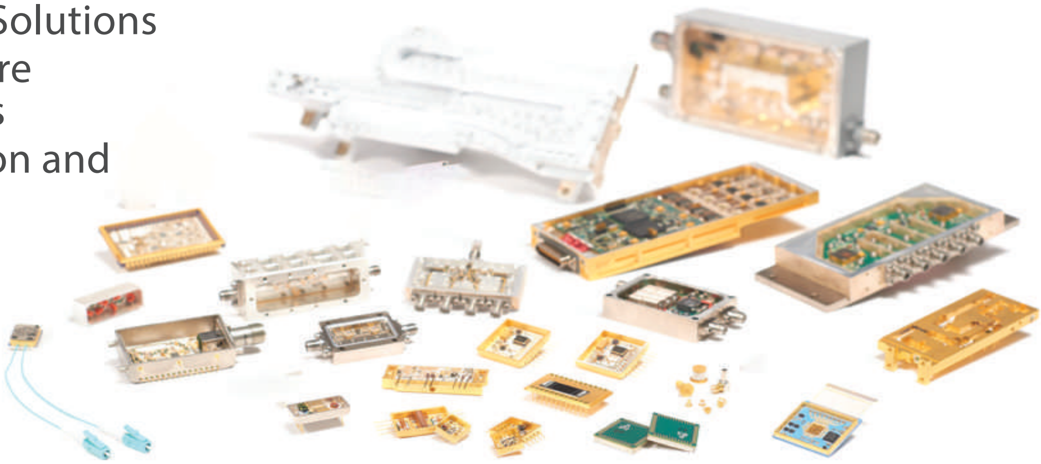


Fig. 2 Order processing flow for military grade coaxial assemblies.

TABLE 1 MIL-DTL-17 INNER CONDUCTOR SPECIFICATIONS

Solid or Stranded	Materials	ASTM Standards Referenced	Additions
Solid Inner Conductor	Bare Copper Wire	B3	
	Tin-Coated Copper Wire	B33	
	Silver-Coated Copper Wire	B298	Coating Thickness > 0.1 μm
	Copper-Clad Steel Wire	B452	High-Strength, 40% Conductivity
	Annealed Copper-Clad Steel Wire	B452	High-Strength, 40% Conductivity, Tensile Strength > 50,000 lbf/in^2
	Silver-Coated Copper-Clad Steel Wire	B501	Coating Thickness > 0.1 μm
	Annealed Copper-Clad Aluminum Wire	B566	Copper Covering 8 to17% by Volume
	Copper-Beryllium Alloy Wire	B197	Tensile Strength 110,000 to 135,000 lbf/in^2
	Annealed Copper-Beryllium Wire	B197	Tensile Strength > 80,000 lbf/in^2
	Silver-Coated Wire	B298	
	High Resistance Wire (80% Nickel, 20% Chromium)	B344	> 100,000 lbf/in^2
Stranded Inner Conductor		B8 or B286	Tensile Strength and Elongation of Conductors Tested Prior to Stranding, No Over-Coating, Joints in Individual Strands No Closer than 5-Lay Lengths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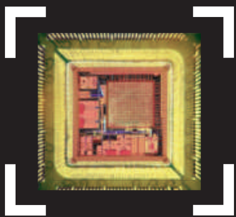

TABLE 2
MIL-DTL-17 MAIN DIELECTRIC MATERIALS SPECIFICATIONS

Material	Description
Polyethylene (PE)	ASTM D1248, Type I, Class A, Grade E-4 Low Density
	Solid PE
	Solid PE: Coated with Talc to Prevent Sticking
	Air-Spaced PE: Filament Threads
	Air-Spaced PE: Foamed
	Conductive PE: ASTM D1248, Type I, Class C, Carbon-Black Type
Polytetrafluoroethylene (PTFE)	PTFE, ASTM D4894, ASTM D4895
	Solid PTFE: Extruded
	Air-Spaced PTFE: Perforated Tape Wrapped
	Air-Spaced PTFE: Filament Threads
	Air-Spaced PTFE: Porous Tape Wrapped
	Solid PTFE: Coated with Semiconductive Material
Fluorinated Ethylene Propylene (FEP)	Solid FEP: ASTM D2116
	Solid FEP: Extruded
	Air-Spaced FEP: Foamed

design requirements for incremental advances in complex systems. The DoD's Reduce Total Ownership Cost (R-TOC) program, implemented in the early 2000s, involves three approaches:[2]

- Improve reliability and maintainability (R&M).
- Reduce supply chain response time and logistics footprint.
- Establish a competitive supply base to support products.

These goals still hold today, as military procurement is increasingly shifting toward evolutionary acquisition, a method that delivers capability in increments, enabling a stepping-stone path to capability improvements. Contrary to the spiral shown in ***Figure 1***, this shift mitigates the major ownership risk of large operation and support (O&S) costs for aging systems, which invariably moves funds from procurement to maintenance and hurts system modernization.

RF CABLE MILITARY SPECIFICATIONS

Passive subsystem components such as interconnects can often use a COTS-based solution, so long as the assembly ensures the quality and reliability necessary for mission-critical applications. For a coaxial cable, this means that every part of the cable assembly—the center conductor, dielectric, shielding, cable jacket and connectors —has to be considered, as well as the testing to validate reliable performance. Vendors of hi-rel COTS components recommended for military applications establish pedigree through open industry standards involving various levels of stringency. Military specifications (mil-spec) are among the most intensive because of the tracking and transparency necessary for every step of cable fabrication and testing. The MIL-DTL-17 standard for flexible and semi-rigid RF cables is the most exhaustive military specification for coaxial cables, often citing MIL-STD-348 for connector interfaces.

In contrast, the complementary MIL-STD-790 standard ensures reliability through a Qualified Products List (QPL), a system established by the DoD to simplify purchasing products that meet defined qualification requirements. Having a product introduced to the QPL involves two main aspects: lot traceability and compliance to the relevant specification test requirements.

Lot traceability is the ability for a manufacturer to trace all piece part acquisitions back to the original source,

TABLE 3 SAMPLE MIL-STD-17 JACKETING SPECIFICATIONS

Materials	Standards Referenced	Notes	Required Tests
Polyvinylchloride (PVC)			Unaged, Oven Aging at 100°C, Oil Immersion, Brittleness Temperature
Polychloroprene Rubber (Neoprene)			Unaged, Oven Aging at 100°C, Oil Immersion, Brittleness Temperature, Ozone Resistance
Fiberglass Braids	MIL-Y-1140	Impregnated with Silicon-Based Varnish, Colored Brown	
Polytetrafluoroethylene (PTFE)	ASTM D4894 & D4895	Colored White	
Extruded Fluorinated Ethylene Propylene (FEP)		Transparent	
Ethylene and Tetrafluoroethylene (ETFE)	ASTM D3159		
Ethylene and Chlorotrifluoroethylene (E-CTFE)	ASTM D3275		
Polyurethane Thermoplastic Elastomer (PUR)			Unaged, Air Pressure Aging, Ozone Resistance, Brittleness Temperature, Torsional Stiffness,Torsional Modulus, Hydrolytic Stability
Perfluoroalkoxy (PFA)	ASTM D3307	Tensile Strength 3000 lbf/in^2, Elongation > 275%	
Cross-Linked Polyolefin (XLPO)			
Thermoplastic Elastomer (TPE)	ASTM D4245		
Metal Armoring	ASTM B211	Aluminum Alloy Braid Construction, Diameter 0.0126 in., Tensile Strength > 52,000 lbf/in^2, Coverage > 88%, Aluminum Paint Covering	

as well as the manufacturing processes to fabricate the end product. This is immensely helpful with failure analysis and quality assurance, as the cause of any failures can be readily discovered and future risks mitigated. Naturally, when considering the number of components that go into an assembly, this task can become overwhelming. An effective enterprise resource planning system is likely required, as well as a systematic process to upload all of the information. Moreover, a training program is mandatory to be able to continually produce qualified parts. ***Figure 2*** illustrates the lot traceability process for a coaxial assembly; it has more than 30 steps.

The ability to demonstrate that in-house testing adheres to the specification requirements is also critical, as a wide range of conformance tests is necessary for coaxial assemblies. Some manufacturers provide the additional transparency of providing test reports for each lot, as datasheets may only reveal a limited amount of data. While test reports are not necessarily linked to a QPL, the ability to access test plots allows a designer to be acutely aware of the performance of a component.

ANATOMY OF A MIL-SPEC CABLE ASSEMBLY

As stated earlier, two major standards can be drawn upon to under-

stand the materials, interfacing and conformance requirements for a coaxial cable and connector: MIL-DTL-17J and MIL-PRF-39012E. Both of these require repeated testing during nearly every phase of connector and cable fabrication to ensure performance. The traceability of this testing is necessary to qualify a product on the QPL.

Inner Conductor

The dimensions and materials of the various coaxial assemblies used in military installations are predetermined in MIL-DTL-17. ***Tables 1*** and ***2*** list some of the materials used in RF cables and some of the additional requirements for military purposes. For center conductors, this includes testing tensile strength and elongation of the individual strands in a stranded center conductor prior to stranding, as well as the minimum distance between the individual wire joints. Solid center conductors that are coated with silver will have a minimum coating thickness, while copper cladding will specify a conductivity of at least 40 percent of copper, as specified in the International Annealed Copper Standard.

