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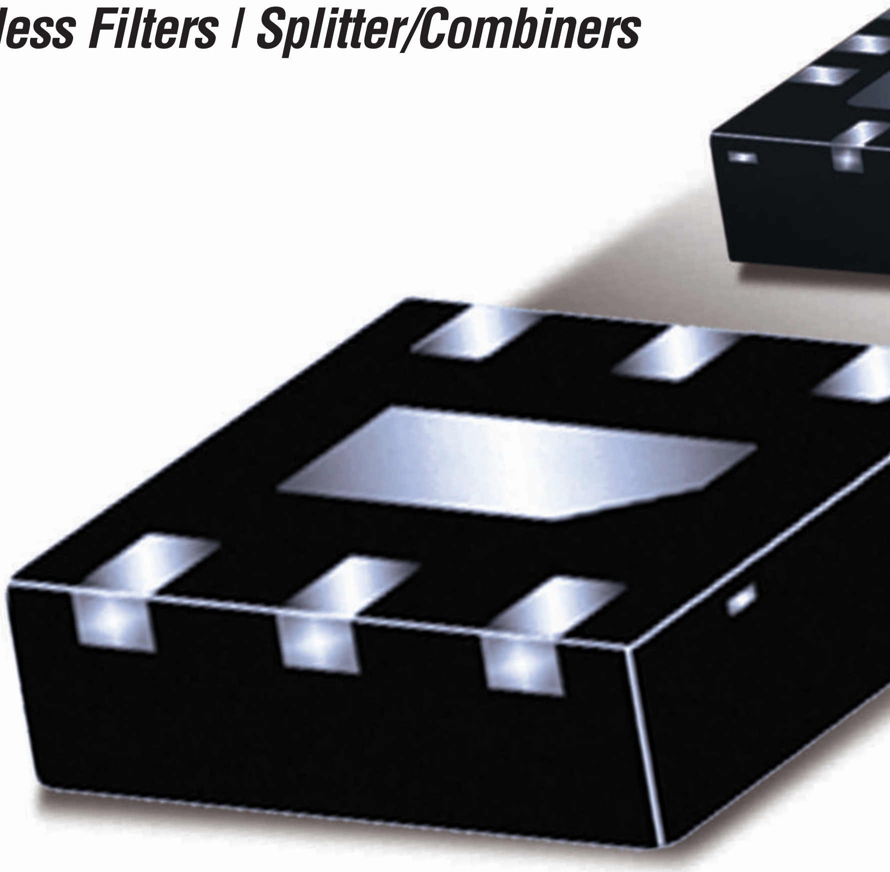

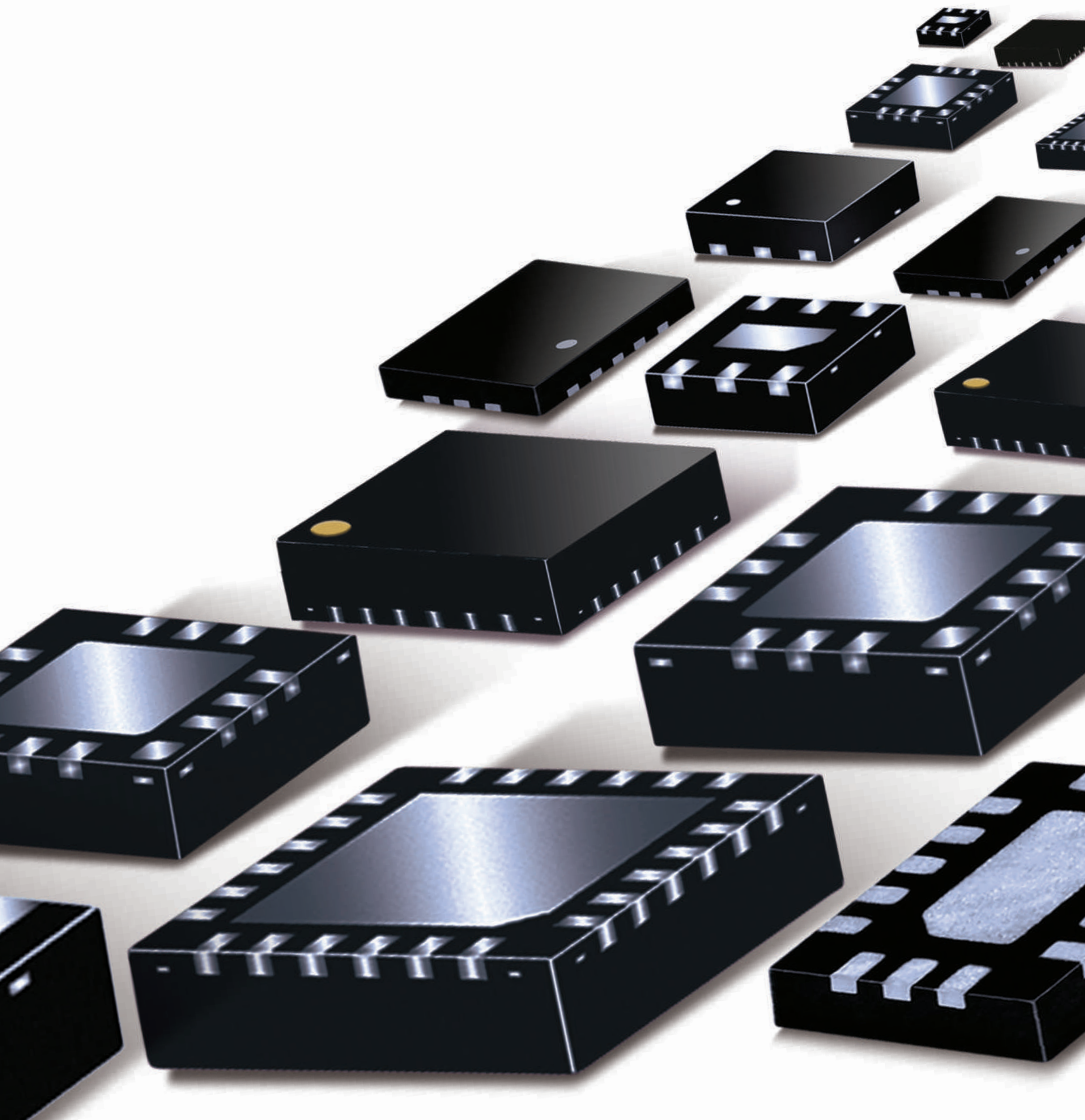

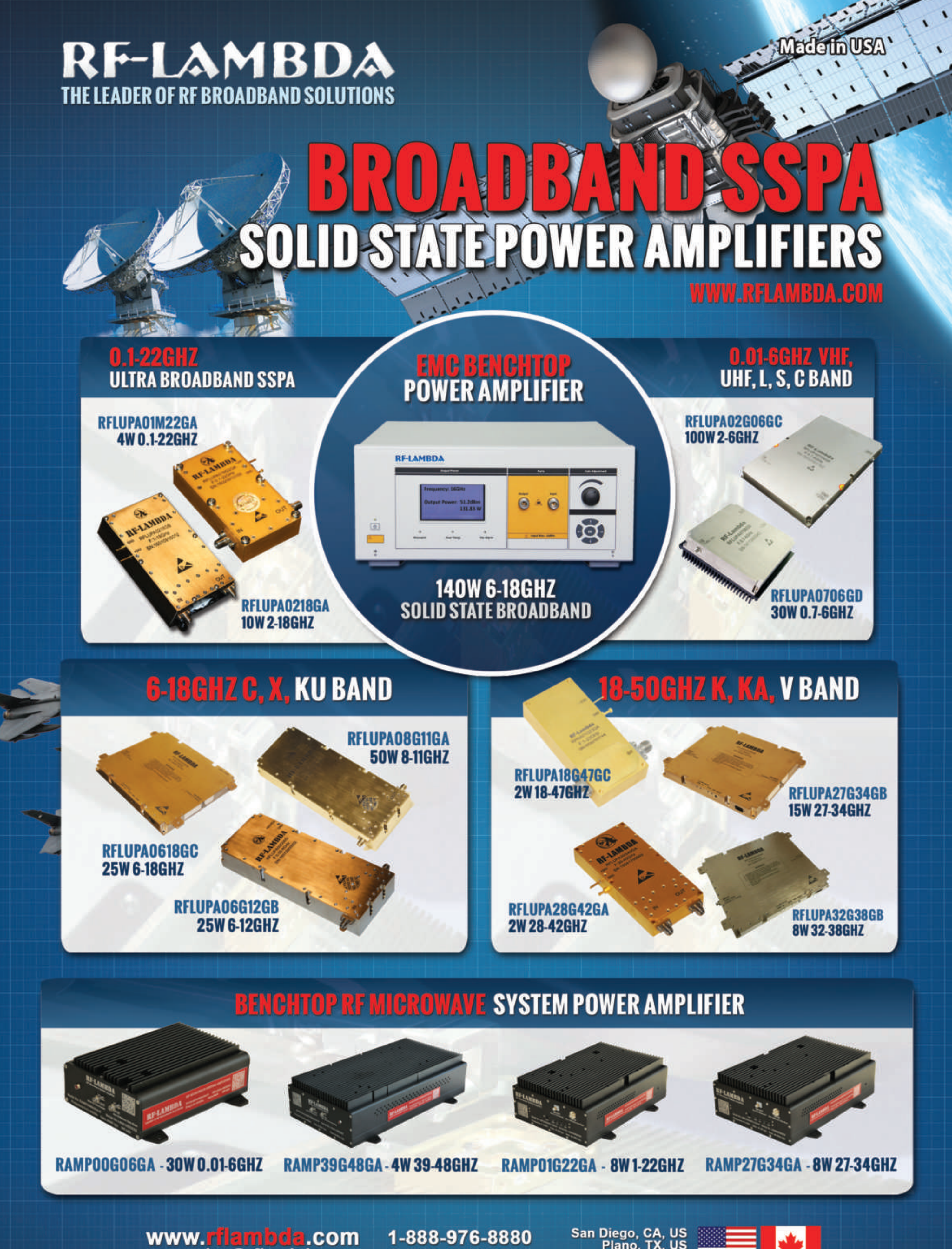

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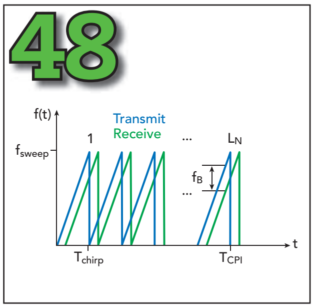

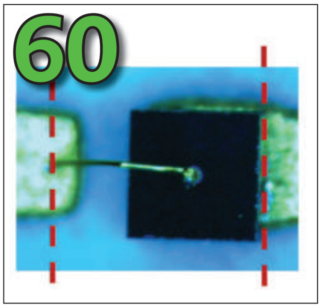

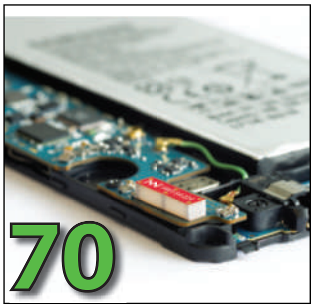


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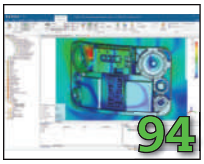

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Microwave Journal (USPS 396-250) (ISSN 0192-6225) is published monthly by Horizon House Publications Inc., 685 Canton St., Norwood, MA 02062. Periodicals postage paid at Norwood, MA 02062 and additional mailing offices.

POSTMASTER: Send address corrections to Microwave Journal, PO Box 1028, Lowell, MA 01853 or e-mail mwj@e-circ.net.com. Subscription information: (978) 671-0446. This journal is issued without charge upon written request to qualified persons working in the RF & microwave industry. Other subscriptions are: domestic, $120.00 per year, two-year subscriptions, $185.00; foreign, $200.00 per year, two-year subscriptions, $370.00; back issues (if available) and single copies, $10.00 domestic and $20.00 foreign. Claims for missing issues must be filed within 90 days of date of issue for complimentary replacement.

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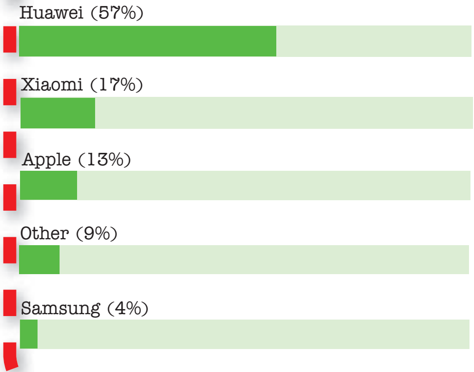

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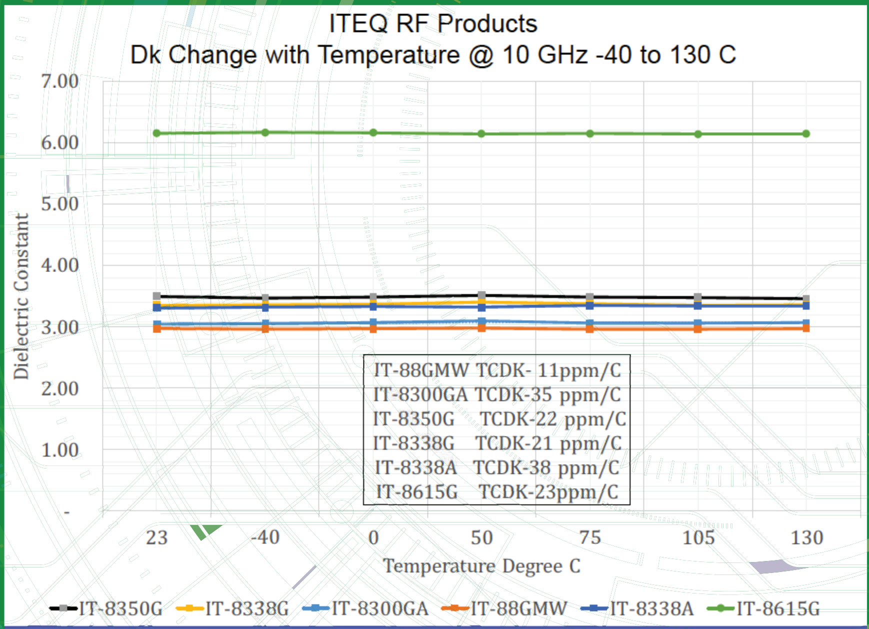

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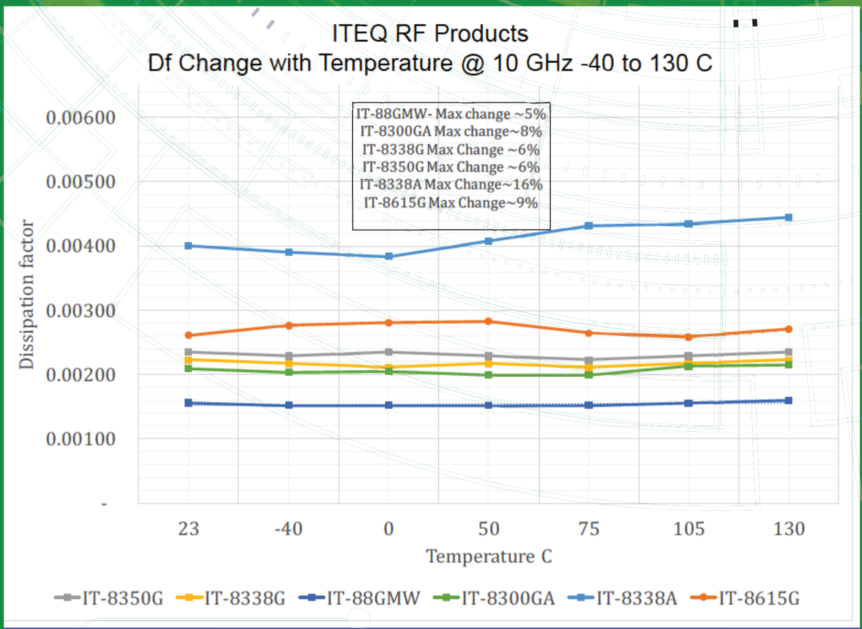

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COVER FEATURE
INVITED PAPER

Client Software-Defined Antennas Improve Link Margins, Reduce Interference

Jeff Shamblin
Taoglas, Enniscorthy, Ireland

With the increase in the number of connected devices and the attendant appetite for sending and receiving data, the demands on cellular networks are increasing. To help address this trend, device and antenna designers are tasked to develop better systems on the client side to improve network performance. Among the options, designers can employ dynamic communication link optimization using software antenna techniques, which provides more capability to the radio architecture and antenna systems. This enables companies to develop more compact and cost-effective radio systems while supporting wider bandwidth and multiple modulation schemes. A number of military and commercial applications for software-defined radios (SDR) benefit from software-defined antennas (SDA), and these benefits can be extended to the multitude of mission-critical applications in IoT, such as controls for railroads, underground gas leak detection and forest fire prevention.

This article outlines the technical approach and benefits provided by SDAs, capabilities that enable antennas to go well beyond the performance of passive antennas, dynamically tracking signals in mobile applications and keeping the communication link optimized.

SOFTWARE-DEFINED ANTENNAS

Companies developing mission-critical systems, where reliable connectivity or high data rates need to be sustained, rely on flexibility in the radio architecture and antenna system to allow for dynamically optimizing the communication link. This optimization can be provided by SDAs, which support the radio system accessing wider frequency ranges and using flexible modulation to maintain and improve performance.

With the number of M2M and IoT devices far surpassing the population of smartphones around the world, cellular signal congestion and interference become major concerns. As more devices get connected to existing networks, the response is to increase the number of base stations or nodes, which exacerbates the interference problem. Today's passive antenna systems used in cellular client devices for metering, vehicle tracking and industrial automation lack the dynamic beamwidth control and front-to-back ratio available from large array antennas. Adopting SDA techniques will provide beamwidth and angular discrimination to minimize interference in node-based cellular networks, both 4G and 5G.

During the last decade, SDAs have become feasible due to innovations on two fronts: RF tuning components and RF modem chipsets. A wide variety of RF tuning components and manufacturing techniques for these components have matured, with available components comprising switches, tunable capacitors, RF MEMS switches and tunable capacitors, BST tunable capacitors and PIN diodes. Modem chipsets provide metrics for real-time dynamic optimization at moderate to low latency, such as signal-to-interference-and-noise ratio (SINR) and channel quality indicator (CQI). Such metrics can be used to decide the optimal tuning state of the antenna system.

PASSIVE ANTENNA LIMITATIONS

In a communications link, the antenna radiates and receives elec-

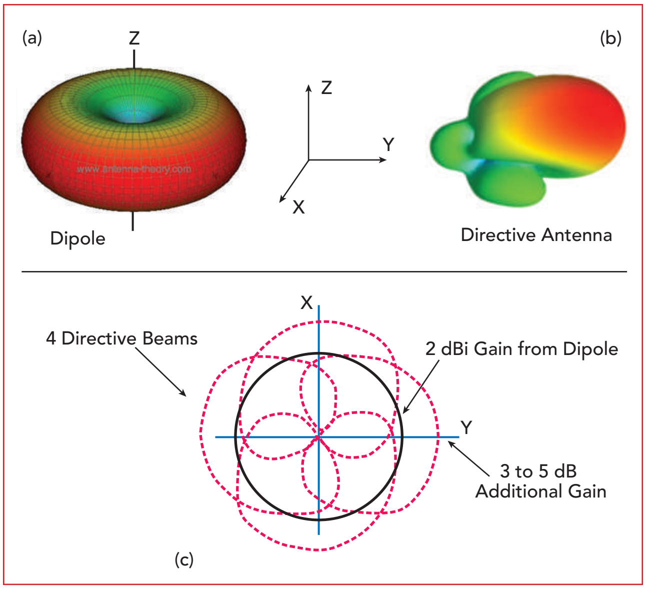


Fig. 1 **Comparison of the radiation patterns of a dipole (a) and more directive (b) antenna, showing the directive antenna provides higher gain (c).**

tromagnetic energy. An antenna a few tenths of a wavelength in size can be used to radiate energy over a broad angular region, approaching the performance of the theoretical isotropic radiator, i.e., radiating equally in all directions. Radiation over broad angular regions is important for mobile communications, due to the multipath environment, time-varying changes in the multipath environment and the mobility of the client device—all causing dynamic variations in the propagation channel. Ideally, the passive antenna in the client device should radiate in all directions, since the direction to the base station antenna is unknown, and multipath causes the radiated signals to and from the base station to scatter and reflect over a wide angle.

An electrically larger antenna, one that is one to several wavelengths in size, can be designed to radiate over a more restrictive angular range. A reduced 3 dB beamwidth between 30 and 80 degrees focuses more of the radiated energy in the desired direction and provides several dB of improved antenna system gain, which translates to higher data rates. This reduced beamwidth radiation pattern also provides better rejection of interfering signals arriving from directions outside the main beam of the antenna. However, a more directive and efficient antenna needs to be pointed in the correct direction for optimal link margin with the intended base station, meaning more information is needed to implement this type of antenna with mobility and non-line-of-sight conditions.

Figure 1 compares the radiation patterns of a dipole antenna and a more directional antenna, which provides more gain. The dipole pattern (see Figure 1a) has omnidirectional coverage in the x-y plane and two deep nulls in the z direction, while the more directive antenna (see Figure 1b) has reduced beamwidth in both the x-y plane and z direction; however, it provides increased gain in the direction of the main lobe. Overlaying the dipole radiation pattern in the omnidirectional plane with the radiation patterns of the more directional antenna (see Figure 1c) shows the increase in gain with the directive antenna. Its beam can be dynamically steered to cover four 90 degree quadrants and provide 360 degree coverage.

Figure 1 shows the benefits of dynamic beam steering afforded by a SDA, comparing the low directivity, wide beamwidth, passive antenna to the multiple beams generated by a beam steering antenna. Taking the multiple beams to form a composite radiation pattern, the best case benefit is achieved when beam steering is coupled with an algorithm calculating the radio link metrics and using this data to select the optimal beam. When low latency metrics are available from the radio baseband chipset to drive the optimization process, a well-config-

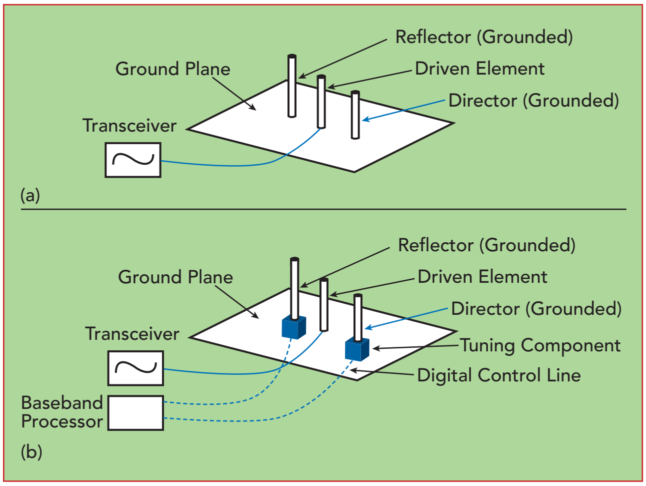


Fig. 2 **Passive Yagi antenna on a ground plane (a). Same antenna with dynamic tuning (b).**

ured algorithm allows for 80 to 90 percent of the composite pattern benefit to be achieved.

SOFTWARE-DEFINED ANTENNA EXAMPLE

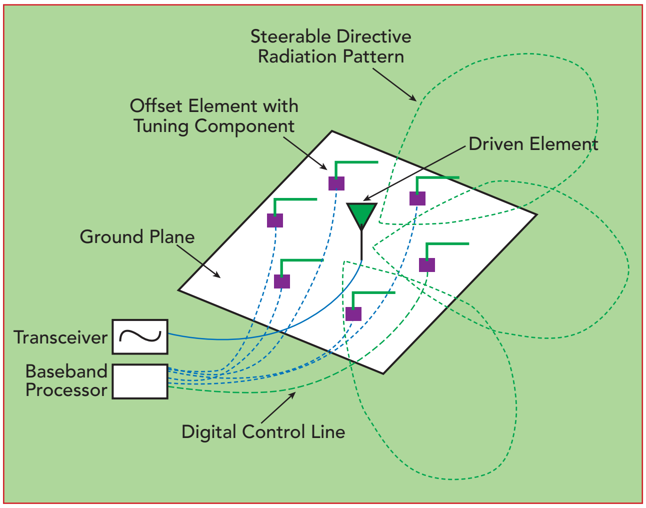
As discussed, a SDA is dynamically reconfigured in real-time to compensate for changes in the propagation channel and to accommodate changes in the radio system. To design a SDA to provide hemispheric or full 3D coverage, a couple of configurations can be used: either a centralized antenna element with parasitic elements on the periphery or the inverse, where multiple antenna elements surround a central parasitic element. The first is easier and more efficient to implement, since there is only one driven antenna element; the second configuration requires multiple antenna elements surrounding a single parasitic element, and these multiple antenna elements need to be switched to change the radiation pattern. Switch cost and losses make this configuration less efficient than using a single antenna with multiple parasitic elements.

In either case, active tuning components are integrated into the antenna element or parasitic elements to provide switching or tuning. An RF switch can be used to connect or disconnect portions of a conductor that is part of a parasitic element or section of the driven antenna; this change in conductor configuration alters the current distribution of the parasitic element or the driven antenna. Alternately, a tunable capacitor can be used at the junction of two conductors, introducing a dynamically-varied capacitance for impedance loading and connecting discrete conductors.

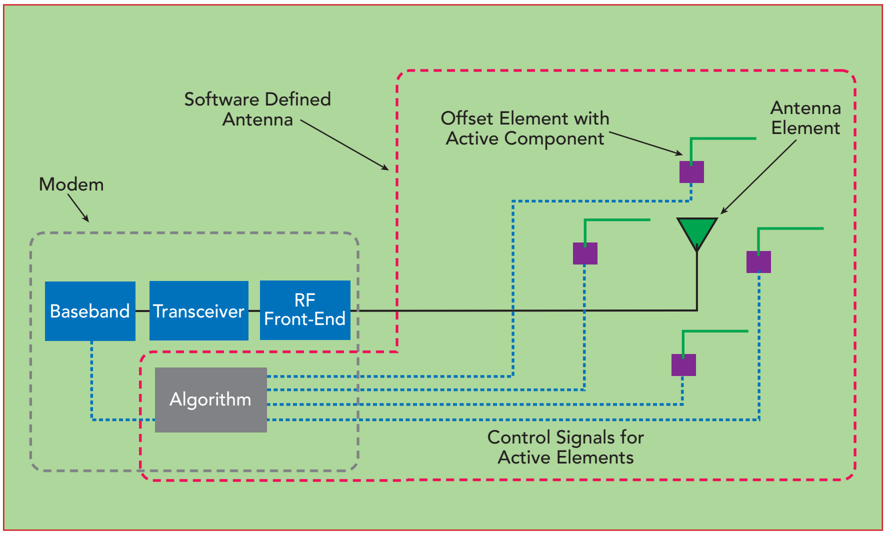
One example of a passive antenna (see ***Figure 2***) is a Yagi on a ground plane, which provides a directive radiation pattern in one direction. By adding tuning components to the reflector and director elements, the elements can by dynamically connected or disconnected from the ground plane. When the reflector and director are connected or "grounded" to the ground plane, the radiation pattern will be directive, with the peak gain pointing in one direction. When the reflector and director are disconnected, the radiation pattern reverts to that of a monopole on a ground plane, with an omnidirectional pattern in the plane of the ground plane. The gain of the Yagi on a ground plane is 5 to 6 dB greater than that of a monopole.

Figure 3 shows a more complex version of a SDA system, where multiple elements with tuning components are located around a centrally-driven antenna element. As the various tuning components are activated, to connect or disconnect the element to the ground plane, a directive radiation pattern is generated and rotated in the plane of the ground plane, steering the direction of the peak gain of the antenna. A combination of the centrally-driven antenna and one of the offset elements with tuning components is a type of Yagi antenna, shown in Figure 2b.

To complete a SDA system, an algorithm is required that uses metrics from the baseband chipset of the radio to determine optimal



▲ Fig. 3 More complex SDA, where the beam is steered to different sectors.



▲ Fig. 4 SDA driven by the radio modem.

beam selection. ***Figure 4*** shows a radio modem and SDA, controlled with the algorithm. The algorithm ties the modem and SDA together; this is highlighted in Figure 4, where the dotted lines that define the modem and SDA overlap at the algorithm.

This discussion of the antenna system architecture only refers to a single port antenna, with two antennas needed for a 2 × 2 LTE MIMO application.

SYSTEM-LEVEL BENEFITS

A SDA with beam steering can provide from 3 to more than 6 dB of additional antenna gain. The additional gain equates to the same level of system gain, resulting in higher data rates. ***Figure 5*** shows the relationship between data throughput and SINR. A measure of the signal level above the level of noise and interfering signals, the SINR will increase on a dB per dB basis as the antenna system gain is improved. Figure 5 shows the benefits of additional antenna system improvement on system metrics, such as throughput.

With low SINR values, an LTE network will use quadrature phase-shift keying (QPSK), essentially the same as 4-QAM. As the QAM index increases, the data rate increases and the SINR needed to support the modulation increases. When the SINR exceeds 7 dB, 16-QAM, which has 2× the throughput of QPSK, can be used for transmission. With an SINR of 13 dB, the best modulation becomes 64-QAM, which has 2× the throughput of 16-QAM and 4× the throughput of QPSK. Antenna system improvements obtained from a SDA will be most noticeable at lower SINR.

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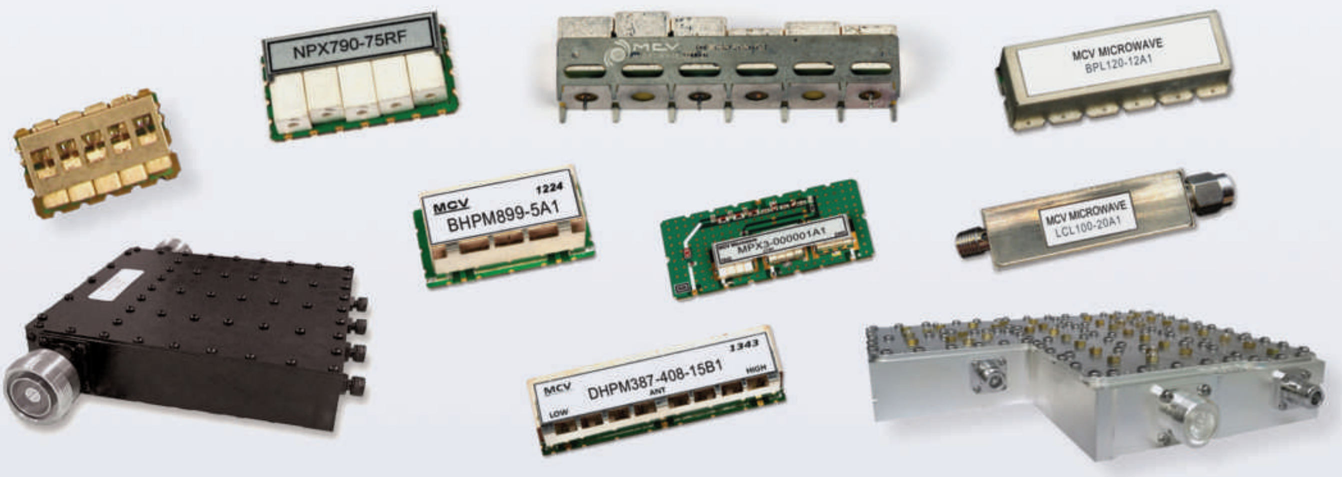

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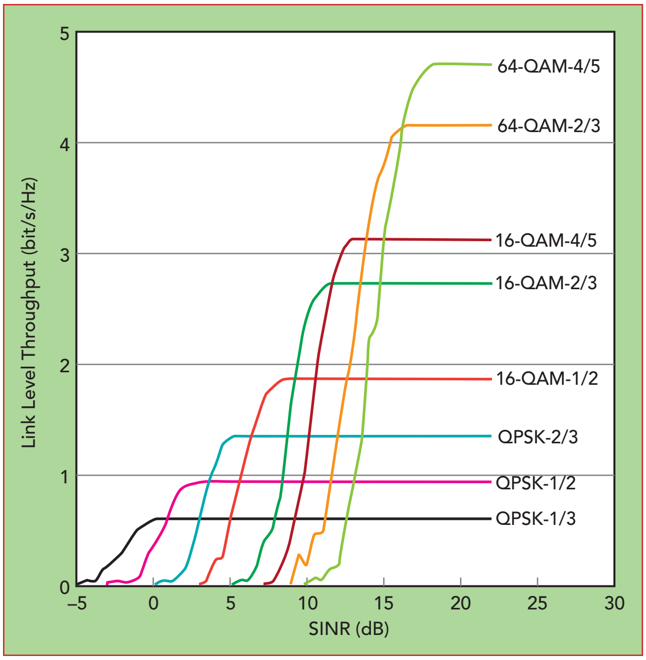


Fig. 5 Link data throughput vs. SINR.[1]

proach for the antennas in the client device has been to design a low directivity, omnidirectional antenna—or as close to omni as possible—to ensure the client is capable of receiving signals across the widest spherical geometry. Since a device with a passive antenna has no understanding of base station location or the angle of arrival, this wide beamwidth approach provides the best method for making the system work, accounting for mobility and the change in orientation and position of the device within the cell. Unfortunately, from a system link budget perspective, this does not efficiently transmit the power from the antennas in the client device, since the power is radiated in all directions, despite the intended direction of the radiated signal to the base station hosting the link. When receiving, the passive, wide beamwidth antenna has a peak gain lower than a more directive antenna. A directive antenna could be used if the antenna "knew" which direction to point.

SUMMARY

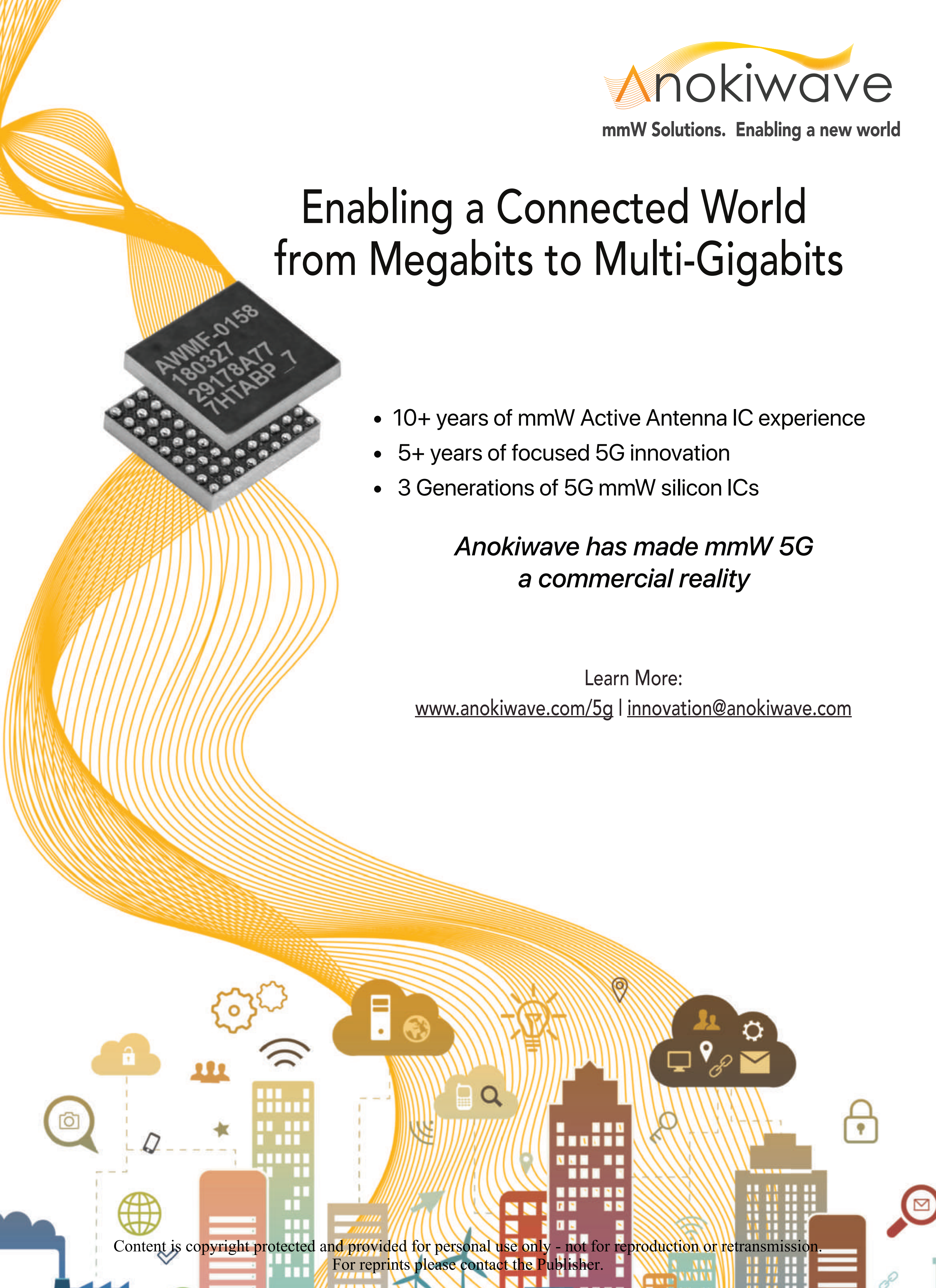
The SDA system can add multiple dBs of system-level benefits when dynamic optimization of the radiating element is incorporated with signaling from the baseband modem, with an algorithm to optimize the antenna. Besides providing more gain in the intended direction, a SDA will reduce interfering signals arriving from directions other than the intended base station. The underlying principle is the relationship between gain and beamwidth of an antenna: generating higher peak gain in the radiation pattern, other angular regions will be illuminated less, i.e., lower gain in directions outside of the main lobe of the radiation pattern.

If an SINR metric is available from the baseband modem chipset with an algorithm to optimize the SDA, the interference in the propagation channel will be considered as the radiation pattern characteristics are surveyed and optimized. This is becoming more important as base stations are more densely deployed to meet capacity demands. As the base station density increases, interference becomes the more limiting factor for throughput, rather than signal strength.

Today's antenna engineer can take advantage of the evolving features in radio modems, such as low latency SINR metrics and tunable component technology, to reconfigure passive antennas to dynamically optimized SDA systems. If radiation patterns are chosen for dynamic optimization, sectorization will provide 3 to 6 dB of system-level improvement compared to a low directivity passive antenna. Optimizing the pattern will become more important as cellular networks increase the density of base stations, enabling the link to be optimized for both signal levels and interference in the propagation channel.■

Reference

1. J. J. O. Bonafé, A. S. Pagès, S. R. Boqué, M. Garcia-Lozano and D. Gonzalez Gonzalez, "Link Level Simulator for LTE Downlink," 2009, www.researchgate.net/publication/47330409_Link_level_simulator_for_LTE_downlink.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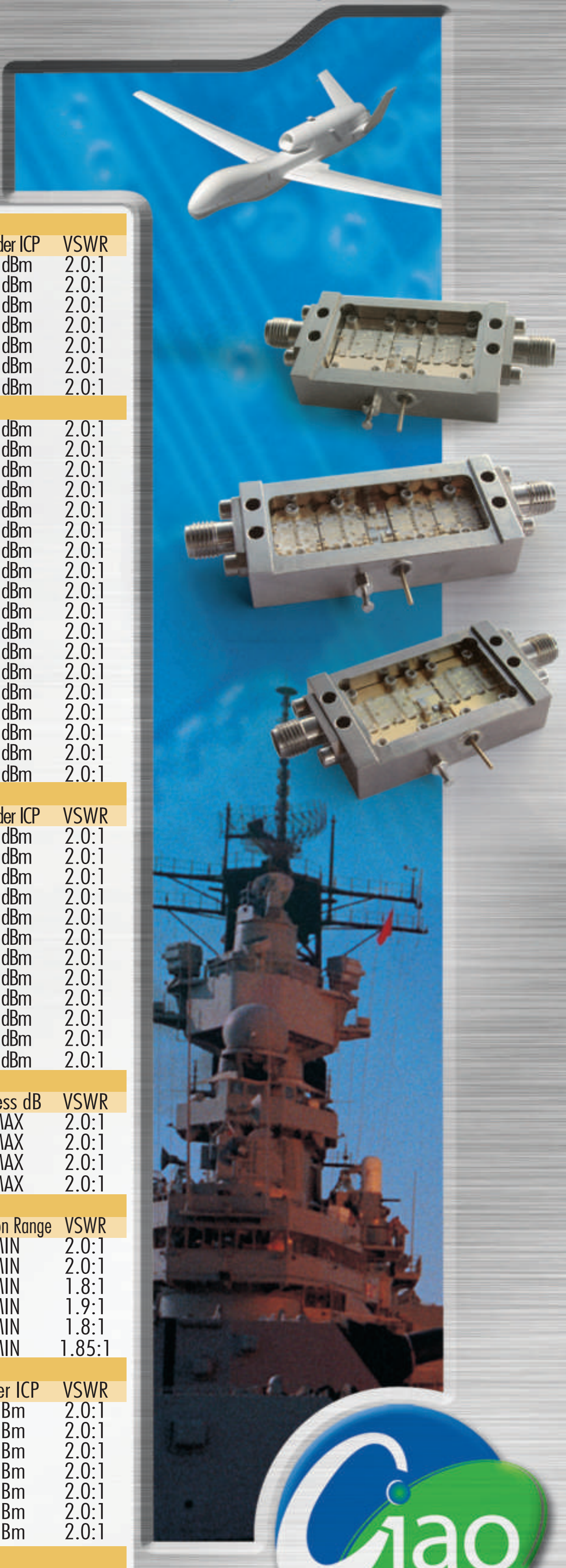

OCTAVE BAND LOW NOISE AMPLIFIERS

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

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

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

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

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

LIMITING AMPLIFIERS

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

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

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

LOW FREQUENCY AMPLIFIERS

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

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Navy Expand Communications Reach with Nanosatellite Launch

A Navy nanosatellite designed to extend the range of ultra-high frequency (UHF) communications into the polar regions was recently launched from Vandenberg Air Force Base, Calif.

Officials at the Navy's PEO Space Systems and developers at Space and Naval Warfare Command Systems Center Pacific are leading this effort known as the Integrated Communications Extension Capability (ICE-Cap). ICE-Cap will demonstrate the ability of low Earth orbit satellites to extend the geographic coverage of the Mobile User Objective System (MUOS) and legacy UHF Follow-On (UFO) satellite constellations to the polar regions.

MUOS gives mobile forces cell phone-like capabilities via the Wideband Code Division Multiple Access (WCDMA) waveform, while also supporting the legacy UHF currently provided by the UFO satellites. Currently, four MUOS satellites with one on-orbit spare make up the constellation, providing UHF coverage between 65 degrees north and 65 degrees south latitude. The ICE-Cap satellite will act as a relay to the existing MUOS constellation and, based on its orbit, extend communications into the polar regions for mobile forces.

"This is a force multiplier," said Capt. Chris DeSena, program manager, Navy Communications Satellite Program Office at PEO Space Systems. "The Arctic portion of maritime domain is becoming more active and important, and MUOS and ICE-Cap help ensure we have advantages in any challenges we might face there."

The small size and low weight of nanosatellites make them an affordable asset. The ICE-Cap payload, a 3U nanosatellite similar in size to a loaf of bread, was commercially launched as part of the Sun Synchronous Orbit-A (SSO-A) mission on a SpaceX Falcon 9 rocket with more than 70 other satellites. In addition, the mission launched three other Navy projects. These even-smaller 1U nanosatellites measure only 10 cm per side.

"The development and launch of these four nanosatellites demonstrates the Navy's interest in leveraging the significant growth and private-sector investment in disruptive, new-space technologies aimed at driving down the costs of developing, building, launching and operating constellations of small satellites, increasing access to space," said Lt. Cmdr. Shawn Kocis, assistant program manager for science and technology, PEO Space Systems.

A traditional satellite often has an eight- to 10-year design cycle and is expected to remain on orbit for 15 to 20 years. A nanosatellite has a 12- to 18-month design cycle and an expected lifespan of about three years. These shortened timelines allow for constant technology insertion. The Navy satellites on the SSO-A mission are a pathfinder for future Navy space efforts.

New Raytheon Radio Tech Delivers Clear Comms in Crowded Environments

Hundreds of troops, dozens of aircraft and a fleet of ships are on the move. The signals are flying fast and furiously. Everybody is on the same frequency; overhead drones transmitting surveillance data, operators on the ground and commanders in the field. And because everyone is on a congested frequency, what should be near-instantaneous transmissions slow as the seconds tick by. On the battlefield, those seconds can mean the difference between success and failure. The answer could be X-Net, a new radio communications system that autonomously and instantly selects the optimal RF to keep communications flowing.

The radio, which is designed for use with missiles, stand-off precision guided munitions and small unmanned autonomous systems, connects host platforms to the tactical network. It made its debut earlier this year at a demonstration, dubbed ESCAPE, hosted by the Air Force Research Lab and the U.S. Navy.

During ESCAPE, Raytheon swapped out two existing radios on a Navy RQ-21A Blackjack for the X-Net system. Its mission was to allow the host platform to freely operate in a dense signal environment and conduct its intelligence, surveillance and reconnaissance mission. X-Net performed the flight control operations and video transmission job of the legacy radios, and also allowed the Blackjack to flip its own switch to the best RF for operations. In fact, it continuously hopped radio signals to avoid busy frequencies.

"We were jumping frequencies often because of the different emitters that were out there," said David Duran, a Raytheon engineer and ESCAPE team member. "Not once did we get a call or hear from anybody that any of the communications were being stepped on."

"This was a valuable opportunity to demonstrate new mission capabilities—such as mesh network radios with dynamic spectrum access like the X-Net Radio—into the RQ-21A, which will lead to significant improvements in battlefield communications," said Steve Brown, mission systems lead for RQ-21A Blackjack. Now that it has proven it can work in congested environments, X-Net could be an option for use in contested environments. It could potentially thwart an enemy's attempts to jam crucial RF.

"We've already seen examples of adversaries trying to disrupt or completely destroy our information advantage on the battlefield," said Barbara Borgonovi, VP of Raytheon Integrated Communication Systems. "X-Net is a part of a solution to make sure those attacks never work."

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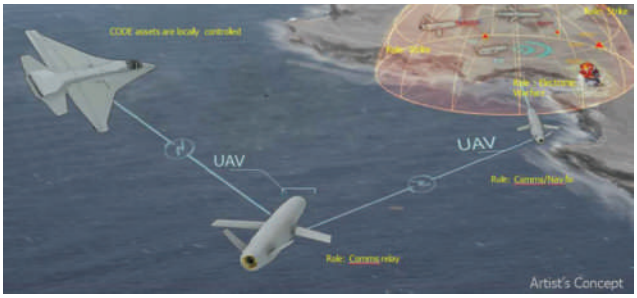
CODE Demos Autonomy, Collaboration with Minimal Human Commands

In a recent test series at Yuma Proving Ground in Arizona, DARPA's Collaborative Operations in Denied Environment (CODE) program demonstrated the ability of CODE-equipped unmanned aerial systems (UAS) to adapt and respond to unexpected threats in an anti-access area denial (A2AD) environment. The UASs efficiently shared information, cooperatively planned and allocated mission objectives, made coordinated tactical decisions and collaboratively reacted to a dynamic, high-threat environment with minimal communication.

The air vehicles initially operated with supervisory mission commander interaction. When communications were degraded or denied, CODE vehicles retained mission plan intent to accomplish mission objectives without live human direction. The ability for CODE-enabled vehicles to interact when communications are degraded is an important step toward the program goal to conduct dynamic, long-distance engagements of highly mobile ground and maritime targets in contested or denied battlespace.