Dielectric

Mainly three dielectrics are specified: polyethylene (PE), polytetrafluoroethylene (PTFE) and fluorinated ethylene propylene (FEP). These can be installed in either a solid extruded fashion, air-spaced with expanded/perforated/porous tapes or with filament threads that can be braided. Most engineers are familiar with PE and PTFE insulating materials; the FEP material exhibits a similar dielectric constant to PE and PTFE, with the benefit of high temperature performance. This material is often used as the jacket for plenum applications. An air-spaced dielectric incorporates air as the dielectric, which can be accomplished using threaded filaments, foamed or some type of porous tape. Ultimately, this enables a lower dielectric constant and less signal loss. This material also supports smaller cable diameters.

Shielding

The shielding of a military standard cable can be either braided or solid tubes. For the braided types, the amount of coverage is crucial, as gaps in shielding allow interference and signal degradation. The amount of coverage is apparent by using the equation in the standard. Solid outer conductors will have a standard purity of at least 99 percent, and they can be either seamless or welded. Welded shields, however, must be recrystallized to produce a uniform grain size across the conductor. Often, hi-rel cables involve at least two layers of shields and a barrier tape to prevent signal leakage and interference.

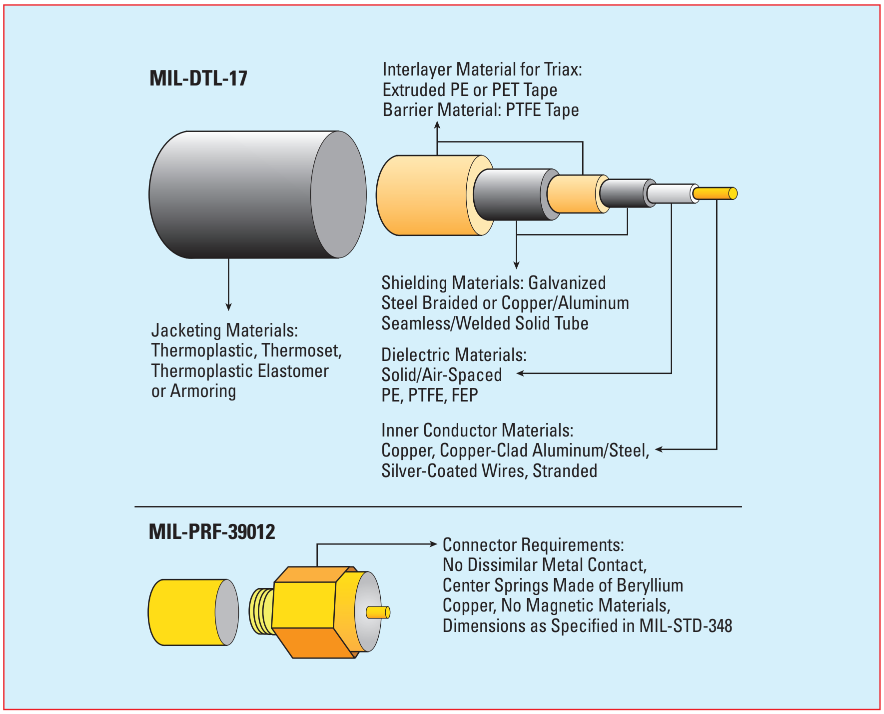

Fig. 3 Anatomy of a mil-spec coaxial cable assembly, showing material and construction requirements.

Jacketing

Jacketing plays an important role in the reliability of coaxial assemblies. These materials must undergo various mechanical stress tests to ensure the integrity of the cable. Parameters such as tensile strength, elongation, ozone resistance, oil resistance, brittleness temperature, flammability, abrasion resistance, tear strength and heat distortion are measured—in commercial applications, most of these measurements are not even considered. A fairly broad range of plastics and thermoplastics can be used for jacketing in military applications. A sample list from MIL-DTL-17 is shown in ***Table 3***.

Generally, four types of jacketing materials can be used in a hi-rel cable assembly: thermoplastic, thermoset, thermoplastic elastomer (TPE) and armoring. A thermoplastic (e.g., PVC, PTFE) is a type of material that can be formed above a certain temperature and solidifies upon cooling; it is often formed using an extrusion process. A thermoset (e.g., neoprene, EPR) is permanently set after the curing process, as the internal cross-linked polymers are very resistant to high heat application and have considerable elasticity. A TPE mixes both these chemical technologies to generate a product that can be molded and remolded, while benefiting from the elongation properties of thermosets. Thermoplastics are typically more conducive to indoor applications, as they are highly manufacturable. Thermosets can handle ultraviolet exposure and aging well in outdoor environments. This is not the case for all thermoplastics, as plasticizers can be added to the thermoplastic to enable properties such as low-temperature flexibility, impact resistance and resistance to chemicals/oils. Armoring a cable enables the assembly to handle mechanical shocks and abrasions, which may be helpful in applications where a large vehicle could run over the cable.

Connectors

The MIL-PRF-39012 standard describes the required visual, mechanical and electrical testing necessary to qualify and inspect coaxial cable connectors, and MIL-STD-348 lists the specific interface dimensions for coaxial connectors. Coaxial connectors have mating mechanisms including bayonet, threaded and push-on. The military standard requires a measurement of the force, or torque, required to engage/disengage the mate. Having a minimum requirement can prevent these connections from becoming unmated under mechanical duress, such as flexure or vibrational strain. It is also prerequisite for dissimilar metals not to be next to each other and for the connector head to be constructed of nonmagnetic materials, as galvanic corrosion can occur due to the electromotive force at a bimetal joint. At high powers, these joints and ferromagnetic materials can be a source of passive intermodulation distortion (PIM). Parameters measured for RF connectors include permeability, leakage (when pressurized), insulation resistance, center contact retention, corrosion resistance and VSWR. The general anatomy of a hi-rel military coaxial cable is shown in ***Figure 3***.

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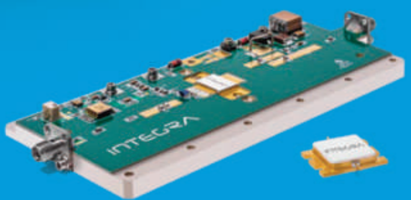

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COMMERCIAL- VS. MILITARY-GRADE

Military standards involve procedures to ensure the structural integrity of coaxial cables and connectors through nearly every step of the design process. While commercial-grade coaxial components generally involve tests for insertion loss, return loss or VSWR, bend radius and, sometimes, capacitance, full mil-spec assemblies require many more electrical tests and extensive physical tests and burn-in. ***Table 4*** broadly summarizes the major differences between commercial and mil-spec, hi-rel cables.

While commercial-grade components are generally less expensive to procure, they are not necessarily cost-effective due to the wide variation in quality between vendors. This leads to interoperability issues during installation, as well as failures in the lab or field. Military-grade coaxial assemblies and their respective fabrication processes are more predictable. This characteristic of process quality and individual component reliability has led to COTS mil-spec coaxial assemblies being used in applications beyond military. Without a doubt, both the commercial and military markets have their own sets of pros and cons. Mil-spec, hi-rel COTS components join many of the best aspects of both.■

TABLE 4

COMMERCIAL GRADE VS. MIL-SPEC COAXIAL CABLE ASSEMBLIES[4]

Parameter	*Commercial*	*Mil-Spec*
Testing	Electrical	Electrical, Mechanical & Burn-In
Quality Variation Among Vendors	Large	Little
Number of Sources	Many	Few and Declining
Pricing, on Average	Cheaper	Higher

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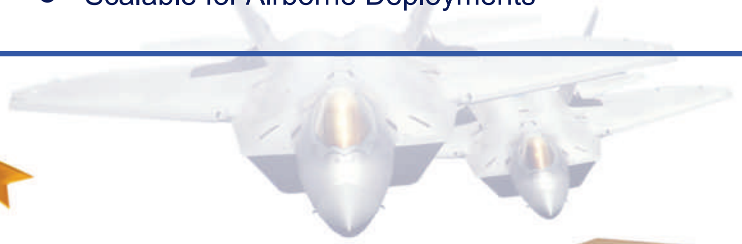

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Thermal Power Handling and Testing of RF PCBs for Deep Space Communication

Varun Joshi
University of Colorado, Boulder, Colo.

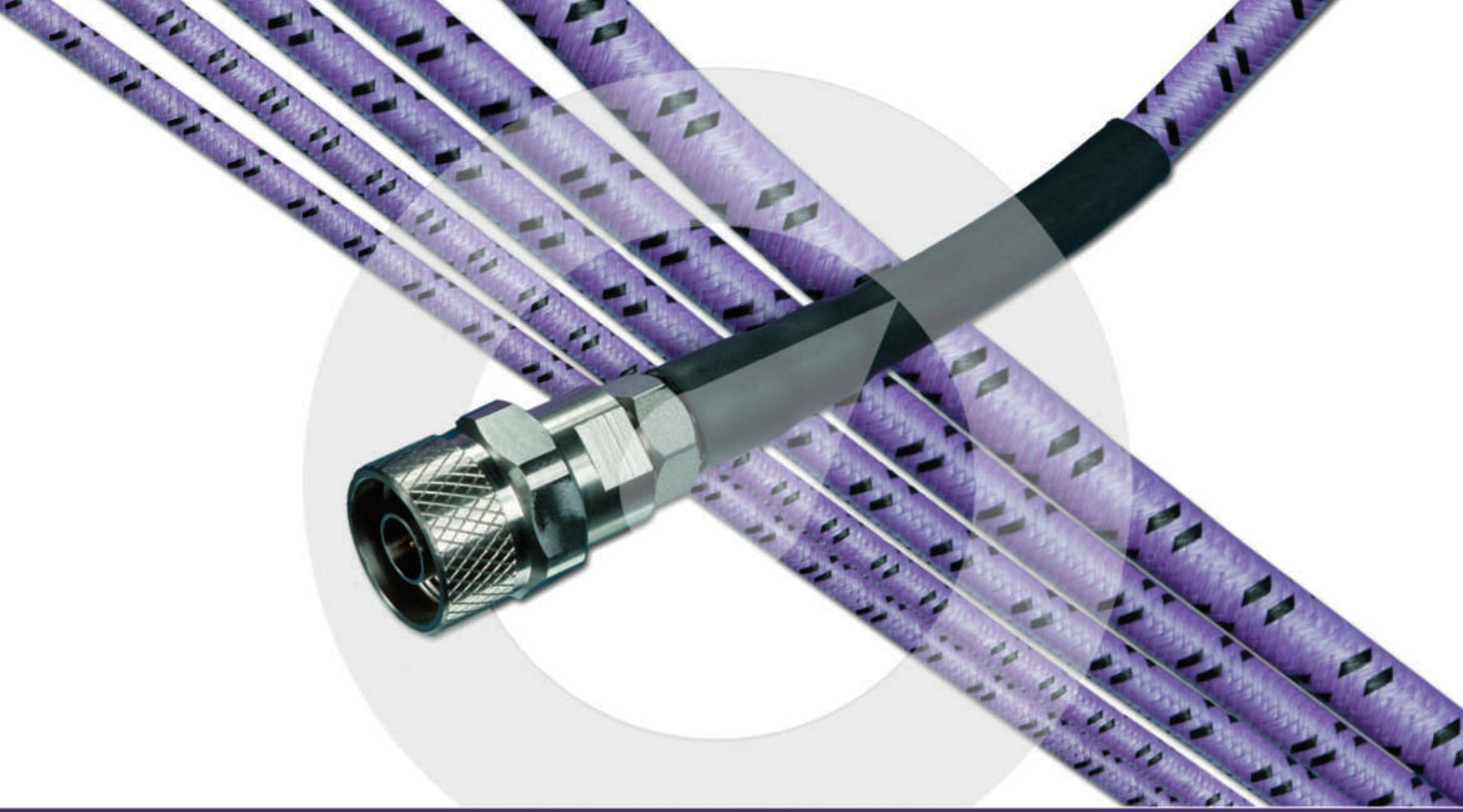
Thermal analysis, simulation and benchtop testing of an X-Band transmitter RF power amplifier (RFPA) printed circuit board (PCB) for the University of Colorado, Boulder Earth Escape Explorer Deep Space CubeSat shows that FujiPoly XR-Um thermal interface material (TIM) provides a better solution compared to the alternatives considered. Results show a reduction in the operational temperature of the PCB from greater than 120°C to 77°C, which is below the maximum 85°C environmental operating temperature of the RFPA.

Dissipation of thermal power generated from RFPAs in CubeSats is a challenge for the effective operation of communications systems. Operation near thermal limits can impact output power and expected lifetime. While a challenge for all satellites, in this article we analyze an RFPA developed for the NASA Cube Quest Challenge by the University of Colorado, Boulder, considering the thermal dissipation problem in overall system design. The RFPA PCB includes an RFPA, bias controller and voltage regulator. The GaAs RFPA has an efficiency of approximately 25 percent and is the dominant system heat source. Low thermal conductivity between the RFPA and the CubeSat introduces a large temperature gradient, causing the RFPA to potentially operate at excessively high temperatures.

The ability to close a satellite communications link is a function of the received signal-to-noise ratio (SNR), which is typically from 2 to 10 dB for current modulation and coding schemes. The received SNR is a function of numerous factors, the most dramatic being space loss, which is proportional to the squared distance to the spacecraft. For deep space missions, space loss can exceed 240 dB (i.e., 24 orders of magnitude). This loss is typically offset by using large antennas with significant gain, by lowering the data rate to reduce the noise bandwidth and by increasing spacecraft transmitter power. While large deep space satellites have the mass, volume and budget to use higher power traveling wave tube amplifiers, most small satellites do not have this option and generally opt for lower power solid-state power amplifiers (SSPA). Some downlink analyses for deep space communication have used RFPA outputs from 2 to 10 W.[1-2]

SSPAs are categorized based on the underlying semiconductor technology, namely more mature GaAs and the more recently available GaN.[3-4] While GaN technology is more efficient than GaAs, consider that GaN amplifiers typically run at drain voltages of 24 to 48 V compared with the 6 to 8 V for GaAs amplifiers. Currently, many CubeSats use 8 and 12 V battery busses, enabling a buck converter configuration for GaAs SSPAs, while GaN SSPAs use boost conversion for the same battery busses. While boost converters are typically less efficient than buck converters, operating a SSPA at a higher voltage requires lower current for the same DC power. These system trades and the differences in efficiency need to be considered in the system design.

The CU Earth Escape Explorer (CU-E^3) communication system used a GaAs MMIC to achieve approximately 25 percent efficiency in its first design iteration. While improved effi-



ciency is expected in future designs, 25 percent is used as the baseline for this study. With a 25 percent efficient RFPA MMIC powered by a 10 W (8 V at 1.25 A) power source, 7.5 W of thermal power is generated. Given the small MMIC size (approximately 25 mm^2), thermal power dissipation is a challenge. The resulting power density is 300,000 W/m^2, compared to the solar constant of 1370 W/m^2. This illustrates the need to effectively address the thermal power handling in high-power, deep space transceivers.

The CU-E^3 design uses a FujiPoly XR-Um TIM at the interface between the bottom copper layer of the PCB and the mounting face of the CubeSat structure. This TIM improves thermal conductivity from the RFPA PCB into the CubeSat, reducing the temperature gradient. Additionally, the TIM is electrically insulating, enabling the typical design goal of a single point ground. Modeling and analysis of the thermal system was aided using desktop simulation software.

THE CU EARTH ESCAPE EXPLORER

The CU-E^3 CubeSat is the University of Colorado entry into the NASA Cube Quest Challenge.[5] The Cube Quest Challenge, sponsored by the Space Technology Mission Directorate's Centennial Challenges program, was NASA's first prize competition in space. Entrants competed for three available 6U CubeSat dispenser slots on the Exploration Mission-1 (EM-1), the first un-crewed lunar flyby of the Orion spacecraft, scheduled for launch by the Space Launch System (SLS) in December 2019. The University of Colorado Boulder's CU-E^3 6U CubeSat was one of the three finalists selected under the Cube Quest Challenge for launch on the SLS.[6]

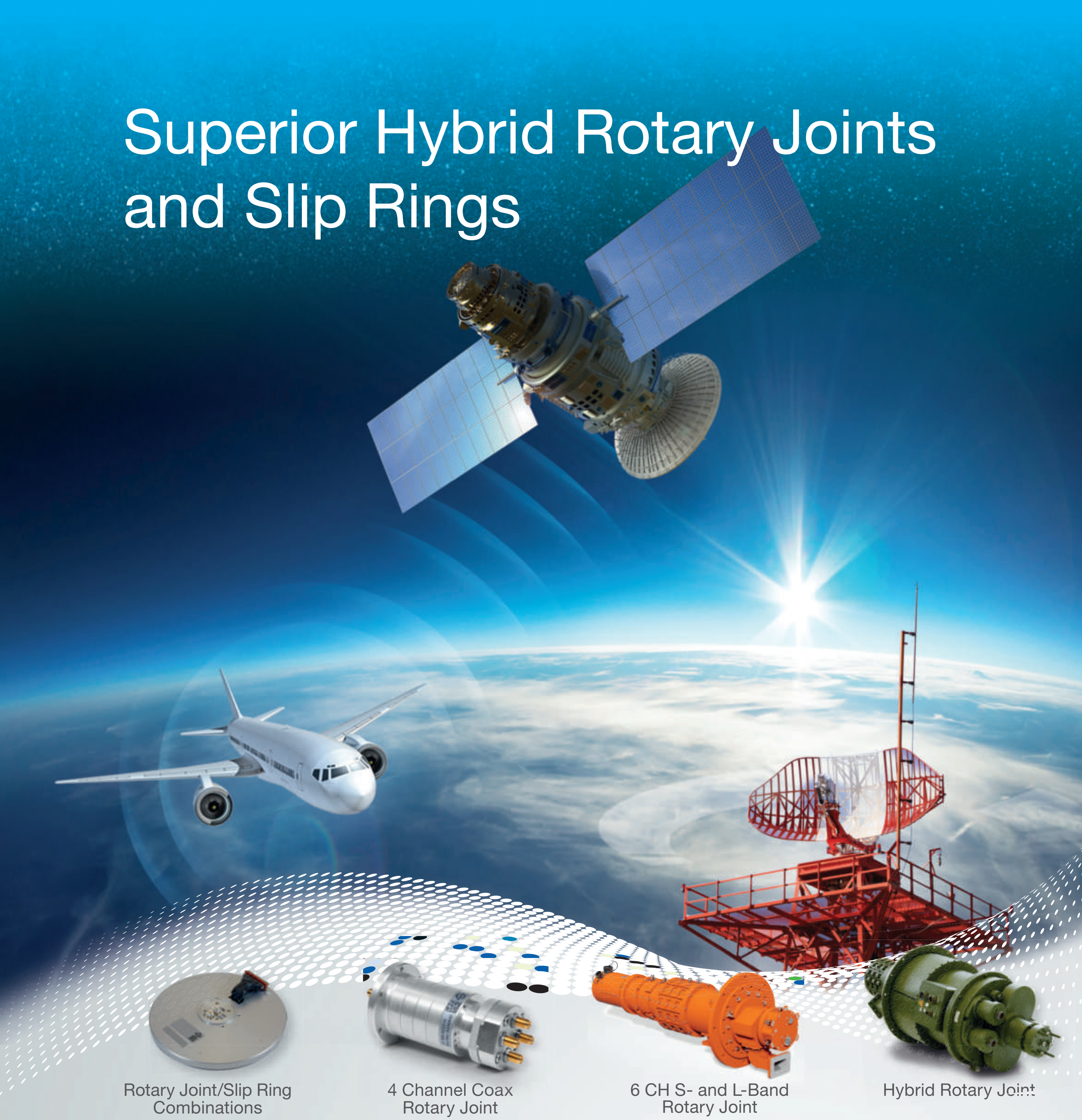
CU-E^3 is designed to compete in the Deep Space Derby portion of the Cube Quest Challenge. To compete, the CU-E^3 CubeSat will travel into deep space using the Earth escape trajectory from the Orion and SLS EM-1, with the duration of the mission one year from launch. ***Figure 1*** shows the approximate Earth escape trajectory of the Orion, with the competition beginning at the 4 million km point, after the spacecraft has passed the moon. The Deep Space Derby competition has four main challenges:

1. **Best burst data rate**—Awards \$225,000 for the spacecraft communicating the largest cumulative error-free data block within a 30-minute period. The minimum requirement is to communicate at least one 1024-bit error-free data block in the 30-minute window.
2. **Largest aggregate data volume sustained over time**—Awards \$675,000 for producing the largest cumulative volume of error-free data in a 28-day period, with 1,000 1024-bit data blocks the minimum requirement.
3. **Spacecraft longevity**—Awards \$225,000 for the longest period (i.e., number of days) between the first and last 1024-bit error-free data blocks, after passing the 4 million km distance and following the 28-day competition period.
4. **Farthest communication distance from Earth**—Awards \$225,000 to successfully communicate at least one 1024-bit error-free block of data from the spacecraft at the greatest distance from the Earth after passing the 4 million km point and before the end of the competition.

▲ Fig. 1 Deep Space Derby mission trajectory for the CU-E^3 CubeSat.

COMMUNICATIONS LINK

A link budget estimates the power and aperture required to close the communications link. ***Table 1*** provides a summary of the CU-E^3 link budget at 8447.6 MHz with an SSPA output pow-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er of approximately 3.5 W.[7] Several parameters, such as the signal and noise powers at the receiver, bit rate, energy per bit over noise power density (Eb/No) and link margin are illustrated for distances of 4 million and 27 million km. The two values for each parameter represent the analyses for a reflector array (RFA) and horn antenna. The transmitted effective isotropic radiated power (EIRP) includes the losses in the spacecraft's transmit chain, the antenna gain and the RFPA output. These values are shown in dBm and assume a 3.5 W SSPA output.

Novel two- or three-stage GaAs RFPA MMICs achieve 30 to 50 percent efficiency in a laboratory environment;[8] however, most commercially available GaAs amplifiers have 25 to 35 percent efficiency. The area near the gate of the MMIC, where the heat is generated, is very small; consequently, the power density is high. ***Table 2*** illustrates this by summarizing GaAs RFPA MMICs operating in the 8 to 8.5 GHz range and reported in the literature, showing output power, power-added efficiency (PAE), PHEMT gate periphery and power density. The power density of the final stage of the RFPA is given by

$$Pd(W/m) = Po(W) / [Gp(mm) \times 10^{-3}N]$$

where Pd(W/m) is the power density of the final stage, Po(W) the output power from the final stage, Gp(mm) the gate periphery of a single PHEMT device in the final stage and N the number of PHEMT devices in the final stage.

The link budget of Table 1 requires the transmitter output power to be approximately 3.5 W to achieve at least a 600 bps downlink bit rate. The power and heat budget in ***Table 3*** shows the need to handle approximately 10 W of thermal power or about 10 J/s of thermal energy, with the RFPA being the major source. Limited RFPA efficiency with the small MMIC size and a large

TABLE 1

COMMUNICATIONS DOWNLINK BUDGET

Parameter	Values		Values	
Tx Antenna	RFA	Horn	RFA	Horn
Slant Range (km)	4,000,000		27,000,000	
Transmitted EIRP (dBm)	56.5	47	56.5	47
Free Space Loss (dB)	−243	−243	−259.6	−259.6
Signal Power Out of Rx LNB (dBm)	−82.5	−92	−99.1	−108.6
Noise Power Density Out of Rx LNB (dBm/Hz)	−123	−123	−123	−123
Noise Power Out of Rx LNB (dBm)	−94.3	−103.8	−111	−112.2
Bitrate (bps)	608	68	13	1
Eb/No (dB)	12.6	12.6	12.7	14.4
Link Margin (dB)	6	6.02	6.12	7.76

TABLE 2

SPECIFICATIONS OF DIFFERENT MULTI-STAGE GaAs PHEMT RFPAs OPERATING BETWEEN 8 AND 8.5 GHz

Input Power (dBm)	Output Power (dBm)	Approximate Power-Added Efficiency (%)	PHEMT Gate Periphery (mm)	Power Density (W/m)	# of Devices in Last Stage	Reference
17	37	55	2.5	500	4	9
11	35	50	1.8	440	4	10
17	35	40	1.62	490	4	11
22	37.5	30	1.4	500	8	12

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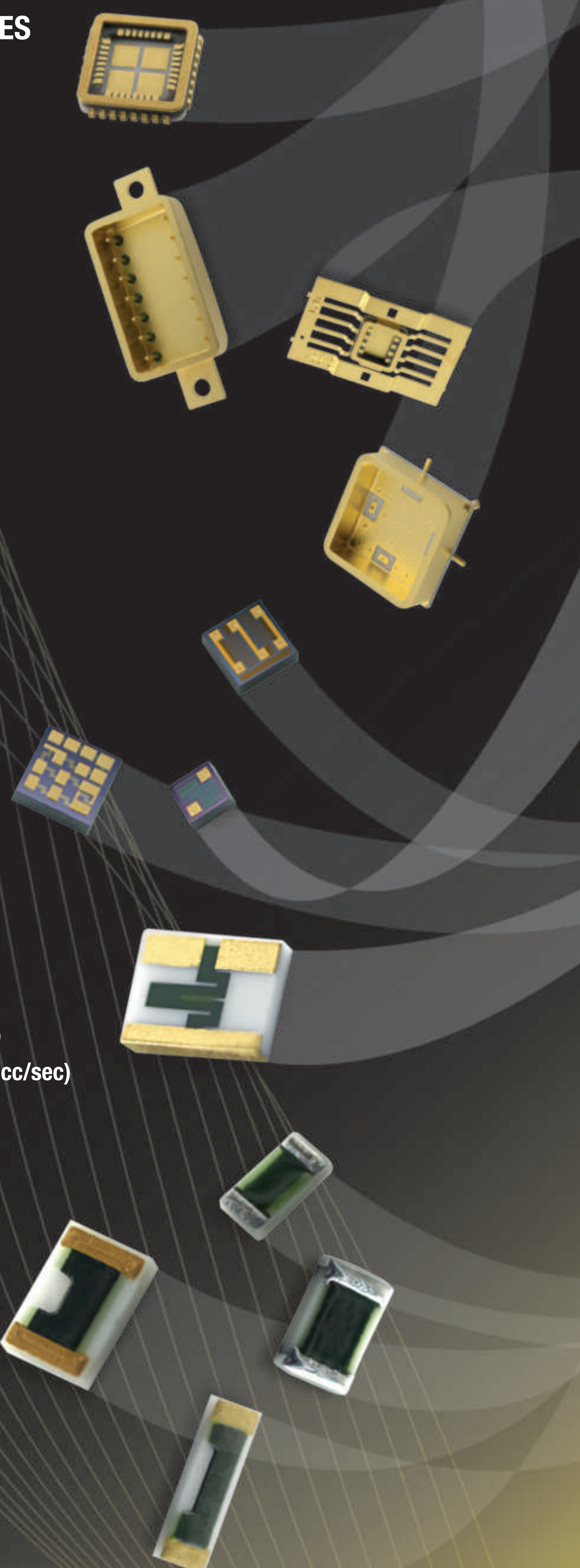

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TABLE 3
RFPA PCB POWER AND HEAT BUDGET

Part	No. of Parts in Subsystem	Total Power Consumed (W)	Power Dissipated as Heat (W)
Preamplifier	1	0.21	0.2
Bias Controller	1	1.26	1.26
Solid-State RFPA	1	10.72	8.7
Buck Converter	1	13.29	1.07

deep space communication distance emphasizes the need to address the thermal power dissipation.