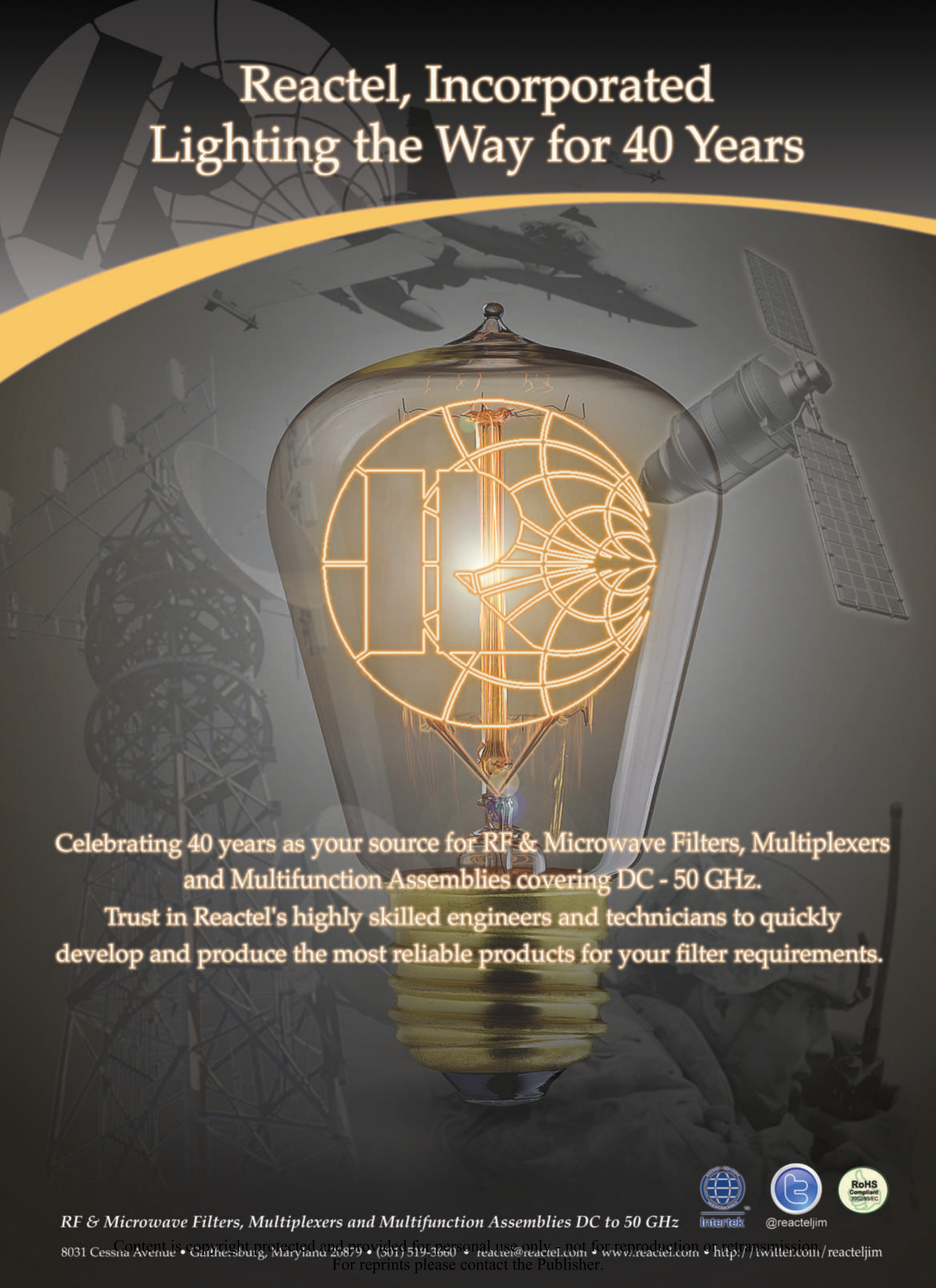
During the three-week ground and flight test series in a live/virtual/constructive environment, up to six live and 24 virtual UASs served as surrogate strike assets, receiving mission objectives from a human mission commander. The systems then autonomously collaborated to navigate, search, localize and engage both preplanned and pop-up targets protected by a simulated Integrated Air Defense System (IADS) in communications and GPS-denied scenarios.



"CODE" (Source: DARPA Illustration)

The DARPA team also has advanced the infrastructure necessary to support further development, integration and testing of CODE as it transitions to future autonomous systems. CODE's scalable capabilities could greatly enhance the survivability, flexibility and effectiveness of existing air platforms, as well as reduce the development times and costs of future systems.

Further development of CODE and associated infrastructure will continue under DARPA until the conclusion of the program in spring 2019, followed by full transition of the CODE software repository to Naval Air Systems Command.



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FCC Approves Broadband Satellite Services, Galileo Access

The FCC has approved requests from Kepler, LeoSat, SpaceX and Telesat proposing to launch low Earth orbit (LEO) satellite constellations to provide global broadband internet or IoT services, as well as officially allowed users in the U.S. to tap into signals from Europe's Galileo satellite navigation system.

The FCC granted Kepler's request for U.S. market access with certain conditions. The approval allows Kepler, a proposed constellation of 140 satellites originally licensed by Canada, to offer global IoT services using sensors and other "intelligent" devices. The satellites will use the 10.7 to 12.7 and 14 to 14.5 GHz frequency bands.

The FCC granted LeoSat's request for U.S. market access. LeoSat, which will operate under the ITU filings of France with a planned authorization from the Netherlands, proposes to provide high speed connectivity for enterprises and underserved communities from a constellation of 78 satellites. LeoSat will use the 17.8 to 18.6, 18.8 to 19.4, 19.6 to 20.2, 27.5 to 29.1 and 29.5 to 30 GHz frequency bands.

The FCC authorized SpaceX to construct, deploy and operate a LEO constellation of more than 7,000 satellites and granted SpaceX's request to add the 37.5 to 42 and 47.2 to 50.2 GHz frequency bands to its previously authorized NGSO constellation. In a written statement, the FCC said the updated approval provides SpaceX with additional flexibility to provide diverse geographic coverage and capacity to support a wide range of broadband and communications services globally, although the FCC has imposed "certain conditions."

The FCC granted Telesat, a proposed constellation of 117 satellites licensed by Canada, access to the U.S. market. Telesat plans to offer high speed, low latency communication services using the 37.5 to 42 and 47.2 to 50.2 GHz frequency bands.

Acting on a request from the EU, the FCC has approved allowing users located in the U.S. to access the Galileo global navigation satellite system (GNSS), developed by Europe. The change allows devices such as mobile phones that already have the capability to access two of Galileo's three signals, augmenting signals from the U.S. GPS. The added bands should improve availability and reliability of GNSS services in the U.S.

The FCC order permits devices to access two of Galileo's satellite signals that are in the same bands used by GPS:

- The E1 signal in the 1559 to 1591 MHz portion of the 1559 to 1610 MHz Radionavigation Satellite Service (RNSS) band.
- The E5 signal in the 1164 to 1219 MHz portion of the 1164 to 1215 MHz and 1215 to 1240 MHz RNSS bands.

By design, the Galileo and GPS systems are interoperable, with Galileo's E1 and E5 frequencies complementary, as reflected in the 2004 EU/U.S. Galileo-GPS Agreement.

However, the FCC did not approve access to Galileo's E6 signal within the U.S. E6 falls in the 1260 to 1300 MHz band, which is not allocated for RNSS in the U.S. nor used by GPS. In a statement, the FCC said access to the E6 signal could constrain future options for using that spectrum.

China Will Ultimately Be World's Largest 5G Ecosystem

China has announced aggressive plans with the superfast 5G connectivity and has positioned the new cellular generation as a key pillar of its economic development initiatives. However, despite China's vigorous pursuit to win the 5G race, it is U.S. operators who will actually deploy 5G before their Chinese counterparts, according to ABI Research.

"While they won't be the first country to deploy 5G, once they do, China will be the world's largest 5G ecosystem. At present, China has more than 160 cities with a population of more than 1 million and 15 cities with a population of more than 10 million," said Emanuel Kolta, research analyst, ABI Research. "This will make China the biggest single mobile broadband market and the Chinese government aims to position 5G as a key technology in its industrial revolution strategy."

China Mobile, China Unicom and China Telecom will all start large-scale deployments in 2020, prior to 2019's pre-commercial deployments. While the provision of enhanced mobile broadband to consumers will be the core proposition in early Chinese 5G deployments, industrial applications and network slicing will be the target of all Chinese operators. The Chinese central government has positioned 5G as a core component of its 13th Five-Year Plan and Made in China 2025 strategic plan to upgrade the Chinese industry. AR and VR have significant importance in consumer and industrial applications. While consumer application VR games are more well-known within the public, the Chinese government has high expectations for industrial applications of AR/VR, such as for virtual instruction manuals and virtual assistance.

"China has a unique position because its government does not just regulate the telecommunications market, but also actively shapes and encourages the market and its participants," Kolta concluded.

5G Americas Reveals Potential of URLLC

With 5G new services and applications requiring lower latency, better reliability, massive connection density and improved energy

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efficiency will be enabled, making our connected lives and industries faster, smoother and more efficient. 5G networks are being architected to support the service category of ultra-reliable low latency communication (URLLC). A variety of advanced services for latency sensitive connected devices will be supported by URLLC to enable wide-ranging applications like factory automation, autonomous driving, industrial internet and smart grid.

5G Americas announced the publication of "New Services & Applications with 5G Ultra-Reliable Low Latency Communication," which details the principles of achieving URLLC, explains the need for a new approach and highlights key requirements of URLLC services with an emphasis on technical challenges and solutions.

"With the wide range of unique 5G services, the context of communication will expand to vehicles, high speed trains, drones and industrial robots with the change agent being URLLC. With such advancement, mission-critical applications have stringent communication performance and reliability requirements," said Chris Pearson, president, 5G Americas. "To support such complex communication, low latency is seen as a crucial ingredient with URLLC as a key enabler in this new age of connectivity."

The 5G Americas report describes upcoming use cases of URLLC in smart transportation, industry automation and tele-surgery and presents the latency and reliability requirements for these applications. The white paper also identifies possible latency bottlenecks in current cellular networks as well as future 5G networks and lays out the necessary implementation blocks for achieving end-to-end latency reduction required to support mission-critical applications. In addition, the report summarizes the recent performance evaluation results of the basic designs and implementation of the 5G physical layer, multiple access layers and air interface blocks essential to reducing latency and achieving the desired reliability. It also discusses other potential latency reduction measures including Multi-Access Edge Computing (MEC).

"Although the first commercial 5G deployments are focused on enhanced mobile broadband use cases, the future of 5G will include ultra-high reliability and/or low latency features. We are living in a time where mobile and vertical industries are undergoing a rapid transformation boosted through critical communication capabilities," noted Rao Yallapragada, director of Advanced Technologies, Intel and co-leader of the 5G Americas URLLC white paper team. "URLLC will unleash an array of innovative applications and digitize a legion of verticals touching each aspect of human lives."

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

API Technologies has signed a definitive agreement to sell 100 percent of the capital stock of API Defense USA, its Electronics Manufacturing Services (EMS) business, to **Kitron Inc.**, a subsidiary of Kitron ASA. EMS, based in Windber, Pa., is a leader in the manufacture, testing and repair services of electronic components and assemblies for U.S. OEMs. Kitron is one of Scandinavia's leading electronics manufacturing services companies for the energy/telecoms, industry, defense, medical devices and offshore/marine sectors.

COLLABORATIONS

Keysight Technologies Inc. announced that the company has extended its collaboration with **SGS** on 5G conformance testing. SGS has been leveraging Keysight's solutions for more than 10 years. Since then, SGS has relied on Keysight's test & measurement solutions for 3GPP LTE and 3G (WCDMA) regulatory, protocol and RF testing. SGS selected Keysight's 5G NR network emulation solutions, based on Keysight's UXM 5G wireless test set, for regulatory RF, radio resource management (RRM) and protocol testing of 5G mobile devices across sub-6 GHz and mmWave frequencies.

HUBER+SUHNER has announced it has joined the **Next Generation Mobile Networks (NGMN) Alliance**. The Alliance advocates and seeks to encourage expansion of the communications experience by providing an integrated and cohesively-managed delivery platform that brings affordable mobile broadband services to the end user. The Alliance has a particular focus on 5G, while accelerating the development of LTE-Advanced and its ecosystem.

ACHIEVEMENTS

PowerSphyr has been awarded a patent to deliver the first truly intelligent near-field and far-field wireless charging solution. It is a full-fledged utility patent that defines PowerSphyr as the only platform to deliver truly intelligent "drop & go" wireless charging. The patent covers both transmission and receiving of multi-mode near-field and far-field wireless charging to intelligently identify optimal power requirements between power and charging units, dynamically switch between near- and far-field charging based on distance and power required, optimize charging time by mapping device capacity to charge delivery and extend the architecture to support all viable near- and far-field charging standards.

Isola Group announced that it has achieved IATF 16949: 2016 certification for their Chandler, Ariz. headquarters and their facilities in Duren, Germany, Huizhou and Suzhou, China and Taoyuan and Yangmei, Taiwan.

CONTRACTS

CACI International Inc. announced that it has been awarded a $413 million prime contract by the **General Services Administration (GSA) Federal Acquisition Service (FAS) Federal Systems Integration and Management Center (FEDSIM)** on behalf of the U.S. Army Communications-Electronics Research, Development and Engineering Center (CERDEC) Intelligence and Information Warfare Directorate (I2WD) to provide support for ground-based intelligence and communications systems within the Army's TROJAN STRONG family of systems (FoS). This five-year contract represents both the continuation of current support as well as new work in CACI's Command and Control and Intelligence Systems and Support market areas.

The **U.S. Army's Program Executive Office for Enterprise Information Systems (PEO EIS)** has named **ECS** the prime awardee of an $87 million contract to provide ongoing operational support for the Integrated Personnel and Pay System-Army (IPPS-A) Project Management Office Support Services (PMOSS). IPPS-A serves both active and reserve components of the Army, and will provide a centralized resource for service members and human resource professionals to better manage personnel and pay information. Awarded as a CPFF contract, the IPPS-A PMOSS project has a four-year period of performance.

Ultra Electronics Holdings plc (ULE) and **Sparton Corp.** announced the award of subcontracts valued at $39.6 million to their ERAPSCO joint venture, for the manufacture of sonobuoys for the **U.S. Navy**. The award is a GFY18 ERAPSCO IDIQ contract release for sonobuoy requirements under ERAPSCO's five year contract. ERAPSCO will provide production subcontracts in the amount of $19.4 and $20.2 million to Ultra Electronics USSI and Sparton DeLeon Springs LLC, respectively. Production will take place at Ultra Electronics USSI's Columbia City, Ind. facility and Sparton's DeLeon Springs, Fla. facility and is expected to be completed by September 2020.

Battelle was awarded a five-year, $14.6 million task order by the **U.S. Air Force Installation Contracting Agency (AFICA)** under the DoD Information Analysis Center's (IAC) Cyber Security Technical Area Task (CS TAT) Multi-Award Contract to support the Defense Technical Information Center (DTIC) in the development and enhancement of DTIC's capabilities for search, discovery and analysis of technical data and information.

Teledyne Microwave Solutions has been awarded a $7.5 million sole source contract from the **Naval Supply Systems Command Weapon Systems Support (NAVSUP)** in Philadelphia, Pa. The contract is for the repair of traveling wave tubes (TWT) used on the ALQ-99 system in support of the EA-18G "Growler" aircraft. Teledyne has supported the ALQ-99 system and its associated aircraft since the 1970s. Teledyne's engineering innova-

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FCTS1000-10-5	1000	10	+5, +12	-75	-109	-140	-158	
FCTS1000-10-5H	1000	10	+5, +12	-84	-116	-144	-160	
FCTS1000-100-5 *	1000	100	+5, +12	-75	-109	-140	-158	
KFCTS1000-10-5 *	1000	10	+5, +12	-75	-109	-140	-158	
FCTS2000-10-5 *	2000	10	+5, +12	-80	-105	-135	-158	
FCTS2000-100-5 *	2000	100	+5, +12	-80	-105	-135	-158	
KFCTS2000-100-5 *	2000	100	+5, +12	-80	-105	-135	-158	
FSA1000-100	1000	100	+3.3, +5, +12	-105	-115	-145	-160	
KFSA1000-100	1000	100	+12	-105	-115	-145	-160	
FXLNS-1000	1000	100	+5, +12	-120	-140	-149	-154	
KFXLNS-1000	1000	100	+12	-120	-140	-149	-154	

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Mail: 201 McLean Boulevard, Paterson, NJ 07504 tions in TWT technology continue to be deployed today to meet the stringent requirements of the U.S. Navy and other military purposes.

Kratos Defense & Security Solutions Inc. announced that it has been awarded a contract by **SKY Perfect JSAT Corp. (SJC)** to design and build gateways for SJC's new High Throughput Satellite (HTS) network. The JCSAT–18 HTS satellite, launching in 2019, will deliver broadband and mobile communication services to Asia-Pacific and Eastern Russia. Kratos will design and build a state-of-the-art Ka-Band multi-site gateway solution for SJC's new JCSAT-18 satellite. Kratos' breadth of gateway solutions are assembled and tested in their integration facility to enable rapid on-site assembly and commissioning. This results in both higher quality and faster time-to-market than traditional piecemeal ground station deployments, and protects SJC's investment by reducing complexity and risk.

Modelithics has recently been named as a partner in the **Qorvo**-led team that was recently awarded an **Air Force Research Lab (AFRL)** contract related to Broad Area Announcement (BAA) solicitation titled "Engineering Predictable Behavior into GaN Devices Foundational Engineering Problem (FEP)." The Qorvo team includes Modelithics, **University of Padova**, **HRL**, **University of Colorado** and **NI AWR**. The goal of the project is to develop an advanced GaN device modeling framework that accounts for aging and reliability effects along with electrical performance, thermal and mechanical considerations and material variations.

General Atomics Aeronautical Systems Inc. (GA-ASI) has been advised that, following consideration by the Australian government, it has been selected to provide the Armed Remotely Piloted Aircraft System (RPAS) under Project Air 7003 for the **Australian Defence Force (ADF)**.The ADF joins other top-tier military forces in choosing a MQ-9 variant because of its proven multi-role combat performance. Known as the "operators" choice, the MQ-9 is part of GA-ASI's Predator® series of RPAS, which is the world's most trusted and capable Armed Medium-Altitude, Long-Endurance (MALE) RPAS, and hails from a family of RPAS which recently surpassed five million flight hours.

Accel-RF has won a follow-on contract with **The Air Force Research Laboratory** through the Small Business Innovation Research (SBIR) program. The Phase II SBIR will continue development efforts for mmWave accelerated life test systems and spans from September 2018 to December 2020. The object of the Phase II effort is to demonstrate a system platform capable of performing end of life reliability analysis on multiple individual test devices at V- and W-Band frequencies.

PEOPLE

Anokiwave Inc. announced the appointment of **Alastair Upton** as senior VP of business development.

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Around the **Circuit**

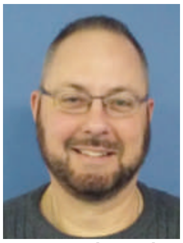
▲ *Alastair Upton*

In this role, Upton will lead the company's strategic accounts, manage partnership programs and provide telecommunications expertise. This appointment comes at a strategic time for Anokiwave, with tremendous opportunities for continued growth in the rapidly developing mmWave 5G, SATCOM and A&D markets. Upton joined Anokiwave in June 2018, and brings 38 years of experience in the semiconductor industry covering both defense electronics and high volume commercial applications at companies such as GE Aerospace, Lockheed Martin, RF Micro Devices (now Qorvo), MACOM and IDT.

▲ *Sean Hulin*

Sunstone Circuits® announced the addition of **Sean Hulin** to their marketing and sales team. In his role of marketing and sales manager, Hulin's vast background in brand marketing, strategy and sales will be a tremendous asset to the Sunstone team. In addition, Hulin brings valuable experience from his previous roles including building and managing successful teams, developing and executing sales and marketing strategies across many different industries and products, years of digital marketing expertise as well as his involvement in successfully growing a technology company from the ground up.

▲ *Michael Hallman*



▲ *Ed Kiessling*

Microwave Journal announced the promotion of **Michael Hallman** to associate publisher. Hallman has been with *Microwave Journal* since 2003, serving as eastern regional sales manager. He will continue in that role along with his new position and responsibilities. Sister publication ***Signal Integrity Journal*** announced **Ed Kiessling** has been named sales manager. Kiessling has been with parent company Horizon House Publications Inc. since 1991, most recently serving as ad traffic manager for *Microwave Journal*.

REP APPOINTMENTS

Antenna Systems Solutions S.L. announced it has formed a new alliance with **Next Phase Measurements (NPM)** to serve North and South America. NPM will be the distributor and Value-Added Reseller (VAR) across both American continents. This new partnership leverages world-class established products, including, near-field, CATR, RADOME and RCS test ranges, positioners, antennas, probes and antenna measurement software. The team's experience will be applied to find innovative solutions to customer antenna measurement require-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AtlanTecRF announced the appointment of **D&L Technical Sales Inc.** as its new sales representative for Arizona and Nevada. The team at D&L Technical Sales will sell AtlanTecRF's complete range of RF satellite simulators and SATCOM test equipment. The range includes everything from single and multi-path satellite simulators, to AtlanTecRF's unique drone and HAPS payloads. D&L Technical Sales will also sell AtlanTecRF's range of manual, battery powered, weatherproof, portable and ethernet control loop test translators (LTT), noise and signal generators and noise injection test translators.

Southwest Microwave announced that **Milexia** is expanding its presence to include France, in addition to serving as the exclusive distributor for Italy and Greece. Milexia Group is a European leader delivering high tech components, systems and scientific instrumentation. The company operates regionally with Milexia Italia SpA, founded in 1974, and Milexia France SAS, founded in 1971, specializing in RF and microwave components for civilian and military industries.

XMA-Omni Spectra® announced the appointment of **Mission Critical Sales LLC** as its exclusive sales representative in New England.

IN MEMORIAM

▲ *Barry S. Perlman*

Barry S. Perlman passed away on November 5, 2018. He retired in June 2012 as the director of R&D of solid-state electronics for military applications for the U.S. Army Communications-Electronics Research Development and Engineering Center. He was an IEEE Life Fellow and 2009 president of IEEE MTT-S.

The **ARMMS RF & Microwave Society** paid tribute to several members who had passed away since the previous conference. **Terry Oxley** had been a significant contributor to the U.K. microwave industry through his time at the **GEC Hurst Research Centre**. Oxley's work was recognized through numerous awards including Her Majesty's Silver Medal in 1977, the GEC Gold Medal in 1989 and a distinguished service award from the IEEE, as well as being elected a Life Fellow in 1999. **Richard Mumford**, international editor of ***Microwave Journal*** and a frequent attendee of the meetings, had been a keen supporter of ARMMS and valued colleague. His was a warm and friendly smile when and wherever you met him around the world. He will be sorely missed. Lastly, the Society paid tribute to **John "Robbie" Burns**, managing director of **Testime Technology**. A glass was raised to them all at the Society dinner.

INVITED PAPER

Automotive Radar and Congested Spectrum: Potential Urban Electronic Battlefield

Sefa Tanis
Analog Devices Inc., Norwood, Mass.

As automotive radars become widespread, the heavily occupied RF spectrum in an urban environment will resemble an electronic battlefield. Radar will face a combination of unintentional—even intentional—jamming, and designers must implement counter-jamming techniques like ones used in electronic warfare (EW). An automotive radar can experience either denial or deceptive jamming. Denial jamming blinds the victim's radar, reducing the signal-to-noise ratio (SNR) and, as a result, the probability of target detection is degraded. Deceptive jamming makes the victim's radar "see" targets that are really false. The victim's radar loses the ability to track the real targets, and vehicle safety is compromised. These jamming attacks could originate from mutual interference between automotive radars or be deliberate, by simply pointing a strong continuous wave (CW) signal into the victim's radar using inexpensive hardware.

While current jamming avoidance techniques may be adequate today, with the proliferation of radar sensors, more resilient mitigation techniques will be needed, either stand-alone or in conjunction with other approaches. Such techniques include time/frequency domain signal processing or complex radar waveforms.

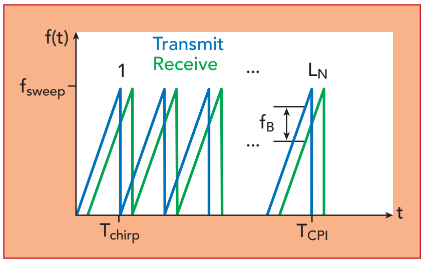

Fig. 1 FMCW chirp sequence waveform.

JAMMING FMCW RADAR

The waveform is a critical system parameter that determines the radar's performance in the presence of jammers. Automotive radars in the 77 GHz band mainly use FMCW waveforms, where a CW signal is linearly swept or "chirped" in frequency across the RF band (see ***Figure 1***). The frequency difference or beat frequency (f_B) between the transmit and receive signals is proportional to the distance to the target (R) and can be determined by

$$f_B = \frac{2}{C}\frac{f_{sweep}}{T_{chirp}}R\ ,$$

where f_{sweep} is the change in frequency and T_{chirp} is the time for the frequency sweep.

Unintended jamming can occur in a dense RF environment when FMCW radar sensors are operating in the same portion of the frequency band. A typical automive jamming example is shown in ***Figure 2a***.

Denial Jamming

An arbitrary FMCW jamming signal that falls in the receiver bandwidth of the victim's radar raises the noise floor (see ***Figure 2b***). Called denial, this jamming may cause small targets—those with small radar cross section (RCS)—to disappear, due to the poor SNR. A denial attack could be purposeful, by simply beaming a strong CW signal into the victim's FMCW radar.