RFPA PCB DESIGN

The RFPA amplifies the –3.5 dBm output from the High Rate CubeSat Communication System (HRCCS) to the required transmit power level of approximately 3.5 W.[13-15] The RFPA PCB contains a buck convertor IC, a power amplifier bias sequence IC, a preamplifier MMIC and a power amplifier MMIC. The PCB has four layers: the RF/signal (layer 1), RF ground (layer 2), power (layer 3) and a ground/heat sink (layer 4).

Figure 2 shows the layout of layer 1. Three dielectrics are sandwiched between the four copper layers (Rogers RO4350B, FR4 and FR4, in the same order). The top copper layer is electroless nickel immersion gold plated to prevent oxidation or other chemical reactions in the harsh space environment. The dielectric specifications of the PCB layers (top to bottom) are:

- **Dielectric 1**—Rogers RO4350B: 6.6 mils thick, Dk = 3.48, Df = 0.0037 at 10 GHz and 23°C.
- **Dielectric 2**—Isola 370HR: 14 mils thick, Dk = 3.92, Df = 0.0250 at 10 GHz and 23°C.
- **Dielectric 3**—Isola 370HR: 6.6 mils thick, Dk = 3.92, Df = 0.0250 at 10 GHz and 23°C.

The total thickness, including the copper and solder-mask layers, is approximately 48.9 mils.

The dielectric layer thickness is uniform along the stack to avoid PCB warping from thermal expansion during manufacturing. Power traces are 60 mils wide for the inner layer, which is not exposed to the environment, and 25 mils wide for the top and bottom layers. Vias have a current rating of 0.5 A per via. The vias and power traces are designed to reduce current density and avoid temperature rises in the PCB.

THERMAL DESIGN

As the highest thermal power density is in the RFPA, additional vias are added around the RFPA MMIC to enable efficient thermal conduction from the top layer (layer 1) to the bottom layer (layer 4). A portion of layer 4, under the RFPA, is designed as a heat sink and electrically isolated from the rest of the layer. One reason for electrical isolation is to provide separation between the RF and DC grounds, which are electrically connected on layer 1. Separation of these ground nets on layer 4 provides distinct locations for the thermal current flow that originates from both the RF and non-RF portions of the circuitry.

Use of a TIM of limited area helps the thermal power dissipation as well as maintaining electrical isolation between layer 4 of the PCB and the aluminum enclosure. The primary reason for electrical isolation between the PCB and its enclosure is avoiding ground loops. The aluminum enclosure is designed to shield the circuitry from radiation in space. FujiPoly XR-Um TIM satisfies the total mass loss (TML) and volume resistivity requirements and is the interface material of choice. The TML specification ensures the outgassing performance acceptable for space. Because the FujiPoly XR-Um TIM offers a thermal conductivity of only 17 W/mK, improvements in thermal conductivity can be obtained using materials which have higher thermal conductivity, such as hexagonal boron nitride nanoribbons (~2000 W/mK) and industrial isotopically enriched ^{12}C diamond (3000 W/mK).

The thermal conductivity of the RFPA PCB is calculated by considering the system in a vacuum. A vacuum environment ensures that heat transfer from the hot PCB-TIM-Al plate system is solely through thermal radiation, as encountered by the spacecraft in deep space. For the analysis, a 46 cm × 46 cm × 46 cm volume at 20°C and an aluminum mounting plate of 9 cm × 5 cm × 0.635 cm were used. Only one side of the aluminum plate was assumed to radiate energy, and its emissivity was assumed constant at all temperatures and IR wavelengths. Sixteen vias were included to aid heat transfer from the RFPA MMIC through the PCB to the TIM. Emissivities of 0.09 and 0.72 were used. A higher emissivity value of 0.72 was chosen to represent a coating on the CubeSat face where the RFPA PCB is attached, while the rest of the CubeSat sides were assumed to have an emissivity of 0.09. For a given thermal power sourced at the RFPA, energy radiated by the system in vacuum environment was calculated from

$$Q(J) = \varepsilon AF\sigma(T_1^4 - T_2^4)$$

where Q(J) is the heat energy radiated from the system, ε the emissivity of the system, A the area that aids the thermal radiation, F the view factor (ranging between 1 and 2), σ Boltzman's constant, T_1 the temperature of the heat source (i.e., the Al plate in this system) and T_2 the temperature of the heat sink (i.e., the vacuum environment).

The material specification for the hot PCB-TIM-Al plate system was analyzed using thermal desktop software. ***Figure 3*** shows the materials stack, including the RFPA MMIC. The RFPA, the primary source of thermal power, was modeled as a resistor with equivalent power generation. The sink for the thermal power was chosen to be one of the aluminum faces of the CubeSat, which radiates the heat energy into a vacuum. The source of thermal power is at the bottom because the RFPA PCB will be mounted inverted to the top face of the CU-E^3 CubeSat to achieve the most effective thermal radiation. Because the top face of CU-E^3 radiates to cold space, it is the best location to mount the RFPA. Analytic and software analysis of the thermal system gave similar results for different operational scenarios and different emissivities. ***Table 4*** shows the RFPA heat load temperatures determined using both methods.

Along with the RFPA PCB placement, the software analysis determined the effect of the PCB area on PCB temperature, and ***Figure 4*** shows the change in temperature as the area is increased. A significant drop from approximately 450°C to 75°C was predicted as the area was increased from approximately 5 to 45 cm^2.

Desktop simulation was also used to estimate the maximum transmit time of the communication system based on the RFPA PCB's thermal dissipation. A more complex model of the entire CubeSat was created, including the helio-centric trajectory of the spacecraft. The analysis found a cold PCB in the off state quickly reaches a temperature of approximately 67°C once the RFPA is turned on. The PCB reaches a temperature of about 77°C within 40 minutes, which is below the maximum operating temperature of the MMIC. Once turned off, the PCB takes about 60 minutes before reaching the steady state temperature of the environment.

RFPA PCB TESTING

Benchtop tests were performed to measure the effectiveness of the Fuji-Poly XR-Um TIM. A resistor of equivalent power handling capacity (greater than 8.7 W) was used as a heat source in place of the RFPA. Two thermocouples connected to the data acquisition system were attached to the system, one to the top of the RFPA PCB, another to the aluminum plate underneath the TIM (see ***Figure 5***). Power supplied to the resistor was varied and temperature readings recorded. ***Figure 6*** shows one set of temperature versus time readings

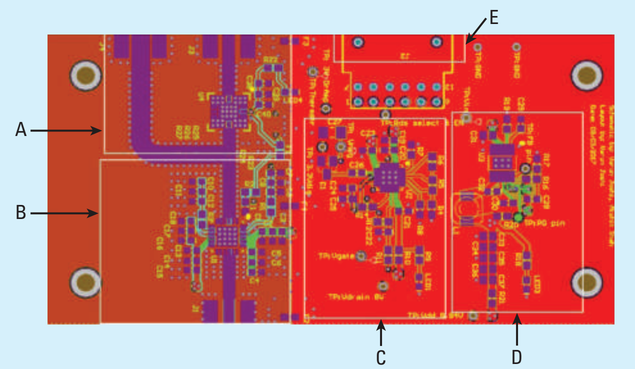


Fig. 2 RFPA PCB layout showing the area for the preamplifier chip and peripherals (A), power amplifier chip and peripherals (B), bias controller/sequencer chip and peripherals (C), buck converter chip and peripherals (D) and DSUB connector (E).

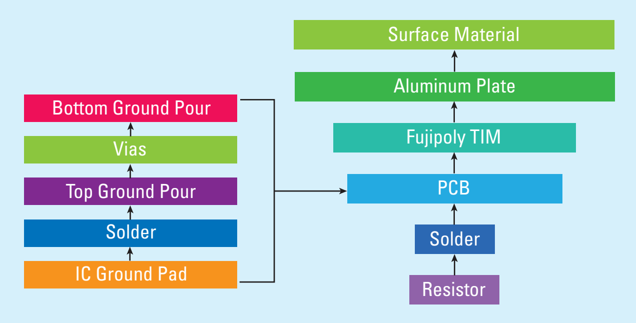


Fig. 3 Thermal model material stack.