Deceptive Jamming

If the swept frequency of the jamming signal is delayed and synchronized with the victim's radar, the impact is a false target generated at a fixed range (see ***Figure 2c***). This technique is commonly used by EW jammers. However, this can occur unintentionally with an oncoming automobile having a similar FMCW radar, although the


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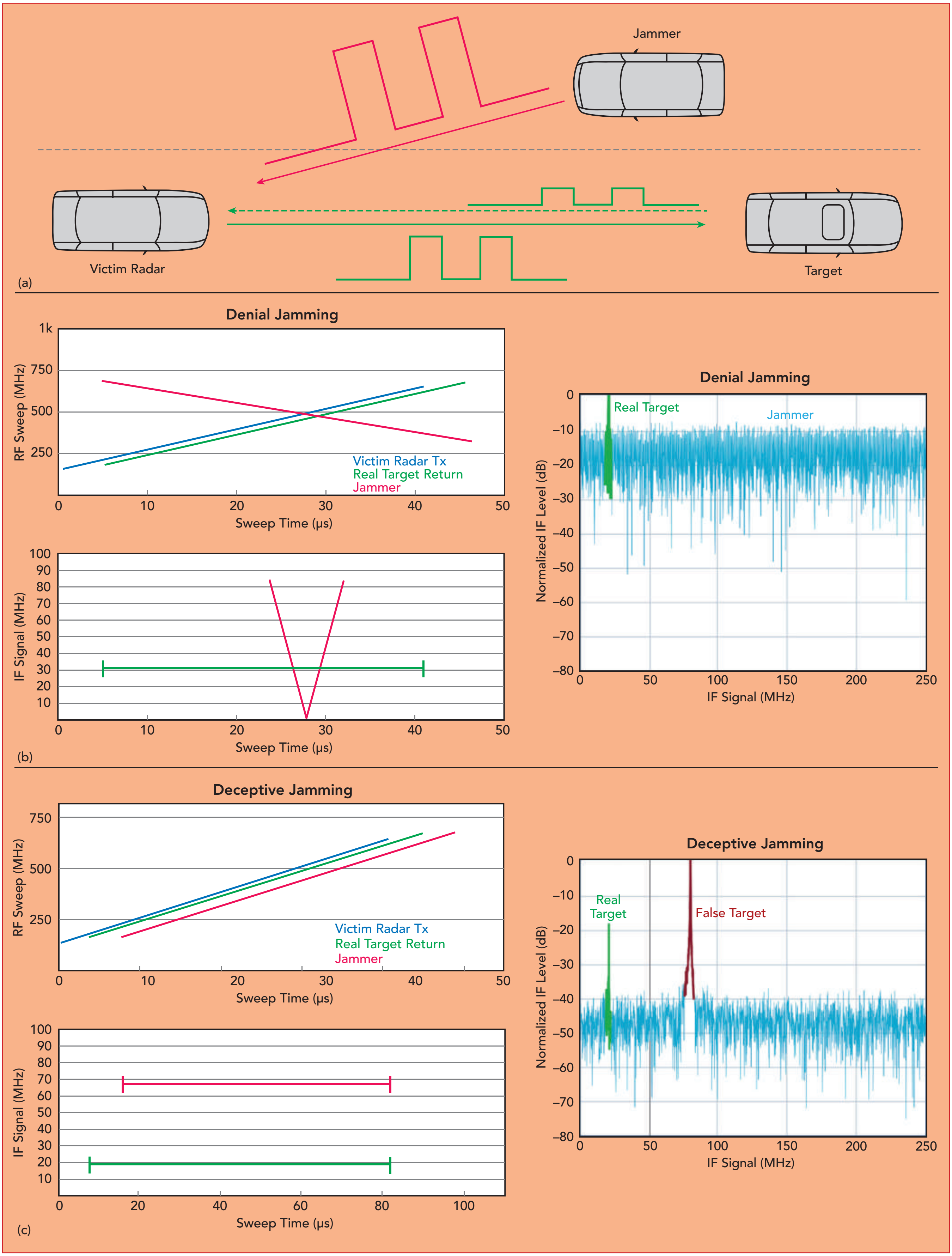


Fig. 2 Driving scenario (a) with denial jamming (b) and deceptive jamming (c) of an FMCW radar.

probability of time alignment between the victim and jamming radars is small. Nonetheless, a jammer delay offset less than the maximum range delay of the victim's radar could look like a real target. For example, a radar with 200 m maximum range would require sweep alignment of less than 1.3 µs. Such a deceptive attack could be intentional using sophisticated EW equipment mounted on the oncoming automobile.

Generally, deceptive jamming is based on retransmitting the victim radar's signal with a systematic change in delay and frequency. This signal can be noncoherent, in which case the jammer is called a transponder, or coherent, termed a repeater. Repeaters receive, alter and retransmit one or more jamming signals, while transponders transmit a predetermined signal when the desired victim's signal is detected by the jammer. A sophisticated repeater-based attack typically requires a digital RF memory (DRFM). A DRFM is capable of carrying out coordinated range delay and Doppler gate pull-off attacks, with the false target range and Doppler properties maintained to deceive the victim's radar.

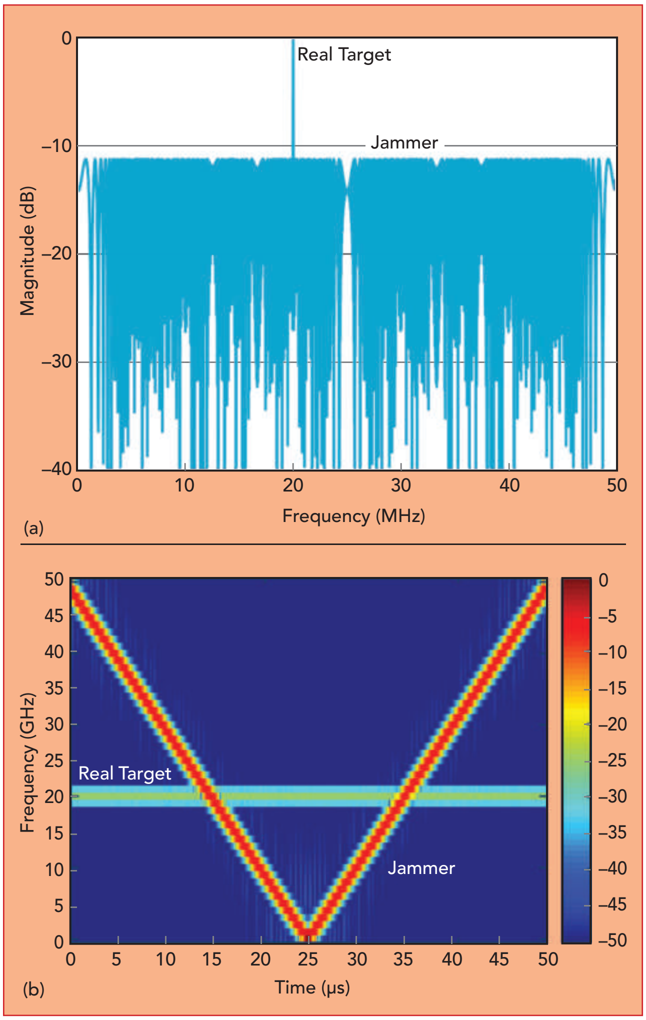


Fig. 3 FFT (a) and STFT (b) of the radar echo IF waveform with jamming.

JAMMING MITIGATION

Basic radar jamming mitigation techniques rely on avoidance. The objective is to reduce the probability of overlap in space, time and frequency, using methods such as:

- Spatial: Using a narrow and electronically-scanned beam to reduce the risk of jamming. A typical field of view for long-range automotive cruise control radar is ±8 degrees. Nonetheless, a strong jammer could be effective via the antenna sidelobes.
- Temporal: Randomizing the FMCW chirp slope parameters to avoid periodic jamming.
- Spectral: Randomizing the FMCW chirp start and stop frequencies to reduce the probability of overlap and jamming.

The basic methods of randomization would avoid accidental synchronization with other radars but might not be as effective in dense RF environments. The growing number of radar sensors will require more sophisticated techniques to mitigate possible jamming.

Detect and Repair

An alternative method to avoid jamming is to repair the received waveform using signal processing algorithms. Time/frequency domain techniques can be effective against

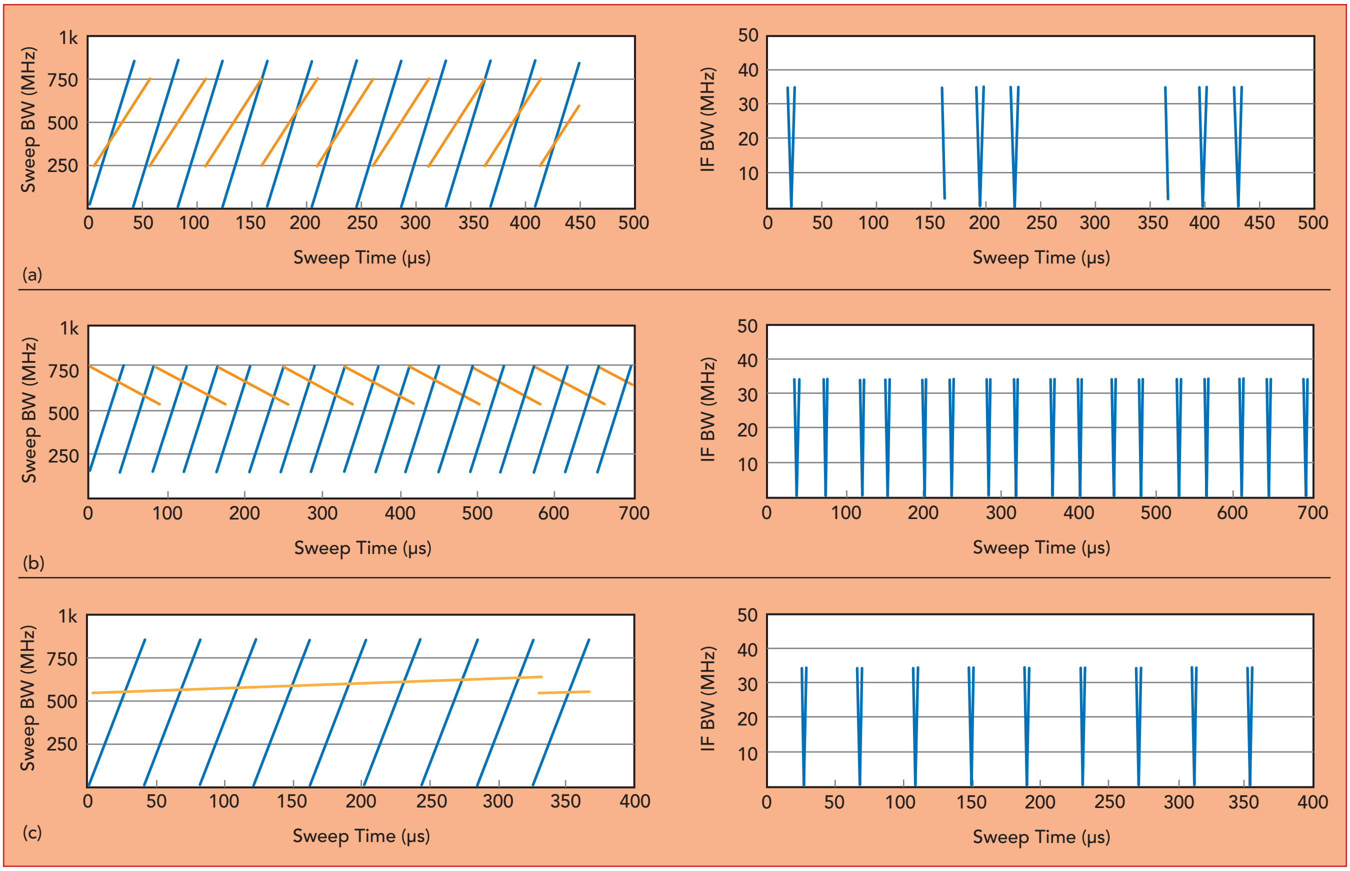


Fig. 4 **Radar and jammer chirps (left) and STFT-processed IF (right) for similar direction (a), opposite direction (b) and CW interference (c) scenarios.**

denial type jamming. In the oncoming automobile scenario (see Figure 2), the jammer sweeps all frequency bins for a very short time duration. This fast time-varying signal manifests itself as a raised noise floor in the fast Fourier transform (FFT) domain. Time/frequency domain signal processing transfers the signal to another domain where it is easier to filter out the jamming.

For time-varying signals, a short time Fourier transform (STFT) provides more information than a regular FFT, and STFT-based techniques can be used for countering narrowband jamming (see ***Figure 3***). The STFT essentially moves a window through the signal and takes the FFT of the windowed region. The signal is filtered in the frequency domain to remove the jammer components before being transformed back to the time domain. ***Figure 4*** shows a typical FMCW jamming scenario of overlapping RF chirp sequences and the IF signals obtained using STFT processing. The plots on the right show the beat signal from mixing the radar (blue) and jamming (orange) signals. A horizontal line indicates a target, while V-shaped vertical lines indicate the presence of a jamming signal. Similar or opposite direction FMCW jamming or a CW-like slow chirp have similar effects on the IF signal. In all these jamming scenarios, the fast moving V-shaped IF signal raises the noise floor in the regular FFT domain, as was seen in Figure 3.

Amplitude-based masking can be used to filter out jamming in the STFT domain. This assumes, of course, that the victim's radar front-end and quantization have enough dynamic range to linearly process the stronger jammer signal and the small intended target at the same time. ***Figure 5a*** shows the STFT signal with a strong jammer, and ***Figure 5b*** shows the STFT after amplitude-based masking. Without processing, multiple real targets will not be visible in the presence of a strong jammer; however, amplitude-based masking excises the V-shaped jammer in Figure 5b, enabling the low SNR targets to be discerned when transformed back to the time domain.

While STFT-based jamming mitigation can be used against strong jammers in denial jamming scenarios, with deceptive jamming attacks, STFT alone cannot authenticate whether the return signal is real or false.

Encrypted RF

The simple countermeasure to reduce the impact of deceptive jamming from repeater attacks is using a low probability of intercept (LPI) radar waveform. The objective of an LPI radar is to escape detection by spreading the radiated energy over a wide frequency spectrum, usually via a quasi-random sweep, modulation or hopping sequence. FMCW is a type of LPI waveform, and if phase coding or encryption is used with the frequency chirp, it is possible to further reduce the probability of a DRFM intercepting the radar signal. An encrypted RF signature unique to each radar sensor can authenticate the return signal.

Figure 6 shows a use case where two identical radars are on two different automobiles, and the frequency offset and delay between

them generates a false target in the victim's radar. The jamming radar is time aligned with the victim radar, i.e., having the same chirp slope and a short offset. Phase-coded FMCW radars will provide high jamming robustness in this case, and the use of orthogonal codes will also make MIMO radar operation possible, by enabling multiple simultaneous transmit waveforms.

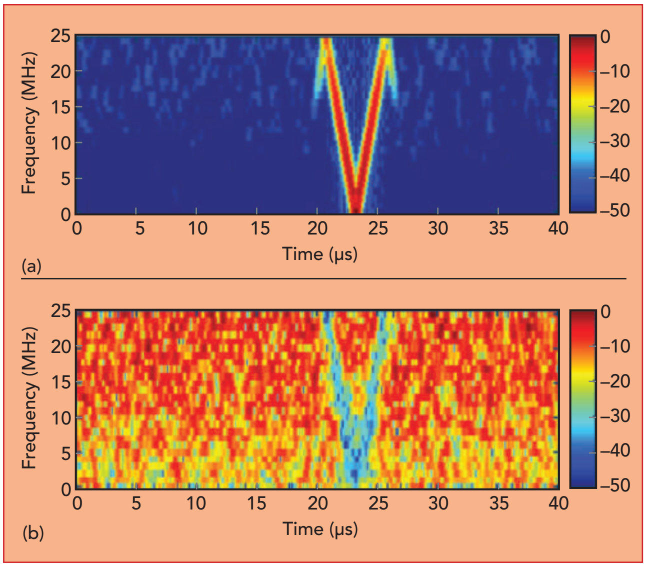


Fig. 5 STFT chirp return with strong interference (a) and after amplitude-based masking (b).

The requirements for coding are:

- Code length: The code length should achieve minimal range sidelobe levels with short sequences. A pseudo-random-noise (PRN) sequence length of 1024 results in a peak sidelobe level (PSLL) of about 30 dB, i.e., $10 \bullet \log_{10}(1024)$. Transmit codes together with receive filter weights can be optimized to improve the PSLL at the expense of SNR.
- Good cross-correlation properties: Cross-correlation coefficients of the members of a set should be zero to achieve separation between sensors.
- Doppler resistance: Phase-coded radar performance can suffer from the Doppler shift. Binary codes are Doppler intolerant, while polyphase codes degrade less rapidly.
- Available number of different codes: A large family size is better to assign a unique code to each radar sensor.

Figure 7a illustrates a radar echo with no phase coding, where the jamming signal appears as a

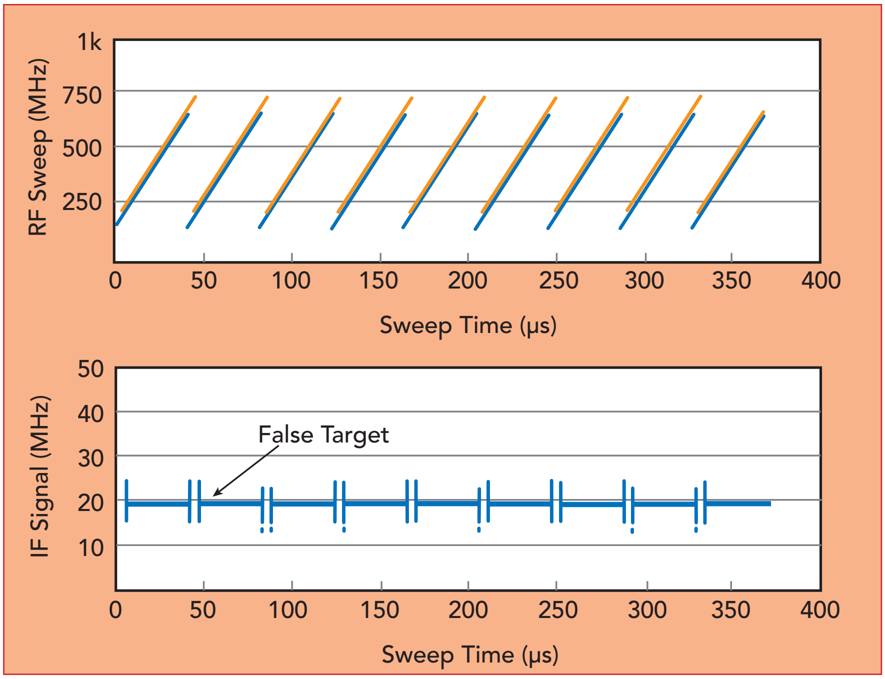


Fig. 6 Jamming due to identical radars with frequency offset and delay.

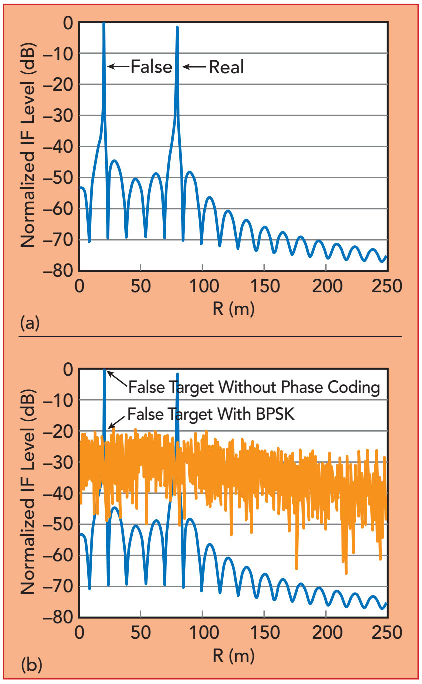


Fig. 7 **Radar return without phase coding, showing false and real targets (a). Phase coding reduces the false target by some 20 dB (b).**

false target. When the transmitted FMCW waveform is phase-coded with a PRN sequence, the jamming signal is suppressed, as shown in ***Figure 7b***. The dynamic range is compromised with this method; however, the radar signal processor could use phase-coded FMCW for a few chirps to flag a false target, then switch back to normal operation.

FUTURE TRENDS

In congested automobile radar environments, jamming can be mitigated using advanced signal processing algorithms and complex waveform generation techniques. STFT-based signal processing can be used against denial attacks. Phase-coded FMCW provides an additional layer of resistance to both noncoherent and coherent deceptive attacks by using processing gain and interception avoidance. ***Table 1*** summarizes these mitigation techniques. The jamming mitigation principles for automotive radar are also applicable for other radar sensors: robotics, road tolling, GPS and UAV landing or collision avoidance systems.

Currently, automotive radar sensors are operating in a non-cooperative mode, i.e., not communicating with each other. Although a cooperative mode of operation requires industry-wide harmonization, the arbitration between radar sensors would help resolve interference. A future radar concept including sensor cooperation is the fusion of communication nodes and radar sensors. Future radars with complex waveforms offer the possibility to include information in the radar signal, enabling the same hardware to be used simultaneously for radar and communications (RADCOM). Such a capability has the following benefits:

- Multi-user capability without interference.
- Coding the radar signal with OFDM or similar communication codes enables information to be contained in the radar signal.
- Simultaneous RADCOM.

5G mmWave transceivers with multi-GHz bandwidth and beam steering capabilities are candidates for use in a RADCOM system.■

TABLE 1

JAMMING MITIGATION FOR FMCW AUTOMOTIVE RADAR

Jamming Type	*Denial*	*Deceptive*	
Jamming Hardware	Another Radar Sensor or a Simple CW Generator	DRFM (Coherent)	Transponder (Noncoherent)
Impact on Victim Radar	Poor SNR	False Target	
Resilient Mitigation Technique	STFT	Phase-Coded FMCW	
Mitigation Principle	Repair the Radar Return Waveform	Escape Detection	Processing Gain of the Coding Sequence
Mitigation Effectiveness	High	Moderate	Good

Nonlinear Modeling of a High Peak Power PIN Limiter

Hetvi Patel, Kevin Kellogg, Hugo Morales and Larry Dunleavy
Modelithics Inc., Tampa, Fla.

Rob Jones and Paul Head
Raytheon, Andover, Mass.

This article describes an innovative approach for accurate nonlinear modeling of a high peak power limiter circuit. The modeling approach involves "inside out" modeling of the individual constituent components, which are used to build a composite model. The constituent models include nonlinear models for discrete PIN diodes and linear models for other components, including the coaxial package, capacitors and microstrip circuits. The developed 8 to 18 GHz coaxial limiter model is validated against broadband S-parameter data through 20 GHz and with large-signal power compression measurements at 8 and 13 GHz. The diode models are also validated over temperature at 25°C and 100°C.

Limiter circuits are used extensively in RF/microwave applications, such as the front of receiver chains to protect low noise amplifiers from high-power levels. The limiter's role is to attenuate the output power to a defined level when high-power signals are received and to let signals pass through the limiter with minimum attenuation when the received power is low.[1]

A limiter typically consists of PIN diodes and RF inductors in a shunt configuration, with DC blocking capacitors in series. A limiter circuit can consist of a single diode or multiple cascaded diodes separated by quarter wavelength sections of transmission line.[2] This work describes a model for a MACOM broadband, high peak power, PIN diode-based limiter (part number 2690-1011).

To obtain an accurate integrated model of the MACOM 2690-1011 PIN limiter, the internal discrete diodes, capacitors, inductors, peripherals (i.e., DC feedlines, bondwires, microstrip circuits) and SMA connectors were measured and modeled. The overall model was then validated with small-signal and large-signal measurements of the limiter at its coaxial reference planes.

DISCRETE DEVICE MODELS

The most important modeling parameters for PIN diodes used in limiters are the intrinsic region thickness, thermal impedance, forward resistance, off-state capacitance, breakdown voltage and minority carrier lifetime. These parameters affect the limiting threshold, power handling, isolation and insertion loss of the limiter. Intrinsic region thickness, breakdown voltage and thermal

impedance are directly related to maximum power handling. Minority carrier lifetime determines the recovery time of the limiter. Forward resistance and junction capacitance affect insertion loss and isolation, respectively.[3-4]

A nonlinear discrete PIN diode model was extracted from a set of measurements that included CV, IV, RF impedance, time domain, S-parameter and large-signal power. The model is based on a Modelithics in-house PIN modeling framework, developed and proven to provide a close fit to broadband linear and nonlinear PIN diode behavior in both the forward and reverse bias regions.[5] For fixturing, bond wires connected the parts mounted in series and shunt configurations to 50 Ω input and output feed lines on a 6.6 mil Rogers 4350B test board (see ***Figure 1***).

The IV measurements and modeling results at 25°C and 100°C are shown in ***Figure 2***. The model was fitted to the measured CV and RF impedance characteristics vs. bias at 1 GHz (see ***Figure 3***).

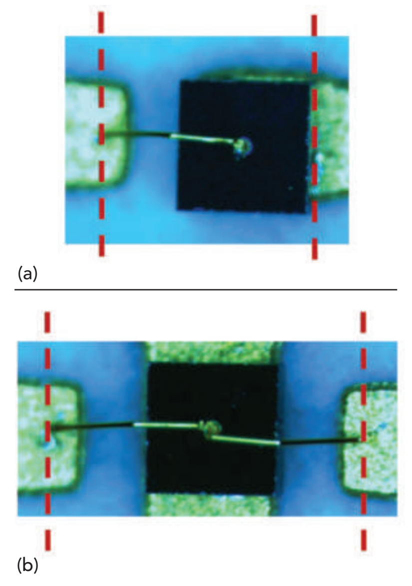


Fig. 1 Discrete PIN diode mounted in 2-port series (a) and shunt (b) configurations.

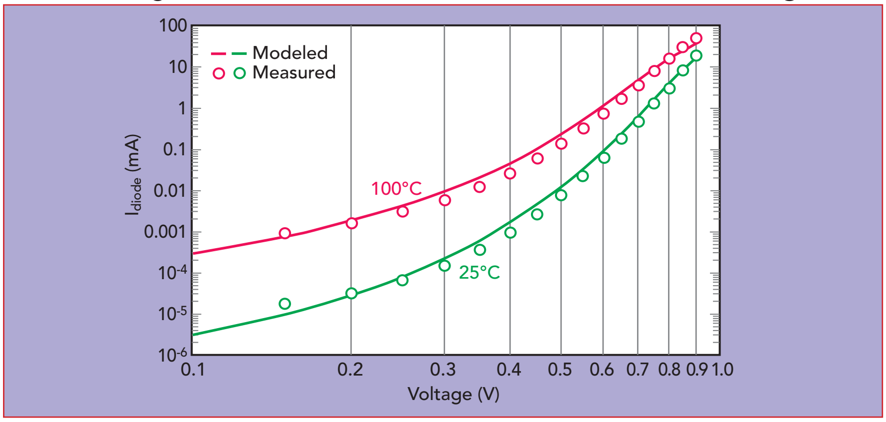


Fig. 2 Modeled and measured DC IV characteristics of a discrete PIN diode internal to the limiter.

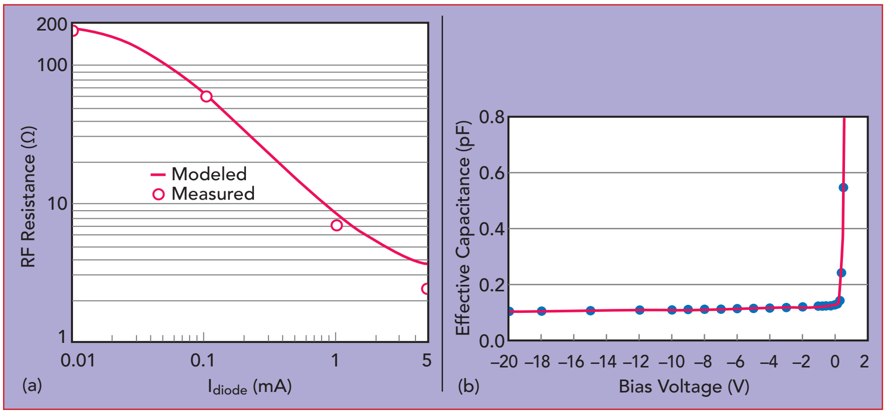


Fig. 3 Modeled and measured RF resistance vs. bias (a) and capacitance vs. bias (b) of a discrete PIN diode at 1 GHz and 25°C.

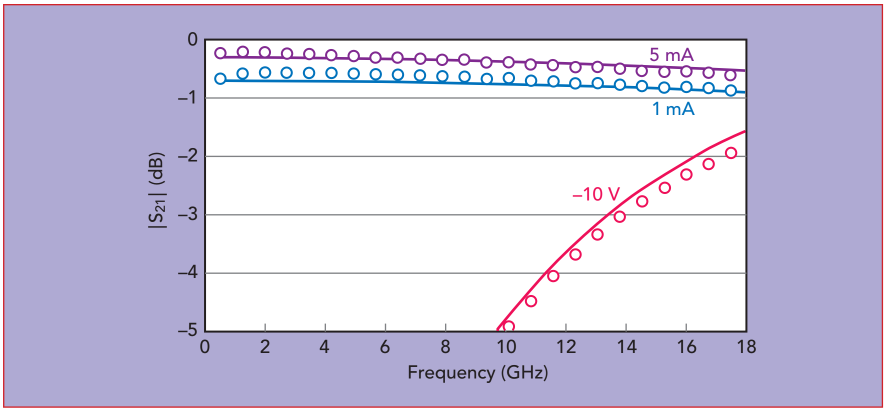


Fig. 4 Modeled (solid lines) and measured (symbols) $|S_{21}|$ of a discrete series diode vs. bias at 25°C.

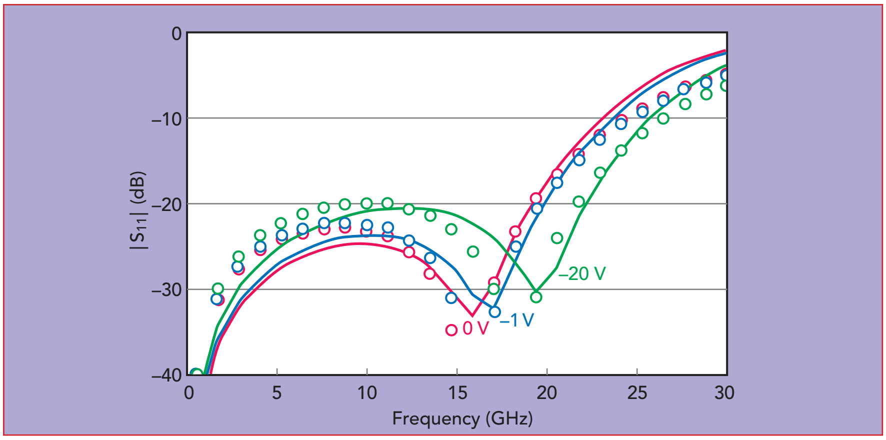


Fig. 5 Modeled (solid lines) and measured (symbols) $|S_{11}|$ of a discrete shunt diode vs. bias at 25°C.

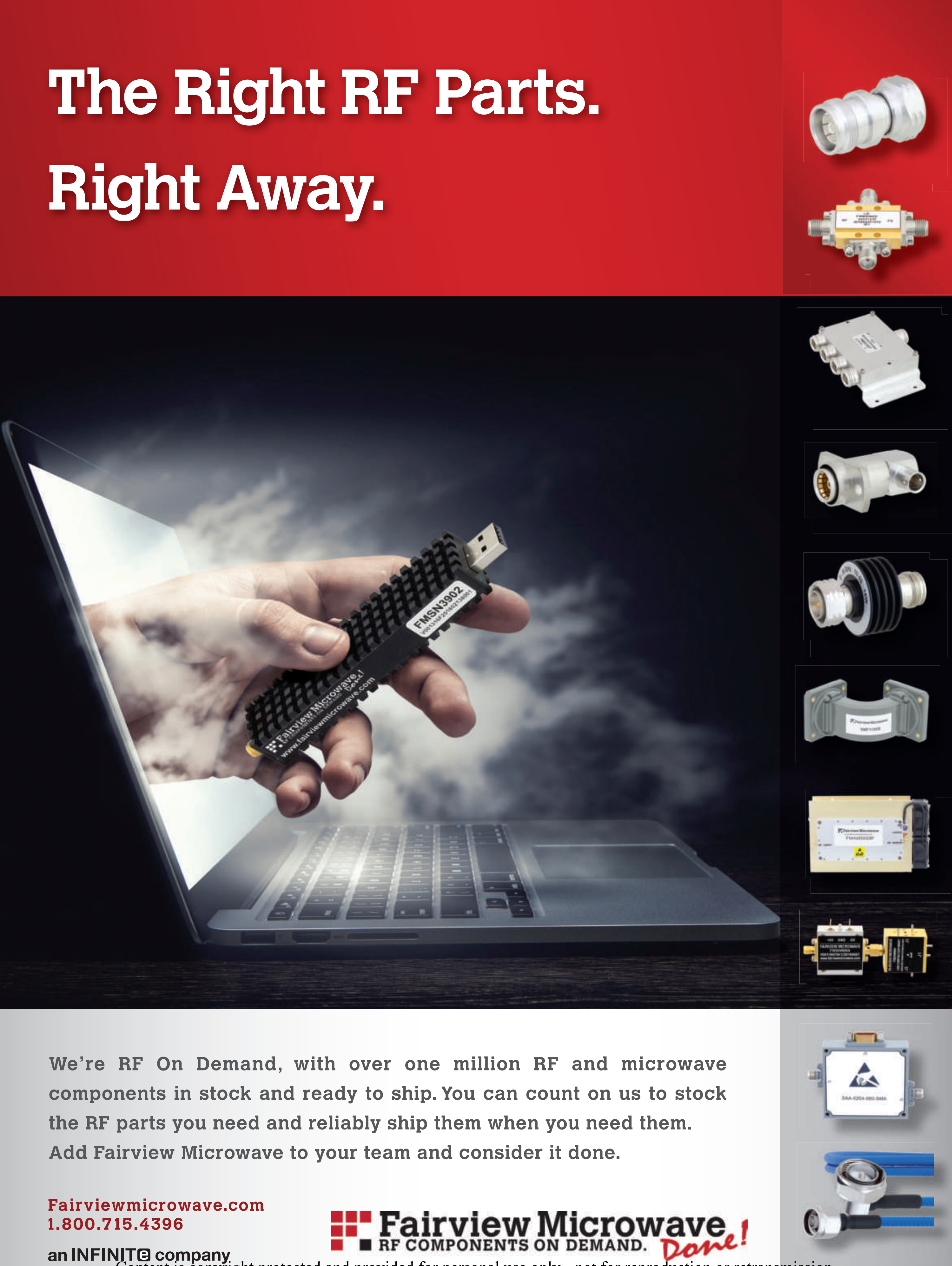
Measured and simulated small-signal S-parameters for a 2-port series- and 2-port shunt-mounted diode are shown in ***Figures 4*** and ***5***, respectively. Although the data is not shown, the PIN model was also validated against large-signal power sweep and time domain transient response measurements. As part of the overall modeling process, a single layer DC blocking capacitor used inside the limiter was characterized and modeled to 30 GHz.

LIMITER MODEL

The MACOM 2690-1011 PIN-based nonlinear limiter is specified for 8 to 18 GHz applications and has 2.3 dB insertion loss and 2:1 VSWR, with 1000 W peak power handling (3 W average) and 1000 ns recovery time. The limiter was characterized and modeled using the discrete diode and capacitor models as primary building blocks. Bond wires and capacitors in the discrete component assembly were modeled using Ansys HFSS 3D electromagnetic simulations. These EM models were used to predict the bond wire and capacitor effects in the limiter.

Multiple samples of the complete coaxial limiter with connectors were characterized with S-parameter and CW power compression measurements. A 3.5 mm short-open-load-through (SOLT) calibration was performed prior to measuring S-parameters from 0.05 to 18 GHz. The measurement and model reference planes were set at the outside edge of the PIN limiter SMA connector, as shown in ***Figure 6***.

The model tracks the measured S-parameters (see ***Figure 7***), with the modeled performance and measurement showing a maximum insertion loss of 2.3 dB from 1 to 18 GHz, which is consistent with MACOM's specifications. For large-signal model validation, with the limiter in a series configuration, power testing was performed at 8 and 13 GHz, with input power levels from −20 to 37 dBm and a tempera-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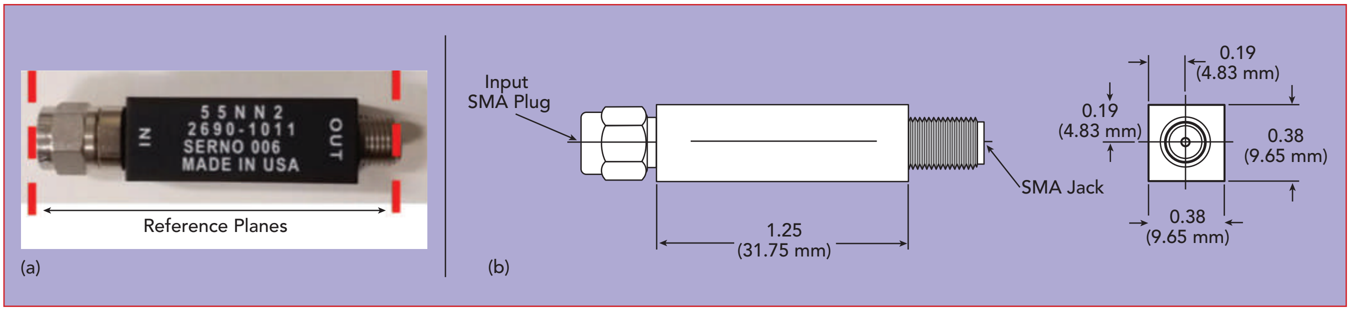
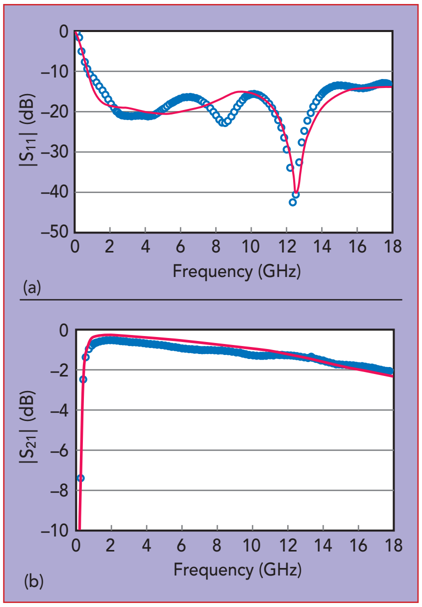
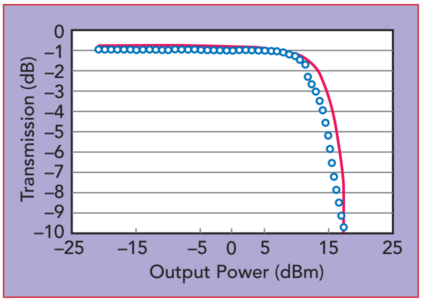


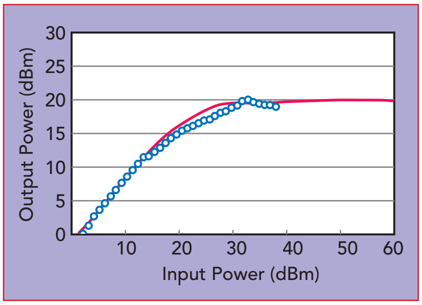
▲ Fig. 6 MACOM 2690-1011 PIN limiter.



▲ Fig. 7 Modeled (solid lines) and measured (symbols) $|S_{11}|$ (a) and $|S_{21}|$ (b) of the MACOM PIN limiter.



▲ Fig. 8 Modeled (solid line) and measured (symbols) transmission vs. output power of the MACOM PIN limiter at 8 GHz and 25°C.



▲ Fig. 9 Modeled (solid line) and measured (symbols) output power vs. input power of the MACOM PIN limiter at 13 GHz and 25°C.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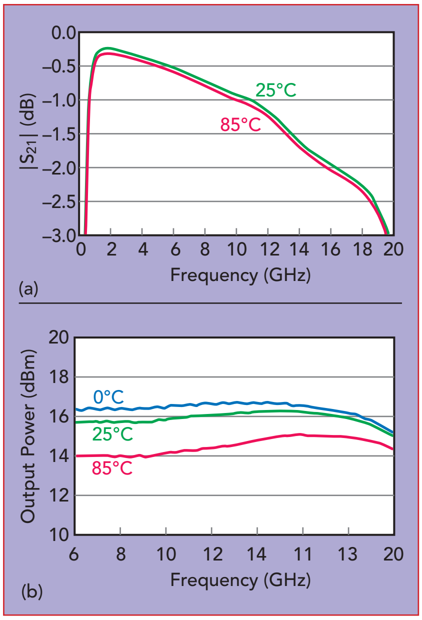
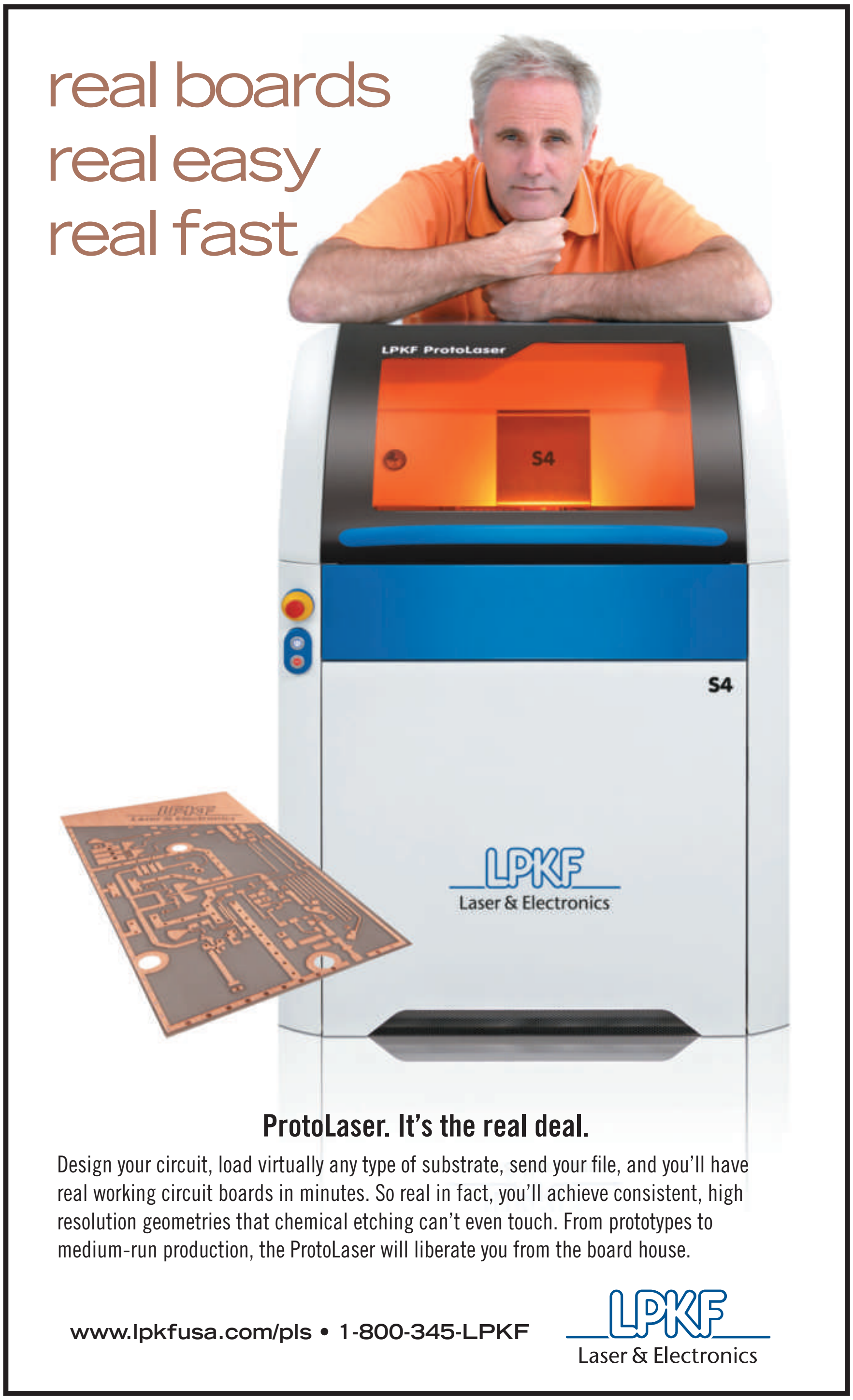
ture of 25°C. The large-signal transmission compares closely with the nonlinear model at 8 GHz (see ***Figure 8***). ***Figure 9*** shows the 13 GHz results, validating the high-power limiter model up to 60 dBm input power. The limiter's performance over temperature reflects the discrete diode's characteristics versus temperature. While the complete limiter circuit has not yet been validated over temperature, the trend predicted by the model is shown in ***Figure 10***.

SUMMARY

PIN limiters are widely used in amplifier receiver chains in the RF/microwave industry. The availability of accurate nonlinear models with advanced simulation features improves the efficiency and cost effectiveness of designing at both the circuit and system levels. Accurate nonlinear models of PIN limiters may be generated using an inside out approach, characterizing, modeling and validating the individual components.■



▲ **Fig. 10** Modeled $|S_{21}|$ (a) and output power (b) of the MACOM PIN limiter over temperature, with an input power of 20 dBm.



ACKNOWLEDGMENTS

The authors would like to thank Joe Bukowski of MACOM for technical collaboration.

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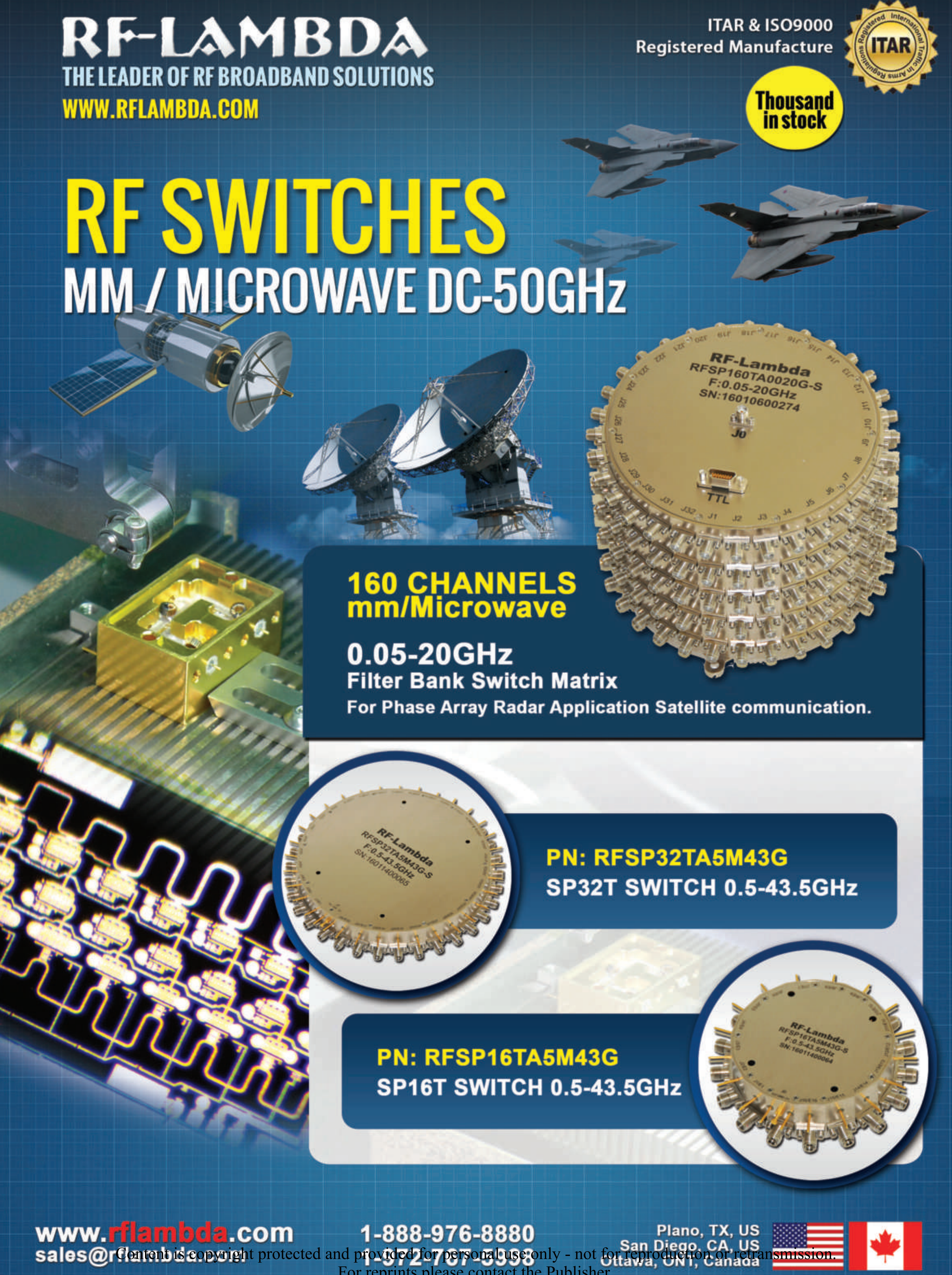
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INVITED PAPER

Chip Antenna-Antenna Tuner Combo Cover LTE Bands

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Jaume Anguera
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Cor Schepens and Robert Gaddi
Cavendish Kinetics, Hertogenbosch, The Netherlands

With the large number of LTE bands, wireless devices require many sophisticated multiband antenna designs.[1-12] One of the biggest challenges with 4G—compared to 2G and 3G, which used only 824 to 960 and 1710 to 2170 MHz—is the large operating bandwidth: 698 to 960 and 1710 to 2690 MHz. The lower frequencies of the low frequency region, especially from 698 to 960 MHz, exacerbate the challenge, since the antennas must be small compared to the operating wavelength.