TABLE 4

PREDICTED RFPA TEMPERATURE

RFPA IC Heat Load (W)	Emissivity	Theoretical Analysis (°C)	Software Analysis (°C)
1	0.09	254.66	256.35
1	0.72	89.5	91.7
7.2	0.72	300.3	312.83

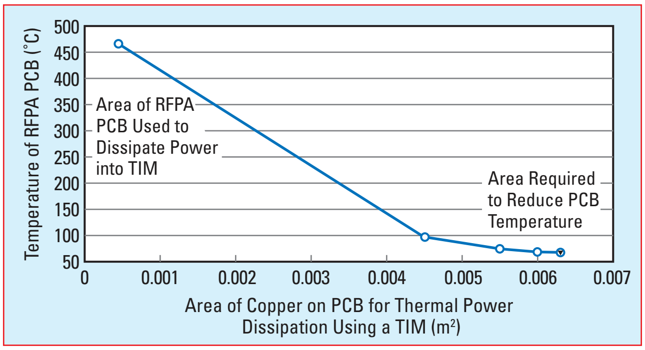
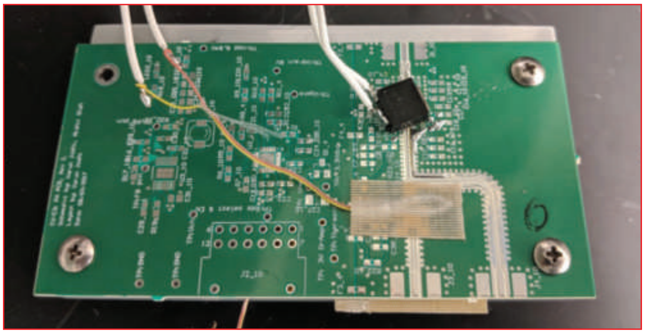
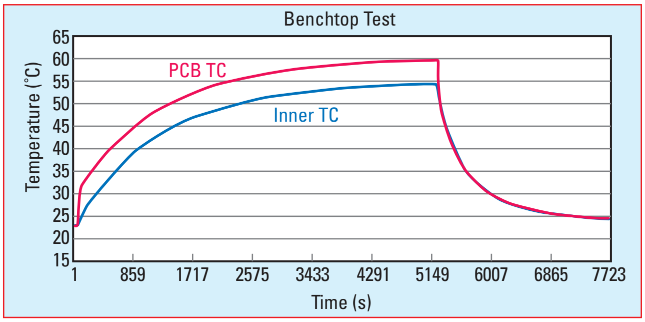


Fig. 4 Predicted RFPA PCB temperature vs. PCB area using thermal software.

from the thermocouple connected to the top of the PCB and the thermocouple connected to the aluminum plate. A heat load of approximately 2 W was used. Within 85 minutes, the PCB temperature reached a peak of 60°C, and the aluminum plate temperature reached 55°C. The 5°C difference between the two surfaces demonstrates the effectiveness of the PCB design and the Fuji-Poly XR-Um TIM for thermal power dissipation. When cooled, both the PCB and aluminum plate followed a similar trajectory to reach room temperature over 43 minutes.



▲ Fig. 5 PCB with dummy heat load in place of the RFPA, mounted to an aluminum plate and instrumented with thermocouples.



▲ Fig. 6 Measured RFPA PCB temperature vs. time.

SUMMARY

The design, simulation and testing described in this article establish a baseline to predict the thermal performance of the RFPA PCB for deep space communications, providing a better understanding of performance drivers such as RFPA efficiency, PCB design, PCB size and the choice of TIM.■

ACKNOWLEDGMENTS

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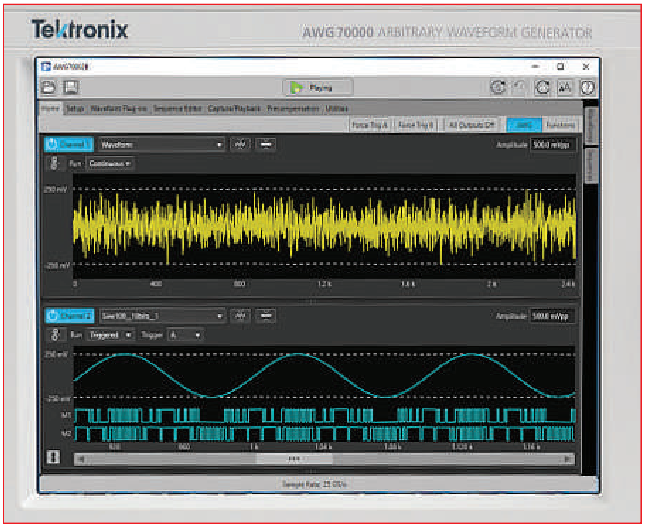


▲ Fig. 1 With 50 GSPS sampling, 20 GHz frequency range and up to 32 GS memory, the Tektronix AWG70001B AWG generates complex waveforms for real-world radar, EW and communications testing.

If a waveform can be defined or captured, chances are the new Tektronix AWG70000B series of arbitrary waveform generators (AWG) can generate the signal (see ***Figure 1***). With waveform sampling rates to 50 GSPS, 10-bit vertical resolution and –80 dBc spurious free dynamic range, these instruments have the precision and resolution for the most advanced radar and EW applications.

Superior digital-to-analog converter performance is not enough to generate realistic signals for testing modern radar, EW and communications systems. Dynamically managing an RF test environment requires keeping track of thousands of individual waveforms, then altering sequence steps as the tests progress. With some commercially available AWGs, the ability to change test sequences is limited to just 256 sequence steps, accessible through an 8-bit pattern jump connector. The AWG70000B addresses this limitation with its new Streaming Waveform ID capability, adding a dedicated Ethernet port to the rear panel of the instrument (see ***Figure 2***). This port allows for direct access to the sequencer hardware using UDP-formatted packets and provides immediate access to up to 16,383 sequence steps in system memory.

Fig. 2 The Waveform Streaming ID function gives immediate access to up to 16,383 sequence steps from system memory, enabled by a dedicated Ethernet port on the back of the AWG.

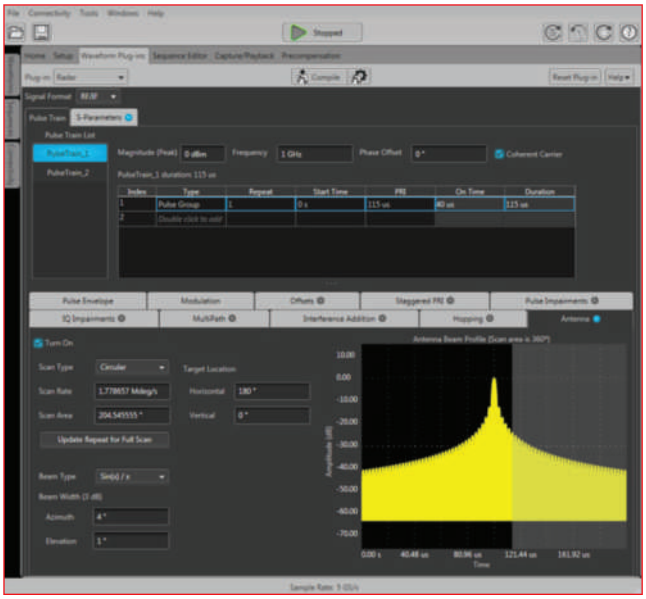


Fig. 3 Radar pulses created with the AWG70000B with the radar plug-in.

By selecting and combining different sequence steps, users can quickly create a variety of complex radar pulses, EW, electronic countermeasures (ECM) waveforms and modulated communications signals. Particularly when simulating ECM, dynamic signal scenarios work in tandem with the deep waveform memory, enabling the AWG to stream longer strings of continuous radar pulses. For such applications, the AWG70000B can be equipped with up to 32 GS of waveform memory, enabling users to play 640 ms of data at 50 GSPS. The Streaming Waveform ID function is also useful for wireless communications research. In these applications, users can change modulation on the fly to simulate Doppler radar, building obstructions and other obstacles, which can help improve OFDM signal durability in real-world deployments.

GENERATING COMPLEX WAVEFORMS

Generating complex waveforms starts by using the AWG70000B's sequencer to string together multiple individual waveforms. The sequencer allows for branching and looping, which speeds waveform generation, reduces memory usage and does not require external program control. The improved waveform output capability with the sequencer enables running a series of waveforms automatically and supports complex pattern jumping, flag outputs, sub-sequences and batch compilation. With Streaming Waveform ID, users dynamically control the AWG70000B's sequencer actions by streaming jump instructions directly to the sequencer in real time, via the new Ethernet Streaming ID connector. Streaming jump instructions directly to the sequencer greatly enhances the speed at which jumps are performed to better simulate the real world.

Creating waveforms happens in several ways. Tektronix offers a growing library of plug-ins to aid creating waveforms optimized for RF, radar, optical and other applications (see ***Figure 3***). The AWG70000B also supports third-party solutions such as MATLAB and Excel, and signals captured using oscilloscopes or spectrum analyzers can be edited and loaded into the AWG70000B for play back. The AWG70000B also works with SourceXpress PC software, which enables users to create signals anywhere and control multiple AWGs.

OPTIONS

The AWG70000B is available in one or two channel configurations. The single-channel AWG70001B offers the full 50 GSPS sampling rate and a maximum output frequency of 20 GHz. The standard available waveform memory is 2 GS, with the option to increase it to 32 GS. The dual-channel AWG70002B samples at 25 GSPS per channel and a maximum output frequency of 10 GHz per channel. The standard waveform memory is also 2 GS per channel, with the option to increase memory up to 16 GS per channel.

For MIMO and more advanced signal generation needs, as many as four of the AWG70001B or AWG70002B AWGs can be synchronized. Testing phased array radar and generating I/Q signals for optical transmission are two examples of applications that require more signal sources. Output signal phase can be maintained within a single clock cycle and tightly controlled within a ±10.8 degree range, and skew can be adjusted by ±10 ps across multiple AWGs.

WINDOWS 10 SUPPORT

The AWG70000B series now includes support for the Microsoft Windows 10 operating system to meet IT security mandates for instrument operation in government agencies and corporate IT departments.