This article shows how combining a small antenna booster from Fractus Antennas—86.4 mm^3—with a small antenna tuner from Cavendish Kinetics—just 2 mm^2 in area—yields an antenna system that covers the LTE frequency bands within the 698 to 2690 MHz frequency range.

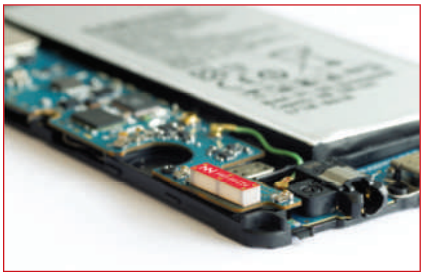


Fig. 1 Antenna booster, measuring 12 mm × 3 mm × 2.4 mm, mounted on a corner of a smartphone PCB.

BOOSTERS + TUNERS

Virtual Antenna™ technology[13-18] relies on very small antenna elements, called antenna boosters, which makes it a good approach to satisfying the bandwidth requirements of LTE. Using a matching network, the bands of operation are not adjusted by designing a complex antenna geometry, only a proper matching network, which is faster and more cost effective. The same antenna booster can operate with different platform sizes, since only the matching network changes from one design to another.[18] This is a different approach than conventional antenna design, where the antenna geometry has to be designed case by case. Besides being small, antenna boosters are surface-mount components, simplifying their integration in wireless devices (see ***Figure 1***).

Antenna tuners are precise, low loss, variable capacitors that tolerate high RF voltages, making them ideal for tunable antennas, dynamic load adjustments, tunable filters and analog RF applications that require high voltage operation. The Cavendish Kinetics antenna tuners use patented RF MEMS technology, which eliminates the high insertion loss and RF voltage handling limitations of traditional silicon on insulator (SOI) or GaAs devices in the RF front-end.

A design combining the Fractus Antennas antenna booster with a Cavendish Kinetics antenna tuner supports all the communication frequency bands within the 698 to 2690 MHz frequency range.[19-20] The main benefit of such a booster-tuner combination: the wireless device can dynamically optimize the performance over a specific bandwidth within the entire frequency range, providing the maximum radiation for the platform to support every coverage and user operation scenario.

Cavendish Kinetics' RF MEMS technology

TABLE 1
32CK301R ANTENNA TUNER CHARACTERISTICS

Capacitance Range	0.4 to 1.0 pF
Resolution	5-bit, i.e., 32 Capacitor States
ESR	~0.3 Ω at Cmax
Power Handling	+39 dBm
Self-Resonance	> 15 GHz
Current Consumption	100 μA Typical
Packaging and Size	WLCSP ~2 mm^2

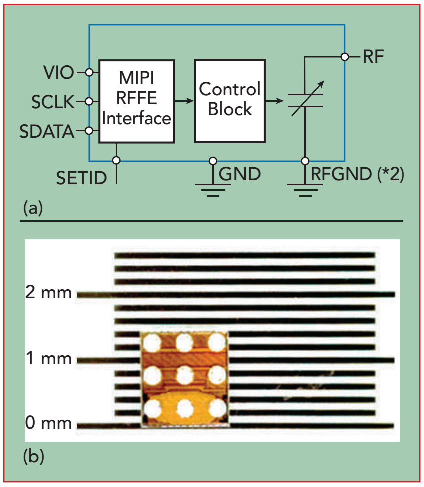


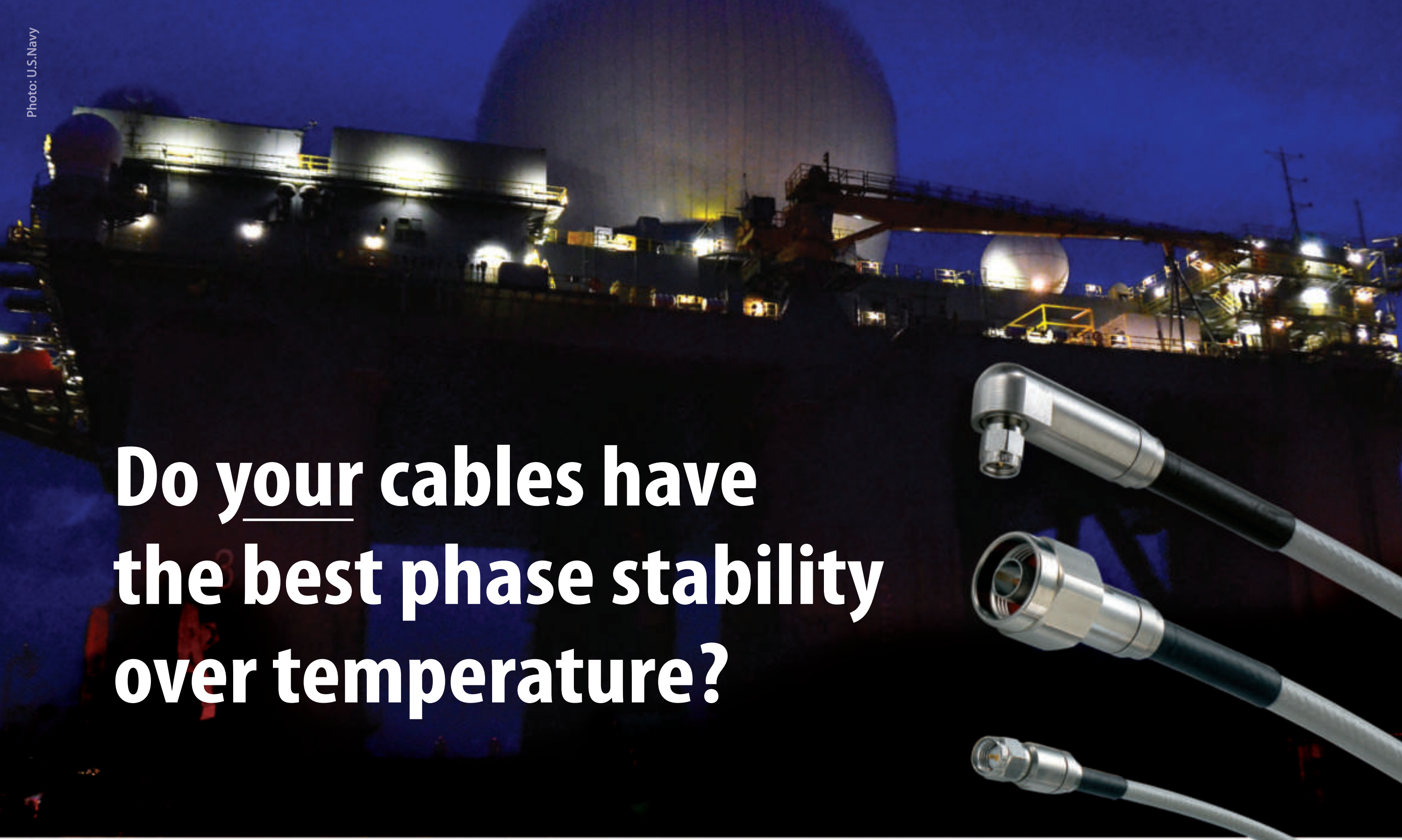
Fig. 2 Antenna tuner block diagram (a) and photo (b), showing the tuner's 1.4 mm x 1.4 mm size.

and manufacturing process produce devices with accuracy and reliability, maintaining full specification compliance even after 100 billion cycles.[21-22] The 32CK301R SmarTune™ Antenna Tuner (see ***Table 1***) was used to demonstrate the design concept in this article. Products with wider capacitor range are available, and the Cavendish Kinetics' family of tuners offers various capacitance ranges between 0.4 and 3 pF. All SmarTune antenna tuners are controlled through a MIPI RFFE interface (see ***Figure 2***), with the tuner's functions self-contained and managed by the logic in the controller.

RECONFIGURABLE MATCHING NETWORK

Referring to ***Figure 3***, the proposed reconfigurable matching network comprises the MEMS shunt tunable capacitor (Z_2) and seven lumped capacitors and inductors (see ***Table 2***). In this design, all the passive components, from Murata, are SMD 0402 type and high Q with tight tolerances. The tunable capacitor has 32 states, digitally controlled, with each state corresponding to a capacitor value ranging from 0.4 to 1 pF. In this design, the values and states are 0.40 (S00), 0.44 (S02), 0.55 (S08) and 0.92 pF (S27).

The impedance of the antenna booster without the matching network is very poor, in particular at the low end, from 698 to 960 MHz, where the $|S_{11}|$ is worse than −1 dB.[17] However, with the multiband matching network, the performance



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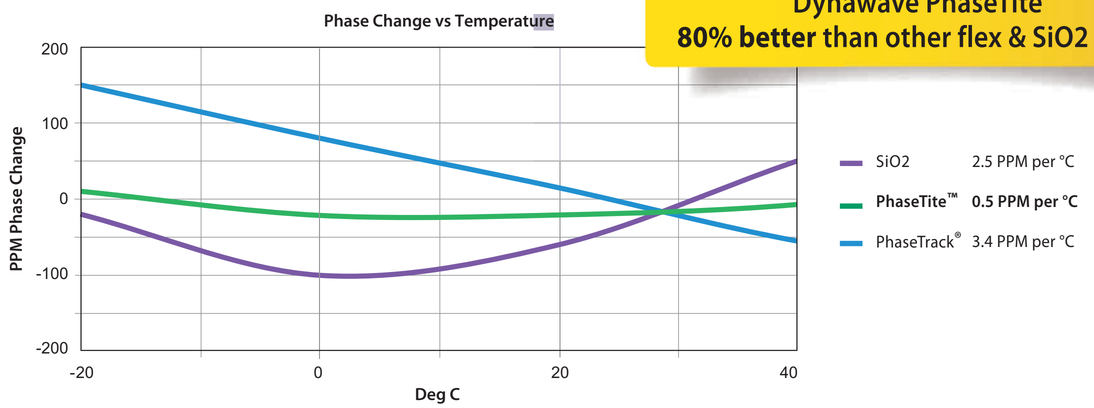

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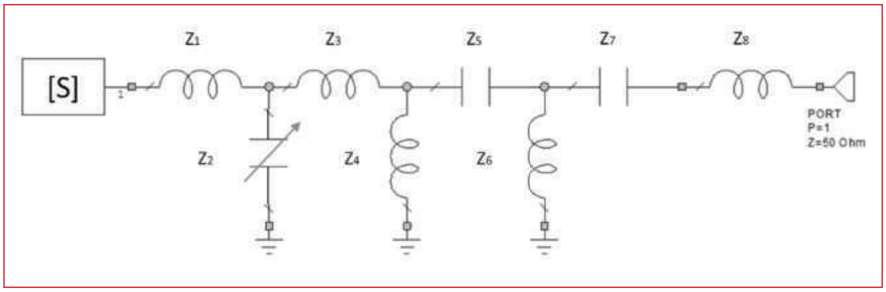

▲ **Fig. 3** **Reconfigurable matching network. Z_2 is the variable capacitor from Cavendish-Kinetics.**

can easily be adjusted without changing the antenna geometry. The location of the antenna booster is important to excite efficient radiation modes of the ground plane. In this design, the corner of the ground plane was selected.[16-17]

The state of the tunable capacitor is software-controlled via a parallel interface connection at the end of the ground plane. The interface connects the evaluation board to a PC running Cavendish Kinetics' SkyWalker software, which is used to set the impedance tuner to any of its 32 states.

Since the ground plane is an important contributor to the radiation, to avoid an undesirable effect from the interface connection when measuring antenna performance, the following procedure was used: The desired state of the impedance tuner was selected with the interface connection attached. After the state was set, the interface connection was removed, with a battery on the ground plane providing a DC voltage to the tuner to maintain the state. This enabled the antenna efficiency and S_{11} to be measured without any impact from the interface connection.

Figure 4 shows the evaluation board, with the battery and 10-pin parallel interface connector on the right-hand side. A UFL cable connects the antenna booster to an SMA connector mounted on the edge of the board.

PERFORMANCE RESULTS

For each of the four states of the antenna tuner, the total efficiency (η_t) was measured inside an anechoic chamber with 3D pattern integration using Satimo Stargate-32 (see ***Figure 5***). Total efficiency includes both the radiation efficiency (η_r) and mismatch losses, where $\eta_t = \eta_r \bullet (1 - |S_{11}|^2)$. Revieiwing the measured data, state S27 covers some of the LTE low bands, i.e., from 698 to 746 MHz, and state S08 is selected to cover 746 to 824 MHz.

To assess the effectiveness of antenna tuning, the performance of a passive matching network designed to cover 698 to 960 and 1710 to 2690 MHz was compared with this active tuning design (see ***Table 3***). The table confirms that the passive

TABLE 2 MATCHING NETWORK DESIGN (ALL PASSIVE COMPONENTS FROM MURATA)		
Circuit Element	**Value**	**Part Number**
Z_1	8 nH	LQW15AN8N0G80
Z_2	Antenna Tuner	Cavendish Kinetics 32CK301R
Z_3	7.3 nH	LQW15AN7N3G80
Z_4	11 nH	LQW15AN11NG80
Z_5	0.8 pF	GJM1555C1HR80WB01D
Z_6	13 nH	LQW15AN13NG80
Z_7	1.9 pF	GJM1555C1H1R9WB01
Z_8	2.5 nH	LQW15AN2N5B80D

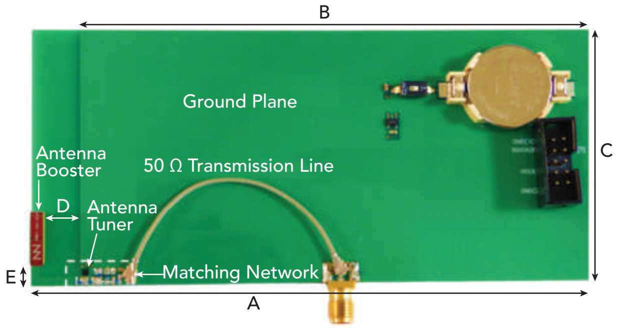

Fig. 4 FR4 evaluation board showing the Fractus Antennas antenna booster, the Cavendish antenna tuner and the matching network.

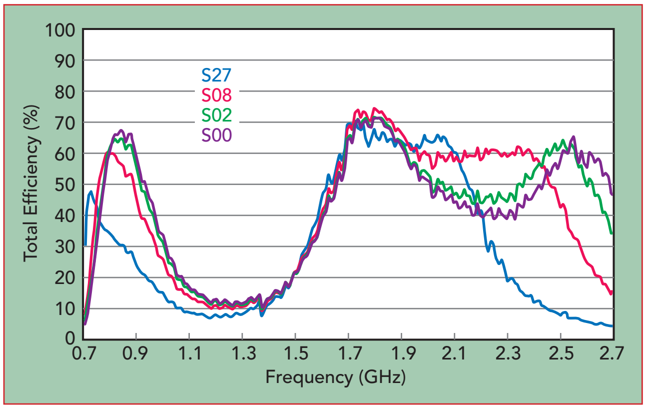

Fig. 5 Measured efficiency for four states.

network does not cover all the LTE bands. The advantage of antenna tuning is remarkable in the low LTE bands, i.e., from 699 to 798 MHz. In band 12, the efficiency of the active solution is 5.4 dB better than the passive design and 3.6 dB better in bands 13 and 14. The efficiencies are comparable in the other bands, i.e., within 1.4 dB.

CARRIER AGGREGATION

The evaluation board design is suitable for use with carrier aggregation (CA), where several LTE frequency bands are used simultaneously to increase the data rate. ***Table 4*** shows the antenna tuner states recommended for each inter-band CA pair.

CONCLUSION

A small antenna booster of 86.4 mm^3 mounted on a ground plane measuring 120 mm × 60 mm and a reconfigurable matching network demonstrated coverage of the cellular bands from 698 to 960 and 1710 to 2690 MHz. To achieve the highest possible performance, the reconfigurable matching network was designed using a MEMS tunable capacitor with passive components. The measured average total efficiency was above 40 percent, making this design approach feasible for most wireless and mobile devices.■

ACKNOWLEDGMENT

This project was co-financed by the Spanish Ministry of Industry, Energy, and Tourism under the National Plan of Scientific Research, Development and Technology Innovation 2015-2017 (Project Ref: TSI-100103-2015-39).

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TABLE 3 PASSIVE MATCHING VS. ANTENNA TUNING AVERAGE TOTAL EFFICIENCY (%)									
Band	12	13, 14	5	8	3	2	1	30	41
Frequency (MHz)	699 to 746	746 to 798	824 to 894	880 to 960	1710 to 1880	1850 to 1990	1920 to 2170	2305 to 2360	2496 to 2690
Passive	11.8	23.1	69.9	72.0	77.1	79.0	74.9	72.4	78.4
S27	41.5	37.7	29.0	22.3	65.8	65.3	59.9	17.2	6.0
S08	19.0	53.6	54.0	41.5	71.5	63.8	59.1	60.4	26.2
S02	13.0	46.8	62.5	50.2	69.0	59.6	50.1	48.8	50.6
S00	11.5	44.1	65.4	53.7	68.4	58.5	47.7	42.5	57.2

TABLE 4
ANTENNA TUNING FOR CARRIER AGGREGATION

CA Configuration	Band 1	Band 2	Tuner State	Average Efficiency % (Band 1 – Band 2)
CA_1A_5A	2100	850	S08	59.1 – 53.7
CA_1A_18A	2100	850	S08	59.1 – 56.0
CA_1A_19A	2100	850	S08	59.1 – 54.0
CA_2A_17A	1900	700	S27	63.3 – 41.8
CA_2A_29A	1900	700	S27	63.3 – 44.6
CA_3A_5A	1800	850	S00	68.4 – 64.8
CA_3A_7A	1800	2600	S00	68.4 – 57.2
CA_3A_8A	1800	900	S00	68.4 – 53.7
CA_3A_20A	1800	800	S00	68.4 – 64.1
CA_4A_5A	1700	850	S08 or S02	64.4 – 53.7 (S08) / 58.4 – 61.9 (S02)
CA_4A_7A	1700	2600	S00	56.8 – 57.2
CA_4A_12A	1700	700	S27	62.8 – 41.8
CA_4A_13A	1700	700	S08	64.4 – 50.4
CA_4A_17A	1700	700	S27	62.8 – 41.8
CA_4A_29A	1700	700	S27	62.8 – 44.6
CA_5A_12A	850	700	S27	28.7 – 41.8
CA_5A_17A	850	700	S27	28.7 – 41.8
CA_7A_20A	2600	800	S00	57.2 – 64.1
CA_8A_20A	900	800	S00	53.7 – 64.1

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Using RF Power Meters for PAPR Analysis and Reduction

Walt Strickler
Wireless Telecom Group, Parsippany, N.J.

RF peak power meters are the instruments of choice—simple and cost-effective—for measuring amplifier peak-to-average power ratios (PAPR) and assessing the effectiveness of PAPR reduction techniques.

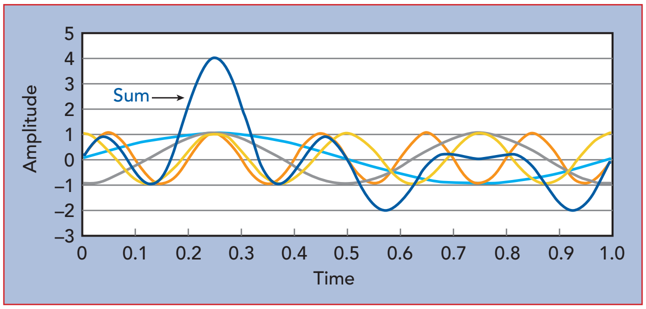

Fig. 1 The sum of four sinusoidal subcarriers results in an occasional large peak.

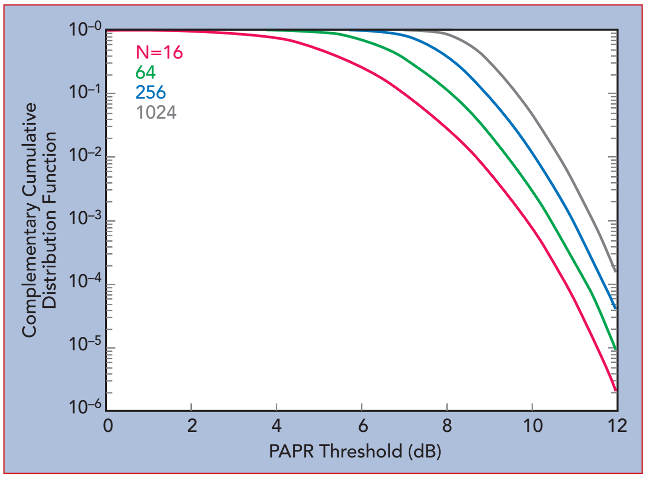

Fig. 2 PAPR vs. number of OFDM subcarriers.

The ongoing, exponential growth in demand for mobile broadband services is no secret. To address this demand, enhanced mobile broadband (eMBB) is one of the cornerstones of the movement to 5G, and higher data rates are also a driver for improvements to military communications networks. To meet these needs, engineers are employing technologies that support high speed data transmission, mobility and more efficient use of the available spectrum and network resources. One of the staples across many communications systems is the use of orthogonal frequency division multiplexing (OFDM), which offers advantages in these areas. Applications include 4G (LTE), WLAN (IEEE 802.11a/ac/ax/g/n), digital radio, cable (DAB and DVB-C2), even broadband access over copper (ADSL).

In an OFDM signal, digital data is encoded on multiple frequencies or subcarriers. Each subcarrier is modulated at a low symbol rate with a conventional modulation scheme, such as quadrature amplitude modulation (QAM) or phase-shift keying, and occupies a sub-band of frequencies. Unlike other modulation schemes, such as frequency division multiplexing (FDM), the sub-bands can overlap to enable higher spectral

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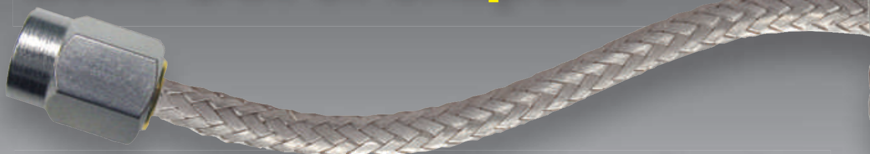

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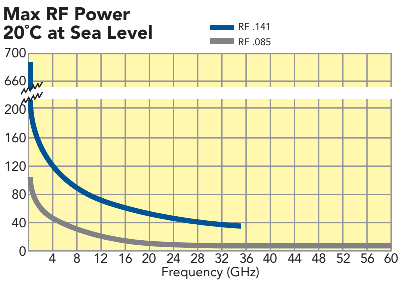

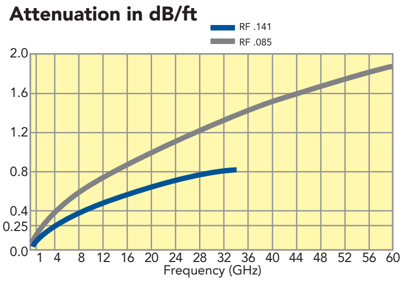

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efficiency, because each sub-band is orthogonal to the next. These factors enable OFDM to have lower susceptibility to narrow-band co-channel interference, inter-symbol interference and fading caused by multipath propagation.[1]

One of the main disadvantages of OFDM is that the multiple carriers can add coherently and produce high PAPRs (see ***Figure 1***). With the requirement for higher data rates, the number of subcarriers must increase to meet the demand, which will increase the PAPR. ***Figure 2*** shows the relationship between PAPR and the number of subcarriers (N).[2]

IMPORTANCE OF PAPR

High PAPRs cause a number of issues for am-

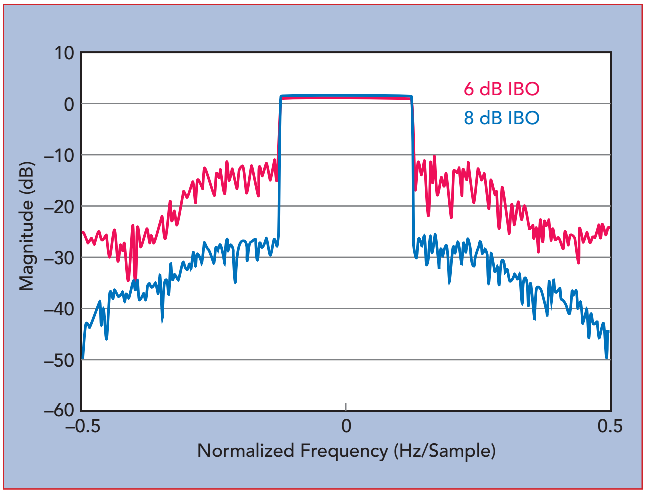

Fig. 3 Spectral regrowth vs. IBO.