When it comes to advanced signal generation, the AWG70000B series combines high resolution and precise signal fidelity with comprehensive PC software. With Streaming Waveform ID, deep memory and support for Windows 10, the AWG70000B provides the precision and resolution needed for testing phased array radar, EW, ECM and other military electronic systems and software-defined radios, as well as high speed and high frequency communications systems. The AWG70000B series is available globally with prices starting at $83,600.

Tektronix Inc.
Beaverton, Ore.
www.tektronix.com

8 kW X-Band PA Powered by GaN

Taking solid-state power to levels formerly captive to tubes, Comtech PST has developed an 8 kW GaN-based power amplifier (PA) for X-Band radar applications. Operating over any 1000 MHz instantaneous bandwidth between 9 and 10.5 GHz, the BMPC9X89X8-8000 provides 8 kW pulsed peak output power, with pulse widths up to 100 µs and a maximum 10 percent duty cycle. Rise and fall times are less than 25 ns, and pulse droop is typically under 0.15 dB/µs. The gain at rated power is typically 69 dB. Harmonics are no greater than –60 dBc at full output, and the amplifier's phase noise is –108 dBc/Hz at 100 Hz offset from the carrier. With the RF off, the noise floor drops to –170 dBm/Hz typical.

Input and output VSWR are better than 1.5:1. The input signal is applied via a female SMA connector, and the output interface is through WR112 or WR90 waveguide. Forward and reflected power, 60 dB down, can be sampled through two female SMA connectors. The BMPC9X89X8-8000 has an Ethernet interface and uses differential RS-422 for on/off gate control. The PA has extensive self protection for high load VSWR, duty factor, pulse width and temperature. Packaged for benchtop or rack mounting, the 19 in. × 12.25 in. × 25.78 in. PA has an internal power supply powered with 115 V AC and uses 3.6 kVA maximum. It will operate from 0°C to 50°C, 0 to 95 percent non-condensing humidity and up to 12,000 ft. altitude.

The class AB design uses modular GaN amplifiers that can be combined to achieve custom PAs with output power from 2 to 16 kW. Because of the modular architecture, the output power will degrade gracefully in case of a power module failure.

VENDORVIEW

Comtech PST
Melville, N.Y.
www.comtechpst.com

RoHS and REACH Compliant MIL-STD-1553B Bus Couplers

MilesTek has released a new series of RoHS and REACH compliant MIL-STD-1553B bus couplers for aerospace and ground vehicle applications. They are in stock, available for immediate shipment.

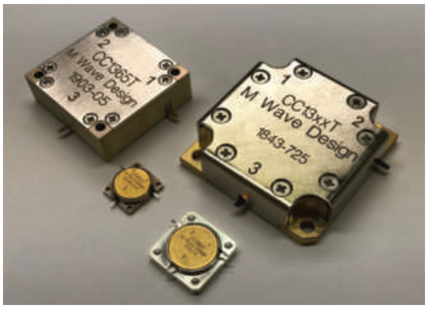
Widely known, the RoHS directive restricts the use of six hazardous materials in the manufacture of electronic and electrical equipment. RoHS was initially adopted by the European Union in 2003 and is now a mandatory requirement for many military and civilian electronic systems. Perhaps not as well known, REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) is also a European Union regulation, implemented in 2006, addressing the production and use of chemical substances and their potential impact on human health and the environment.

To address the growing demand for products that are RoHS and REACH compliant, MilesTek stocks a wide range of MIL-STD-1553B box style bus couplers. They are available with one through eight stub options and models with single, double or no bus jacks. These rugged bus couplers have a transformer ratio of 1.41:1 and stub resistor values of 59 Ω, within 1 percent, and with 2 W power handling.

MilesTek offers one of the industry's widest selections of MIL-STD-1553B box bus couplers, as well as a range of MIL-STD-1553B products, including bus and stub cables, relay devices and terminators.

VENDORVIEW

MilesTek
Lewisville, Texas
www.milestek.com



Low Loss Circulators for UHF, L-, S-, C- and X-Band AESAs

Active electronically scanned arrays (AESA) have proven to be the superior architecture for airborne, ship and ground-based radar. In addition to improved reliability and dynamic beam steering—with multiple beams at different frequencies—AESAs have low probability of intercept, are resistant to jamming and can simultaneously provide functions beyond radar, such as data links.

Achieving the maximum system performance from an AESA requires the best circulator performance. System engineers are always pushing for higher output power during transmit and better sensitivity during receive, within severely constrained size and weight budgets, and the circulator's insertion loss and power handling are key parameters setting the radar's range and overall system efficiency. As AESA radars typically employ thousands of T/R modules, unit-to-unit variability and low cost are also key criteria.

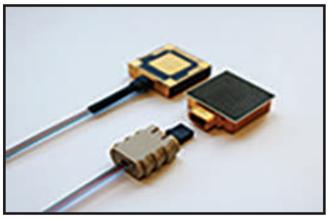
M Wave Design's engineering team has successfully developed many small, high-power circulators for AESA radar systems. Designed for high-volume manufacturing with minimal assembly labor, they are cost-effective and have repeatable performance, high-power handling and low insertion loss, to help maximize the dynamic range of the radar. M Wave Design's current products cover the common radar bands at UHF, L-, S-, C- and X-Band and achieve a small footprint for the operating frequency band.

AESA circulators are one example of M Wave Design's capabilities. During more than 30 years designing and manufacturing passive waveguide and coaxial components, including high-power ferrite products, M Wave has developed a unique set of tools and heritage to solve challenging technical issues, using some of the most innovative design techniques available.

M Wave Design
Simi Valley, Calif.
www.mwavedesign.com

AEROSPACE AND DEFENSE

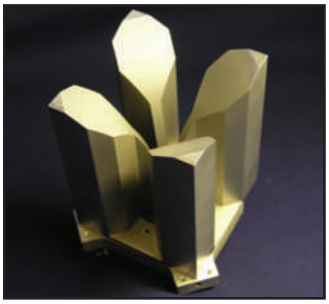
COMPANY SHOWCASE



NEW MICRO-OPTICAL TRANSCEIVER

The new OPTO-FIRE™ micro-optical transceiver from API Technologies enables the improvement of critical data communication systems in airborne, naval and renewable energy applications. With a range of high speed data rates (20 Mbs to 25 Gbs), multiple-channels and protocol agnostic architecture, the OPTO-FIRE™ micro-optical transceivers are specifically designed for harsh environment applications. OPTO-FIRE™ is a major change in optical core technology which enables significant size and weight reductions. Available in customized rugged packaging styles to withstand harsh –58°F to +212°F operating temperature requirements.

API Technologies
www.apitech.com



CROSS NOTCH ANTENNA 94800568

Cobham Advanced Electronic Solutions' new 94800568 Cross Notch Antenna is a dual-linear, high-power, crossed notch antenna. This antenna offers breakthrough performance and is suitable for airborne and high-power ECM applications. In addition, it is also suitable for feeding reflector antennas, wideband antenna arrays and other broadband applications. More information on Cobham's aerospace and defense products can be found on their website.

Cobham Advanced Electronic Solutions
www.cobham.com/ew

MODULAR BUILDING BLOCK SSPA X-BAND SOLUTION

CPI Beverly Microwave Division's high efficiency, modular, 1 kW compact X-Band, SSPA VSX3695, using proven GaN technology and can be easily combined to create high-power X-Band radar transmitters up to 50 kW. CPI BMD's designs and manufactures a broad range of RF and microwave products for radar, communications, EW, medical and scientific applications. They also manufacture a broad range of pressure windows and pressure bypass windows. Their products are found in numerous radar systems operated by the U.S. military and militaries around the world.

CPI Beverly Microwave Division
www.cpii.com/docs/datasheets/278/VSX3695%20SSPA%20PRELIMIARY%20FINAL.pdf

L-BAND 40 kW SOLID-STATE TRANSMITTER

Daico introduces a game-changing transmitter design, part number CTX09634, that delivers 40 kW power at L-Band with unprecedented availability, reliability, maintainability and affordability. It is featured with automatic failover, graceful power degradation and true "hot-SWaP" capability. The ultra-reliable CTX09634 outperforms Klystron and TWT technologies. This flexible and scalable transmitter architecture can be implemented to achieve 100s of kW power at up to C-Band in an air or liquid cooled environment.

Daico Industries Inc.
www.daico.com

2019 DEFENCE, SECURITY & SPACE FORUM

The Defence, Security and Space (DSS) Forum is jointly organized by EuMA and *Microwave Journal*, to complement European Microwave Week's activity in the defence, security and space sector. Each year the DSS Forum focuses on a hot topic that is engaging industry, academia and organisations/agencies to develop, test and implement leading edge technology. This year's one-day focused Forum will address New Radio Architectures: The Evolution of Satellite Constellations. A full itinerary can be found in the conference special events section of the EuMW website.

EuMW 2019
www.eumweek.com

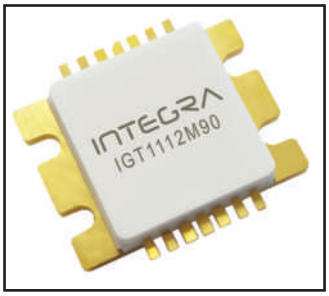
HSM SERIES RF SYNTHESIZER MODULES

The unique, non-PLL-based HSM Series RF Synthesizer Modules offer incredibly agile frequency switching speeds as fast as 6 µS with no settling time. These CW signal sources offer MHz tuning resolution and are available in seven broadband models covering 10 MHz to 1, 2, 3, 4, 6.4, 12.5 and 20 GHz. Having greater than +18 dBm of calibrated maximum output power available, users also have an adjustable dynamic range of down to –60 dBm in 0.01 dB increments. Additional features include pulse modulation and phase offset capability.

Holzworth Instrumentation
www.holzworth.com

AEROSPACE AND DEFENSE

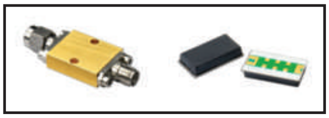
COMPANY SHOWCASE



X-BAND GaN/SiC RF POWER TRANSISTORS

Integra Technologies Inc., a provider of RF/microwave power semiconductor and pallet solutions for state-of-the-art radar, EW and advanced communications systems, announces a new family of X-Band power solutions addressing the increasingly challenging needs of the X-Band radar market for higher sensitivity, improved resolution, superior detection and smaller form factor. The IGT1112M90 operates instantaneously over a frequency range of 10.8 to 11.8 GHz, delivers a minimum peak output power of 90 W at 50 V drain bias voltage and 11 dB of gain, achieving 43 percent efficiency.

Integra Technologies Inc.
www.integratech.com



COMB GENERATOR PORTFOLIO

MACOM's Comb Generator Portfolio is optimized to meet the demanding performance requirements of radar transceiver, VSAT and microwave radio applications. Featuring the lowest phase noise in the industry today, MACOM's MLPNC Series comb generators deliver superior performance and ease-of-design compared to conventional step recovery diode-based offerings. The industry-leading phase noise performance delivered by this family is expected to significantly improve the overall performance of RF multiplier modules, complemented by a variable low input power profile that relaxes the power requirements on power amplifiers and reduces overall power consumption.

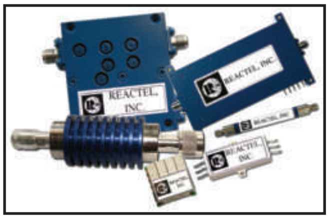
MACOM Technology Solutions
www.macom.com/about/news-and-events/press-release-archive/row-col1/news--event-archive/macoms-comb-generator-portfolio

NEW PRODUCT GUIDE

VENDORVIEW

Mini-Circuits released over 400 models in 2018, and the company continues to develop new products at a rapid clip. Their Q1 2019 product guide highlights some of the latest additions to their portfolio to keep you informed. Highlights include new hi-rel ceramic MMIC amplifiers, wideband MMIC gain slope equalizers, LTCC filters with rejection up to 45 dB, ultra-wideband coaxial couplers and splitters up to 40 and 50 GHz and more.

Mini-Circuits
www.minicircuits.com



FILTERS, MULTIPLEXERS & MULTIFUNCTION ASSEMBLIES

VENDORVIEW

Reactel manufactures a full line of RF/microwave filters, multiplexers and multifunction assemblies covering up to 50 GHz. Supporting aerospace, military, commercial, industrial, medical and research needs, the company has been supplying units that meet the most stringent requirements for the past 40 years. From small, lightweight units suitable for flight or portable systems, to high-power units capable of handling up to 25 kW, connectorized or surface mount, large or small quantities—their talented engineers can design a unit specifically for your application and deliver quickly.

Reactel Inc.
www.reactel.com

BEAM FORMING SYSTEM PRODUCTION LINE

In recent years RF-Lambda has developed a new Beam Forming System production line. These systems cover a range of frequencies, from sub-GHz to 18 GHz, with a number of elements ranging from 16 to 64 to meet a variety of beam width requirements. All antenna systems have a built in T/R Module—with PAs, LNAs and phase shifters. RF-Lambda combined its state-of-the-art design capability for both power amplifiers and transceivers into these phased array systems, creating devices that are higher power and higher sensitivity than market competition.

RF-Lambda
www.rflambda.com

AEROSPACE & DEFENSE SELECTOR GUIDE

Richardson RFPD is an AS9120-certified, global component distributor specializing in advanced connectivity solutions. With A&D as its largest market, the company's GaN technology portfolio and wide range of MMICs, RF transistors, PAs and diodes include leading brands Analog Devices, ATC, Anaren, MACOM, Microchip, Microsemi, NXP, pSemi, Skyworks, UMS, WanTcom and Wolfspeed. Among the latest additions to Richardson RFPD's A&D line are Guerrilla RF, NewEdge Signal Solutions and Tagore Technology products and the Metelics diodes now offered by MACOM.

Richardson RFPD
www.richardsonrfpd.com

AEROSPACE AND DEFENSE

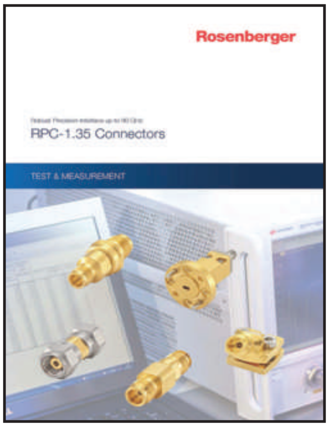
COMPANY SHOWCASE

EXCELLENCE IN AEROSPACE AND DEFENSE TEST

VENDORVIEW

In the aerospace and defense industry, innovation and disruptive technologies are a key element of success. Highest requirements need to be met for design, verification and test of electronic systems. As a recognized industry partner, Rohde & Schwarz provides market leading test & measurement solutions for radar, EW, satellite, navigation, guidance, communications and radio monitoring systems. With decades of industry experience, Rohde & Schwarz provides its customers with the means for technological progress in aerospace, defense and space.

Rohde & Schwarz
www.rohde-schwarz.com



SERIES RPC-1.35 CONNECTORS

Rosenberger introduces a new precision connector series to meet the increasing demand for proper RF connections up to 90 GHz. The newly developed RPC-1.35 connector series—the "E connector"—is characterized by a highly robust mechanical design, minimum 3000 mating cycles, high connector repeatability, maximum return loss values. The product range covers semi-rigid and flexible cable assemblies, PCB connectors, test PCBs, cable connectors, in-series and inter-series adaptors, test port, floating and waveguide-to-coaxial adaptors as well as gauge and calibration kits. The interface standardization is in progress.

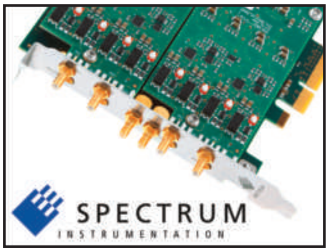
Rosenberger
www.rosenberger.com

NEW WIDEBAND SURFACE MOUNT FIXED ATTENUATORS

VENDORVIEW

Utilizing more than 40 years of experience in refining attenuation solutions for the defense, the TT9 offers a power handling capability of 500 mW while maintaining excellent impedance matching in an SMT package and outstanding performance for high frequency applications, both fixed and temperature variable designs in the same footprint and is ideal for the exacting needs of the defense market. This series has undergone significant qualification testing with proven results of robust performance in extended durations and extreme environments.

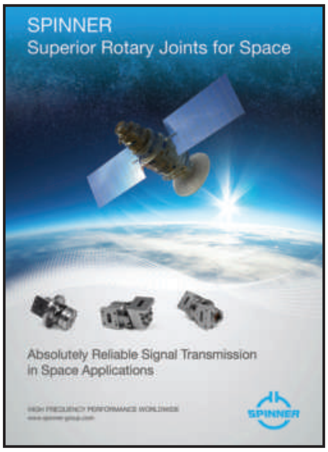
Smiths Interconnect
www.smithsinterconnect.com



PCIe ARBITRARY WAVEFORM GENERATORS

Spectrum Instrumentation introduced eight new PCIe Arbitrary Waveform Generators with up to eight simultaneous channels. These new "65" series AWGs are optimized for signal quality, size and cost. With a card length of only 168 mm they fit into nearly every PC, turning it into a highly flexible signal source with 40, 80 or 125 MS/s. They offer a fast FIFO mode (unique for AWGs) with 700 MByte/s or 8 × 40 MS/s continuous data streaming.

Spectrum Instrumentation
https://spectrum-instrumentation.com/en/



SUPERIOR ROTARY JOINTS FOR SPACE APPLICATIONS

VENDORVIEW

Rotary joints made by SPINNER for use in space make a decisive contribution to technological progress and precise communication because satellites in outer space would be almost worthless if communication links with ground stations were not permanently maintained. The antennas of satellites have to be permanently targeted at their ground stations, a task for which rotary joints are indispensable.

SPINNER GmbH
www.spinner-group.com/space

NEW CLARITY SERIES

Times Microwave introduces its new Clarity Series of 18, 26.5 and 40 GHz coax test cables. Clarity boasts steel torque, crush and overbend protection with abrasion resistance yet does not compromise flexibility. The cable is ultra stable through 40 GHz with exceptionally low attenuation. An industry first includes an ergonomically designed, injection molded strain relief and Times' new, SureGrip™ coupling nut to significantly improve the user's everyday experience.

Times Microwave Systems
www.timesmicrowave.com

AEROSPACE AND DEFENSE

AD INDEX

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