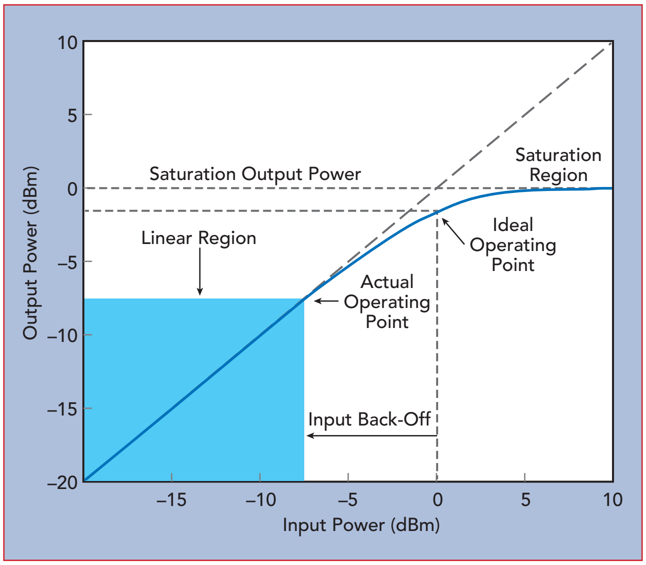

Fig. 4 Input vs. output power for a typical SSPA.

TABLE 1

COMPARISON OF PAPR REDUCTION TECHNIQUES

PAPR Reduction Technique	*BER Increase*	*Bit Rate Reduction*	*Implementation Complexity*
Clipping (and Filtering)	Yes	No	Low
Companding	Yes	No	Low
Selective Mapping	No	Yes	High
Partial Transmit Sequence	No	Yes	High
Interleaving	No	Yes	High
Tone Injection	No	No	High
Tone Reservation	No	Yes	High
Active Constellation Shaping	No	No	High
Constrained Constellation Shaping	Yes	No	High
Linear Block Coding	No	Yes	Low
Golay Sequences	No	Yes	High

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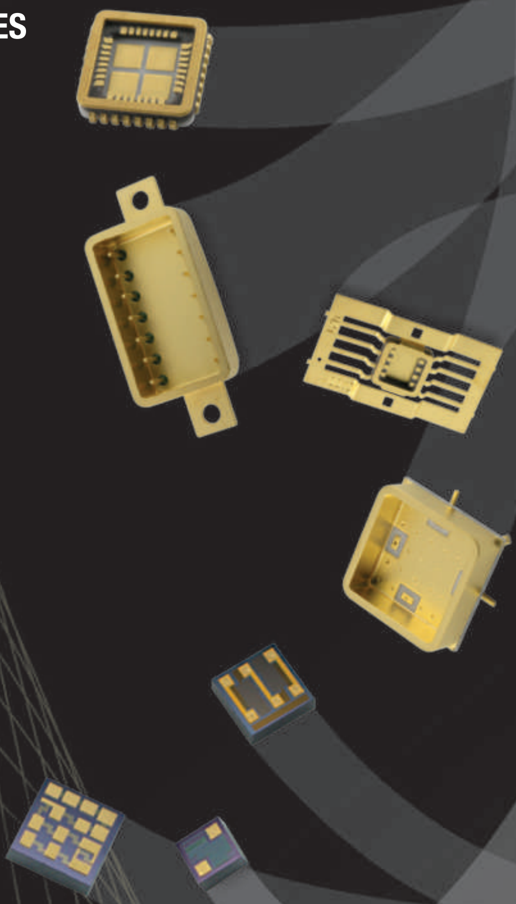

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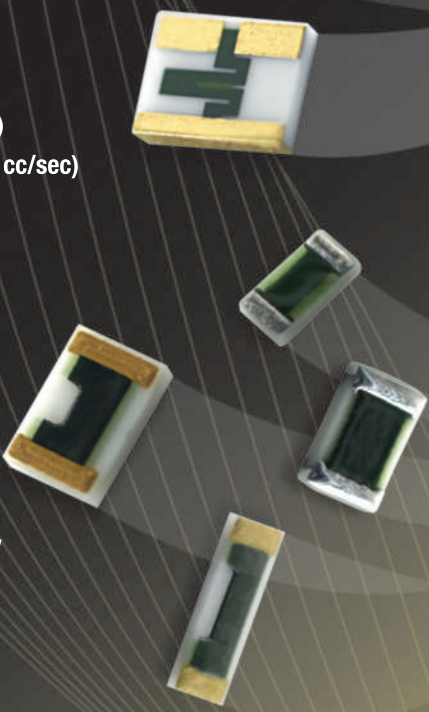

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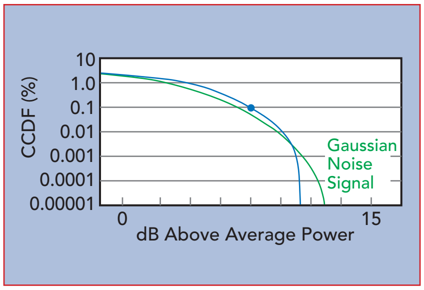


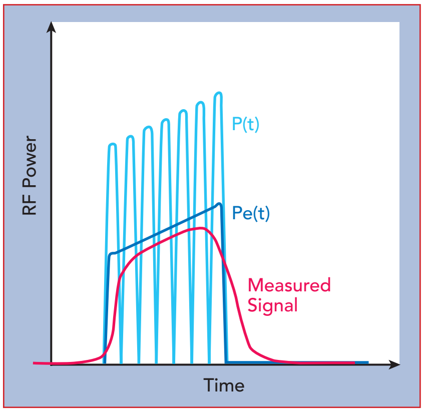
▲ Fig. 5 CCDF of an input signal vs. band-limited Gaussian reference.

plifiers. If peak power is not properly considered, signals enter the nonlinear operating region of the amplifier, resulting in distortion and spectral spreading or regrowth. On the other hand, lowering the power, often referred to as input back-off (IBO), causes the amplifier to operate less efficiently. In ***Figure 3***, the input signal to the amplifier is backed off by 6 and 8 dB; backing the signal off by only 6 dB results in higher spectral regrowth than if the signal is backed off by 8 dB. Spectral regrowth can cause interference among subcarriers, leading to an increase in bit error rate (BER); however, reducing the amplifier output power lowers the signal-to-noise ratio (SNR), which can also lead to an increase in BER. With a goal of higher data rates, poorer BER is counterproductive.

Efficiency is important in many applications. For mobile phones, the efficiency of its amplifiers drives battery life. For network operators, the efficiency of the base station impacts operating expenses. Amplifiers often operate most efficiently just into saturation. To illustrate this, an example of the relationship between input power, output power and efficiency for a solid-state power amplifier is shown in ***Figure 4***.

The only way to minimize spectral regrowth and maintain high efﬁciency is to reduce PAPR. As a result, much research has explored techniques to lower PAPR in OFDM-based systems to reduce amplifier compression while minimizing the necessary IBO. Rahmatallah and Mohan[2] provide an excellent review of the different techniques and trade-offs, summarized in ***Table 1***. Clipping with filtering is most commonly used in commercial products because of its simplicity and ease of implementation.

PAPR is a singular, instantaneous value and does not provide a complete picture of signal behavior over time. As a result, many engineers utilize a complementary cumulative distribution function (CCDF) to monitor PAPR. When plotted, a CCDF curve displays the time a sig-



▲ Fig. 6 Insufficient video bandwidth distorts measurement of a pulsed signal.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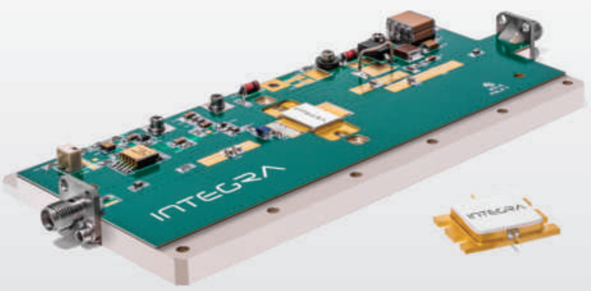
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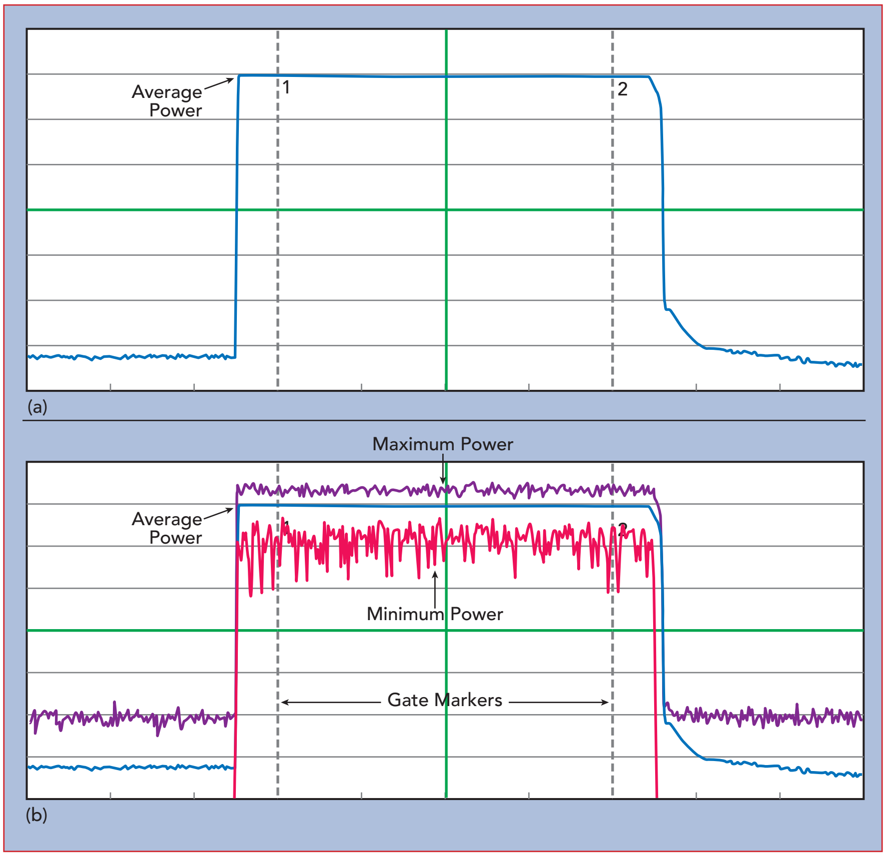

Fig. 7 Unmodulated (a) and modulated (b) pulse power measurement.

nal spends at or above a given power level (see ***Figure 5***). For PAPR reduction investigations, the power level of interest is the signal's average power, so the x-axis designates how much the peak power exceeds the average power in dB. The y-axis indicates the percent of time the signal spends at or above the difference in power specified by the x-axis. The point highlighted on the plot indicates the signal power exceeds the average power by at least 7.5 dB for 0.1 percent of the time. As a reference to compare amplifiers, engineers often plot the CCDF curve for a Gaussian noise signal. As the number of subcarriers increases in an OFDM signal, it approaches a Gaussian distribution.[3] Figure 5 also shows the CCDF curve for a theoretical Gaussian noise signal. A signal with a CCDF higher than this reference is said to have gain expansion, and a signal with a lower CCDF is said to be in gain compression.

MEASURING PAPR

An RF peak power meter with a diode-based sensor (or a USB RF peak power sensor which combines the power meter and sensor into one instrument) is the most widely used tool to measure peak power. Many peak power meters provide CCDF traces.

It is important to ensure that the power sensor is appropriate for the signal being measured. The ability of a diode sensor to accurately capture the peak envelope power requires it to respond at least as fast as the highest frequency component in the modulation envelope. A common measure to determine the ability of the sensor to respond fast enough is video bandwidth. Sensors use a low impedance load across the smoothing capacitors, to discharge them quickly when the RF amplitude drops. This, in combination with a very small smoothing capacitance, permits peak power sensors to achieve rise times in the nanosecond range and corresponding video bandwidths of tens or hundreds of MHz. A rule of thumb relationship between rise time and bandwidth is the bandwidth is approximately 0.35 divided by the rise time of the detection circuit.

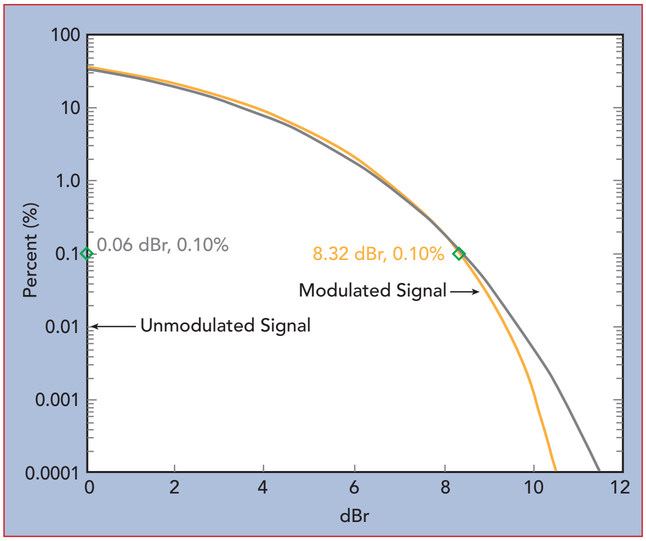

Fig. 8 CCDF of unmodulated and OFDM-modulated pulses vs. theoretical Gaussian signal.

Figure 6 shows a pulsed RF signal, where P(t) is the instantaneous power and Pe(t) is the envelope power measured by a power meter. If the power meter has insufficient video bandwidth, the measured signal will "round" the corners of the signal and lag during the rise and fall times, resulting in an errant measurement, as illustrated in the figure.

As one example of peak power meters, the Boonton power measurement portfolio includes two solu-

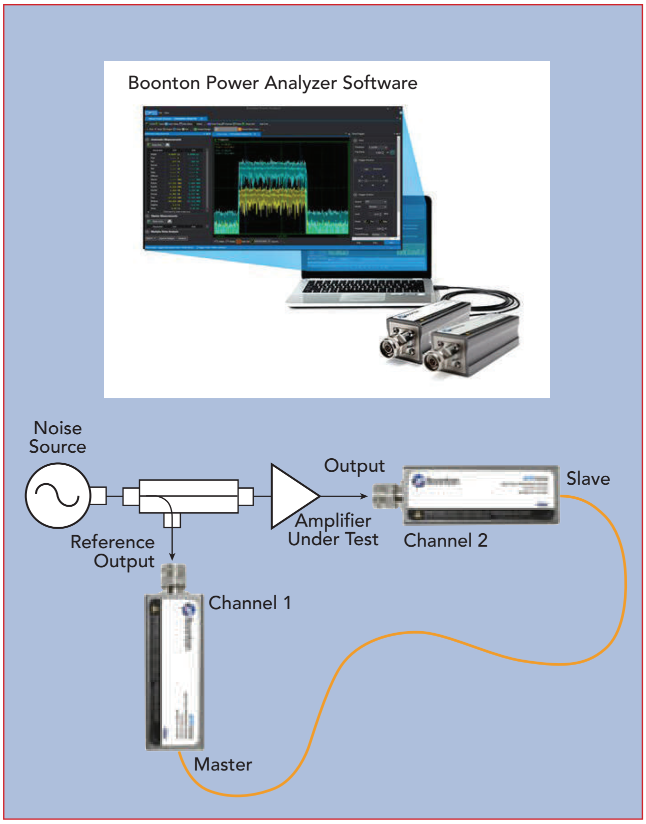

Fig. 9 Amplifier measurement setup.

tions with greater than 100 MHz video bandwidth: the 4500C with 125 MHz video bandwidth and the RTP5006 with 195 MHz, roughly 6× greater than most alternative products. Both models calculate and plot CCDF curves.

Figure 7 shows an 11 dBm, 10 µs pulse measured with the RTP5006 real-time peak power sensor. The RTP5006 provides three power values with each measurement: minimum, average and maximum. Figure 7a shows an unmodulated pulse where the minimum, average and maximum power are the same. Figure 7b shows a pulse modulated with a 2.5 GHz, 40 MHz bandwidth, −3 dBm signal generated with a Noisecom noise source, which approximates an OFDM signal. This shows the minimum, average and maximum power and the envelope of the modulated signal. The measurements can be gated to analyze the signal only when the pulse is on, disregarding transitions and off-time. The CCDF is calculated and plotted (see ***Figure 8***). As expected, the non-modulated signal shows no appreciable peak power, while the modulated signal indicates a high

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PAPR and closely matches the CCDF of a theoretical Gaussian signal.

Some engineers may stop at the measurement of PAPR and calculation of CCDF at the output of an amplifier as representing amplifier performance. Knowing the output PAPR, they believe they can implement PAPR reduction techniques or apply IBO to optimize the amplifier performance. However, just looking at the output power of the amplifier may be misleading, as the output may already be in compression; measuring the input signal to the amplifier for reference is necessary.

Figure 9 shows a test setup for measuring an amplifier's input and output signals. The two sensor measurements are synchronized using a master/slave trigger. ***Figure 10*** shows the input and output signals. Visually, there are no obvious issues; however, calculating the CCDFs shows the input and output PAPRs do not behave the same (see ***Figure 11***). The output power is clearly compressed as seen in the lower PAPR measurements, resulting in a shift of the curve to the lower left relative to

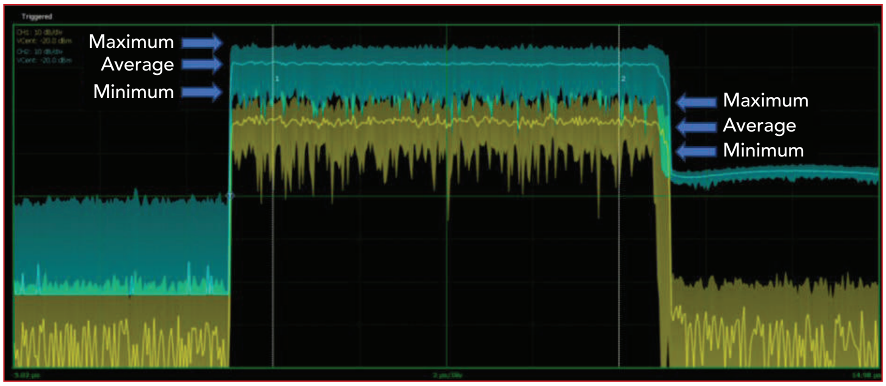

Fig. 10 **Measured amplifier input (yellow) and output (green) power.**

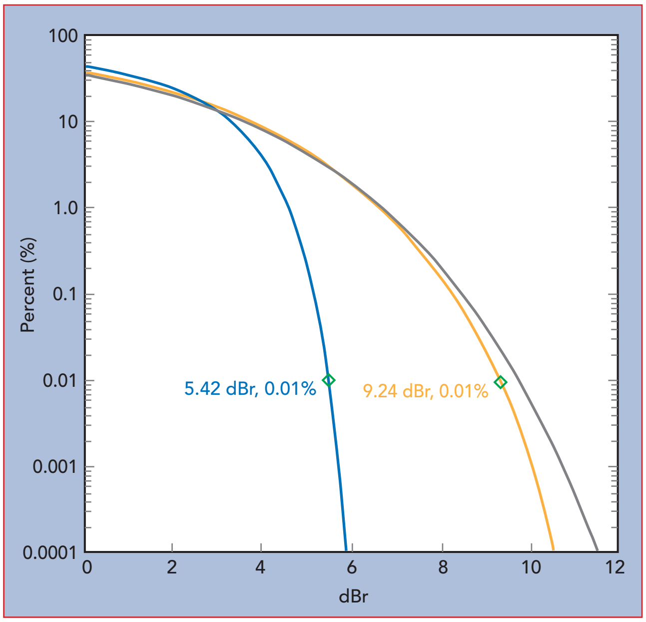

Fig. 11 **CCDF of amplifier input (yellow) vs. output (green) power shows significant compression, with a Gaussian signal shown for reference.**

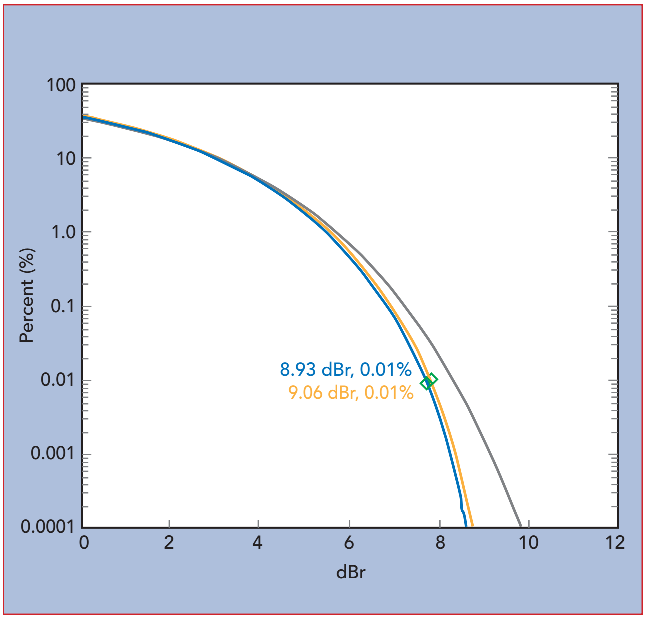

Fig. 12 **Reducing the noise source power reduces amplifier compression, confirmed by the improved alignment of the amplifier input (yellow) and output (green) CCDF curves.**

TABLE 2
AMPLIFIER MEASUREMENTS

Compressed Signal (−2.5 dBm Input Power)	***Channel 1***	***Channel 2***	***Delta Channel 2−Channel 1***
PAPR	9.25	5.40	−3.85
Average Power (dBm)	−2.53	10.83	13.36
Non-Compressed Signal (−12.7 dBm Input Power)	***Channel 1***	***Channel 2***	***Delta Channel 2−Channel 1***
PAPR	7.98	7.98	0.00
Average Power (dBm)	−12.73	1.79	14.52

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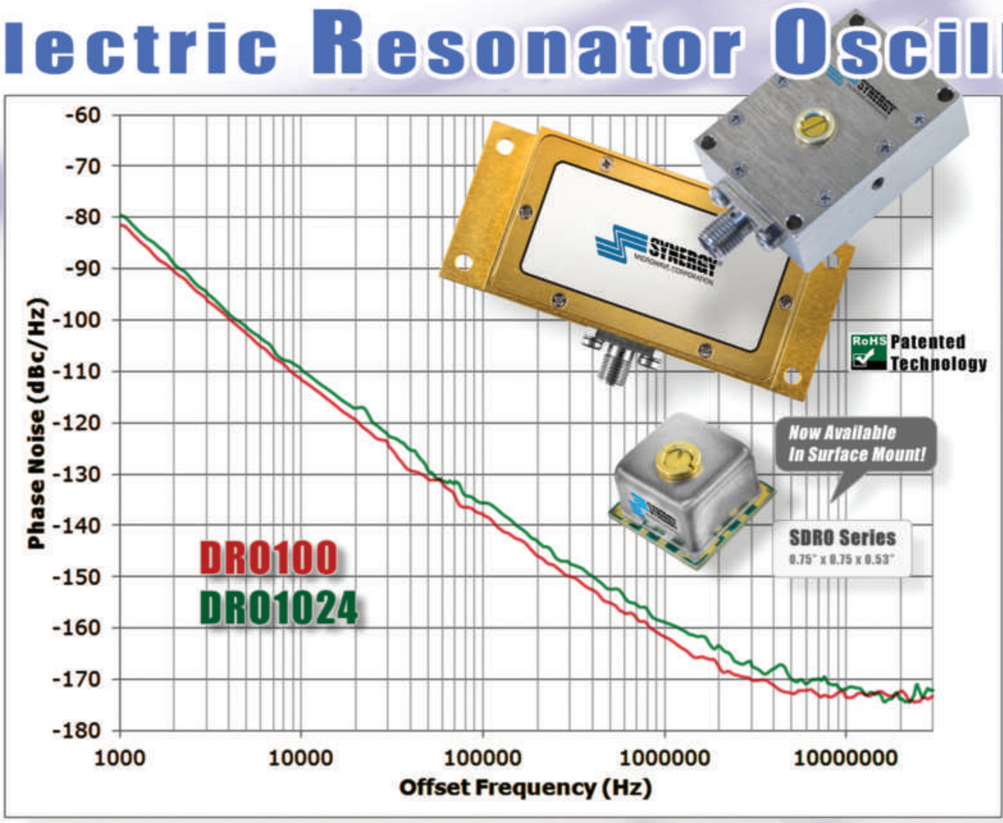

Model	Frequency (GHz)	Tuning Voltage (VDC)	DC Bias (VDC)	Typical Phase Noise @ 10 kHz (dBc/Hz)
Surface Mount Models				
SDRO1000-8	10.000	1 - 15	+8.0 @ 25 mA	-107
SDRO1024-8	10.240	1 - 15	+8.0 @ 25 mA	-105
SDRO1118-7	11.180	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1121-7	11.217	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1130-7	11.303	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1134-7	11.340	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1250-8	12.500	1 - 15	+8.0 @ 25 mA	-105
Connectorized Models				
DRO80	8.000	1 - 15	+7.0 - +10 @ 70 mA	-114
DRO100	10.000	1 - 15	+7.0 - +10 @ 70 mA	-111
DRO1024	10.240	1 - 15	+7.0 - +10 @ 70 mA	-109
KDRO145-15-411M	14.500	*	+7.5 @ 60 mA	-100

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the input channel. By reducing the output power of the noise source and increasing the IBO, the PAPRs align (see ***Figure 12***). This confirms that the amplifier was compressing the signal at the original input power level. Without measuring the input signal PAPR, this would not be apparent. A summary of the amplifier measurements in ***Table 2*** shows with an input power level of −12.7 dBm, the output is not compressed. At an input level of −2.5 dBm, the compression is nearly 4 dB.

OFDM-based systems often use QAM to modulate the subcarriers, and QAM is very sensitive to amplitude distortion. As the order of QAM increases to support higher data rates, that sensitivity increases. Relying only on average output power measurements, the observed compression would significantly understate the issue.

IMPORTANCE OF MODULATED SIGNAL MEASUREMENT

In some cases, engineers characterize amplifiers without modulation because signal sources with modulation—especially at the higher frequencies, such as the bands targeted for 5G—can be very expensive. However, with Gaussian noise removed and the input signal returned to its original value, compression is not observed. This highlights the importance of using modulated signals and peak RF power meters for characterizing amplifier performance, especially when evaluating PAPR reduction techniques. To avoid the cost of modulated signal sources, noise sources provide a much more cost-effective modulation source that closely models high subcarrier OFDM signals. Once the amplifier has been characterized with a Gaussian noise source, engineers can implement PAPR reduction techniques, comparing the results with an RF peak power meter.

SUMMARY

The increasing demand for information has led to increasingly complex data modulation to support high data rates and spectral efficiency. One of the most widely used technologies is OFDM; however, it has the disadvantage of having a high PAPR, which can challenge component performance. This leads many engineers to investigate techniques to reduce PAPR. RF peak power meters and noise sources are the instruments of choice for measuring the effectiveness of these techniques in a simple, cost-effective manner.■

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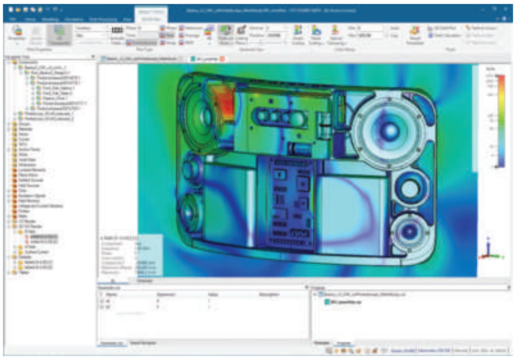

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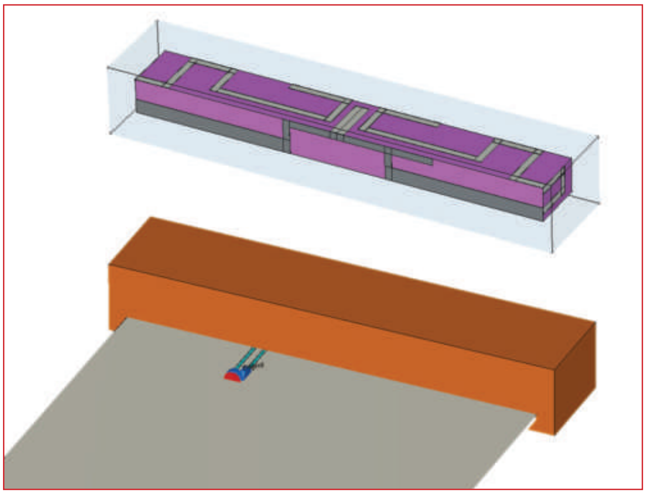

Fig. 1 Antenna design (top) and its encrypted black box representation (bottom), showing how design elements are hidden.

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The 3DEXPERIENCE platform is a business experience platform that offers Dassault Systèmes' portfolio of software solutions in one collaborative environment. With 3DEXPERIENCE integration, CST Studio Suite can be launched directly from the platform, using CAD data from tools such as SolidWorks and CATIA, already available on the platform, and the simulation results can be viewed and shared with others on the platform.

MESH IMPORT

In the 2019 version, an important feature for the automotive industry is the ability to import noise, vibration and harshness (NVH) meshes for the time domain, integral equation and asymptotic solvers. As CAD models for vehicles are typically complex, the manufacturers usually prepare a reduced model with a ready-to-be-simulated surface mesh. The connectivity between the body panels is essential for an EM simulation, and this information can be included within NVH meshes, cutting the time to prepare a simulation model and reducing the potential for errors due to incorrect connectivity. The mesh can be imported using SIMULIA Abaqus and NASTRAN formats.

HYBRID SIMULATION

Each EM solver method has its strengths and weaknesses: some are broadband, while others are better suited to very resonant applications; some can model electrically large structures very efficiently, while others offer very accurate simulations of very small, complex geometries. Yet a system will often include resonant and broadband components with both fine details and electrically large parts. For these applications, combining multiple solver methods with a hybrid simulation can significantly cut simulation time.

With CST Studio Suite 2019, all the general purpose high frequency methods are supported in hybrid simulation: the time domain solver (T solver), the frequency domain solver (F solver), the integral equation solver (I solver), the transmission line matrix (TLM) solver and the asymptotic solver (A solver). This allows, for example, a detailed simulation of an antenna with the time domain solver to be combined with a simulation of the antenna's installed performance on an aircraft body using the asymptotic solver.

ENCRYPTED MODEL SUPPORT

System equipment manufacturers often require simulation models from their suppliers that can be included in their system integration simulations for validation and certification. These models can reveal confidential design information, so sharing them outside the company represents a potential intellectual property risk. To mitigate this risk, CST Studio Suite 2019 includes the ability to produce encrypted black box simulation models that hide the details of the components while allowing accurate simulations with the T solver (see ***Figure 1***).

The protected model appears as a box with all the inside details hidden, including the material properties and geometry of the ports. The model data and simulation results are securely encrypted on the disk. This model can be imported into other CST Studio Suite simulation projects and used by third parties in simulation without revealing what the component looks like.

NEXT-GENERATION PBA

Perfect Boundary Approximation (PBA)® is a proprietary conformal meshing technique allowing curved surfaces to be accurately meshed and simulated in a hexahedral mesh, without staircase elements. CST Studio Suite 2019 sees the official release of next-generation PBA. This meshing engine can handle even more complex CAD models than before, while reducing the number of mesh cells required for an accurate simulation. This increases both the robustness and speed of the time domain solver.

HUMAN VOXEL POSER

Voxel models encode structure information in 3D using small cubic elements. They are widely used for detailed models of the human body for medical device design and exposure analysis. These models are usually supplied standing or lying; however, in scenarios for electronic devices, they may need to be in a variety of realistic poses (see ***Figure 2***). A standalone CST tool for posing voxel models has been available for several years; with CST Studio Suite 2019, it is integrated directly into

Fig. 2 Human voxel model posed as a car driver.

the 3D modeling interface. Human models can be imported into the simulation environment and posed to fit the system, whether raising the model's hand to its head to hold a phone or bending the entire body to sit in a car seat.

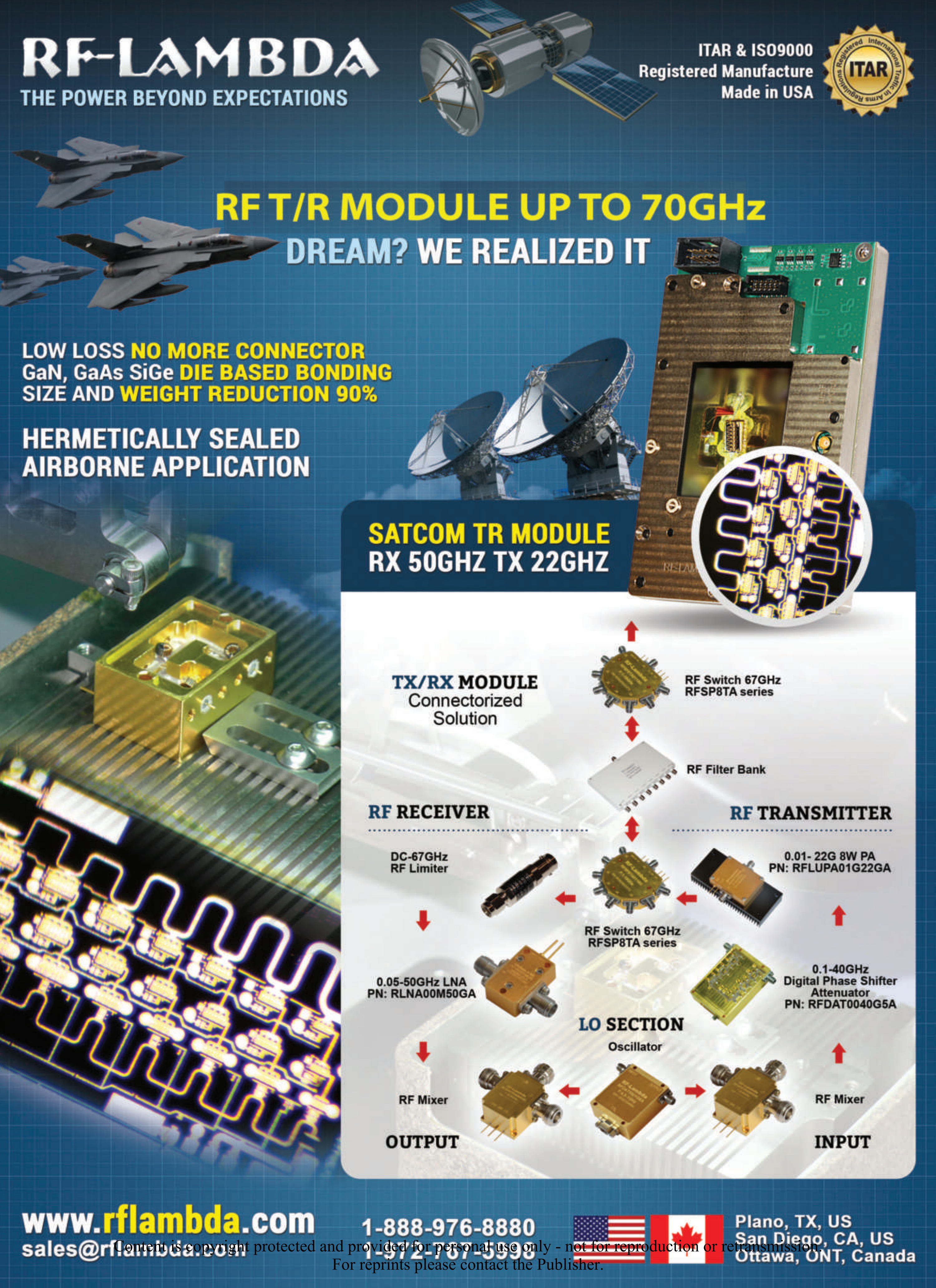
HIGH PERFORMANCE COMPUTING

Support for high performance computing (HPC) options such as GPU acceleration, distributed computing and MPI cluster computing allows users to perform extremely complex simulations, even when these involve large and detailed models, large numbers of ports or sweeps and optimizations over numerous parameter values. The 2019 version of CST Studio Suite expands the HPC offering in several ways. For hardware acceleration, CST Studio Suite 2019 supports the latest Nvidia accelerator cards, the Quadro GV100 and the Tesla V100, which can offer unprecedented performance on servers and workstations. The distributed computing controller has been optimized to improve the speed needed to process results. CST Studio Suite is also now available on an increasing number of cloud computing platforms, with specialist solutions such as Nimbix and UberCloud, as well as the public cloud providers AWS, Azure and Google Cloud Platform.

SUMMARY

The 2019 release of CST Studio Suite offers its most versatile EM simulation offering, helping engineers working on complex products meet their goals, optimize performance and cut development time and cost. It marks a significant step toward full multiphysics simulation on the 3DEXPERIENCE platform, allowing EM simulation to become a standard part of many industry workflows.

Dassault Systèmes SIMULIA
www.3ds.com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OCXOs Reduce Power Consumption, Maintain Stability

Syrlinks
Cesson-Sévigné, France

Field-programmable gate arrays (FPGA) are used in many RF applications for their parallel and fast digital data processing. In many such systems, a common frequency reference is used for the components doing the digital sampling (i.e., the analog-to-digital converters) and the FPGA processing (see ***Figure 1***). For high performance RF designs, the question becomes the choice of the local oscillator (LO): Which type of LO to choose? Which frequency? The frequency stability, short and medium-term and the thermal sensitivity of the frequency? These questions are common and consistent for all radio system designs. Multiple technical demands constrain the LO, particularly for battery-powered systems where a precise power budget must also be met without sacrificing performance.

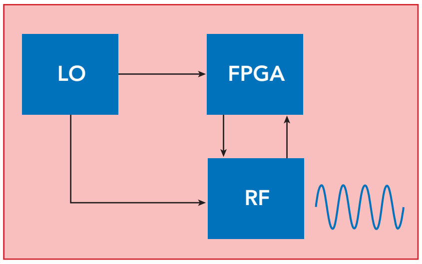


Fig. 1 A common LO is often used for data conversion in the radio and data processing in the FPGA.

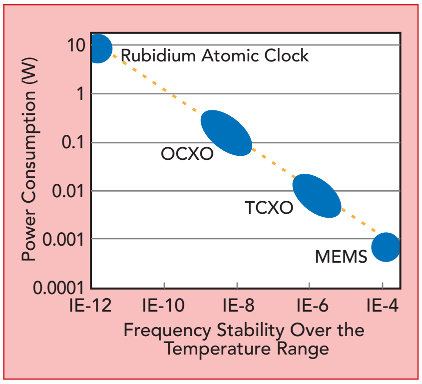


Fig. 2 Typical power consumption vs. frequency stability for various oscillator types.

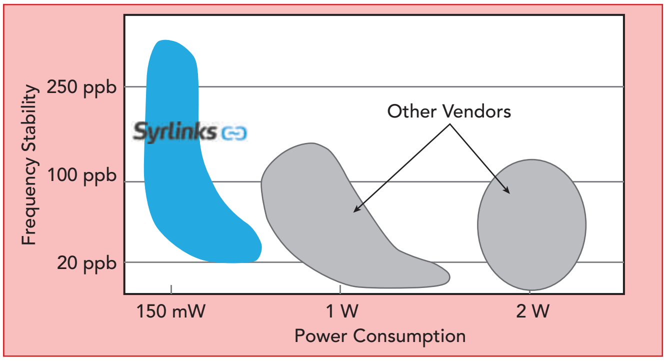
OSCILLATOR TECHNOLOGIES

Several oscillator technology choices are available, each with performance and price trade-offs (see ***Figure 2***). Most consumer electronics products use basic oscillators costing just a few cents or euros, such as MEMS crystal oscillators or, in some cases, temperature compensated crystal oscillators (TCXO). For RF systems requiring high frequency stability and low temperature sensitivity, oven controlled crystal oscillators (OCXO) provide the highest frequency stability from among the various crystal oscillator technologies. They are typically 1000 to 10,000× more stable than an entry-level crystal oscillator.

OCXOs are complex, hybrid components that require significant know-how to develop. The frequency stability performance of an OCXO is driven by a simple physical principle: to maintain the quartz resonator at a precise temperature, regardless of the ambient temperature. Any quartz resonator's frequency drifts strongly with temperature. For example, the frequency of a 10 MHz oscillator drifts ±250 to ±500 Hz between −40°C and +85°C. Maintaining the quartz at a precise temperature, an OCXO will reduce this drift to the range of ±0.05 to ±2.5 Hz, depending on the OCXO.

LOWERING OCXO POWER CONSUMPTION

Power consumption is the main disadvantage of OCXOs compared to TCXOs. To counter this, Syrlinks has developed a range of OCXOs with extremely low power



▶ Fig. 3 The EWOS OCXO family reduces power consumption while maintaining frequency stability.

consumption, mass and volume. These designs were optimized for the space radios developed by Syrlinks for small satellites, where little power is available. The EWOS™ OCXO family covers the frequencies between 10 and 40 MHz, with thermal sensitivities between ±5 to ±250 ppb and power consumption between 65 and 400 mW at 25°C. These power levels are extremely low, about 10× lower than competitive, commercial OCXOs (see ***Figure 3***).

As well as being used in the space radios developed by Syrlinks, the EWOS OCXO products have been designed in other space applications, such as global navigation satellite system (GNSS) space receivers, where the combination of the FPGA and OCXO is ideal. For example, the EWOS0525 10 MHz OCXO is used in the GNSS receiver G-Sphere-S, where it is simultaneously clocking the RF digitization stage and the FPGAs. It demonstrated global position precision less than 10 m at high velocity (7700 m/s). This remarkable performance was achieved because of the very low phase noise of the OCXO, particularly close-in to the carrier frequency. For precise positioning or precise ranging functions, where position or distance are computed in less than a microsecond, OCXOs are always preferred. The performance and precision of positioning or distance measurements is directly linked to the short-term stability of the LO, making OCXOs preferred over TCXO. OCXOs provide better results for the designer.

The EWOS83x family relies on SC-cut quartz resonators with a higher quality factor (Q-factor), which yields better phase noise and long-term frequency drift. Long-term drift is crucial for applications requiring precise time keeping when GNSS time is unavailable, such as underwater or other areas denied GNSS access. The quality of synchronization and time keeping depend exclusively on the intrinsic performance of the OCXO to keep accurate time. The EWOS083x provides aging of 0.3 ppb/day. The EWOS0835 is specified for underwater applications and has one of the lowest power consumption in the world: 80 mW at 25°C. For some applications, it is a low-cost alternative to chip-scale atomic clocks. ***Figure 4*** shows the family of Syrlinks EWOS OCXO products.

NEW CLOCKS, TIMING MODULES

For the ultimate performance, Syrlinks innovates in the time-frequency domain with breakthrough MEMS-based miniature atomic clocks (MMAC™). Applying MEMS technology improves medium- and long-term stability by 100× compared to OCXOs, while keeping power consumption very low (< 200 mW at −40°C). For frequency synthesis applications between 8 and 50 GHz, Syrlinks is developing a new generation, 100 MHz OCXO adapted to embedded radio systems; this OCXO's phase noise floor is −175 dBc/Hz.

For designers looking for synchronization solutions, Syrlinks has developed a range of timing modules (see ***Figure 5***) synchronized to a GNSS signal (e.g., Galileo, GPS) or an external reference (PPS_in). Embedded algorithms lock the phase and frequency of the OCXO, canceling drifts (i.e., thermal, aging, power supply, etc.). When GNSS time is not available (e.g., underwater), the SGTM keeps time and provides a precise PPS signal to the embedded system. The jitter between PPS_in and PPS_out is typically 12 ns, and the time holdover accuracy is ±35 µs per 24 hours, benefiting from advanced OCXO compensation.

An announcement exclusive to *Microwave Journal*: In the coming months Syrlinks will release a new 100 MHz OCXO for X- and S-Band low noise frequency synthesizers. This new EWOS will have extremely low phase noise close to the carrier (−130 dBc/Hz at 100 Hz offset), while keeping the power budget below 400 mW at 25°C.

Syrlinks
Cesson-Sévigné, France
www.syrlinks.com

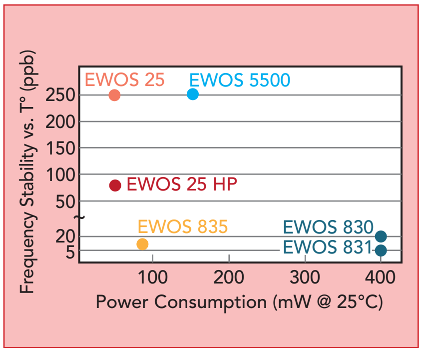


Fig. 4 EWOS OCXO family frequency stability vs. power consumption.

Fig. 5 Syrlinks timing module with GNSS synchronization.

40 GHz RF Probes for RF and Signal Integrity Testing

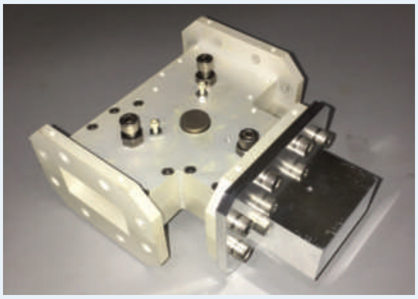
Pasternack has expanded its line of 50 Ω coaxial probes to 40 GHz, extending the capability to measure microwave components and signal integrity in high speed communications and networking equipment. With this frequency extension, Pasternack adds four models to its line of coaxial RF probes, providing ground-signal (GS) and ground-signal-ground (GSG) configurations (two models each), with 800 or 1500 µm pitch (two models each). All have a 2.92 mm coaxial interface and have less than 0.5 dB insertion loss and better than 10 dB return loss—typically 20 dB—over the broad range from DC to 40 GHz.

Gold plated, the probes have compliant pogo pin contacts, enabling a wide range of probing angles. They can be used manually with a coaxial cable assembly or with Pasternack's probe positioner. A pair of coaxial GSG probes can be used with delay matched cable assemblies to perform high speed differential measurements. The 40 GHz probes support a wide range of measurement needs: signal integrity, MMIC evaluation, Gigabit SERDES, 28 Gbps data channels, substrate characterization, coplanar waveguide circuits and test fixture applications.

Pasternack's new 40 GHz coaxial RF probes are in stock, ready for immediate shipment with no minimum order quantity.

VENDORVIEW

Pasternack
Irvine, Calif.
www.pasternack.com



4.2 to 5 GHz Isolator with < 0.1 dB Insertion Loss

Exceed Microwave's ISO-W-4600-800-187 is a waveguide isolator with a passband covering 4.2 to 5 GHz, achieving insertion loss less than 0.1 dB and return loss and isolation better than 23 dB. The passband of the ISO-W-4600-800-187 covers the n79 5G frequency band (4.4 to 5 GHz), as well as the 4.2 to 4.4 GHz aeronautical radionavigation band.

The low insertion loss makes the isolator well suited for protecting power amplifiers from reflective loads. The isolator can handle power levels as high as 50 kW peak, 2 kW CW and is specified to operate from −20°C to +75°C. To achieve such low loss, the isolator is a WR187 waveguide design fabricated with aluminum 6061-T6 and silver plated for high electrical conductivity. The size of the unit is 5.1 in. × 6.25 in. × 2.5 in., and it weighs 1 kg.

Exceed Microwave is developing low insertion loss, waveguide circulators and isolators to WR28 (26.5 to 40 GHz), all designed, assembled and tested at the company's facility in Torrance, Calif. Exceed Microwave also designs and manufactures other custom, high performance passive waveguide and coaxial components for defense, space and commercial applications. Waveguide products include the WZ series low loss filters, WC series compact filters, notch filters with broad passbands and phase equalizers. Exceed's coaxial products include lowpass, bandpass and notch filters and electro-mechanical switches to 40 GHz, with existing designs encompassing SPST and DPDT to SP12T.

Exceed Microwave's engineers work directly with customers, providing immediate response to find the optimum solution and striving to always provide the highest performing components. The company is AS9100 certified.

VENDORVIEW

Exceed Microwave
Torrance, Calif.
www.exceedmicrowave.com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TechBrief

RFSoC SoM for SWaP Critical Environments

To meet the growing demand for deployable RF system on chip (RFSoC) FPGA solutions, Pentek introduced the QuartzXM™ Model 6001, a high performance system on module (SoM) based on the Xilinx Zynq® UltraScale+ RFSoC FPGA. Integrated in the Zynq FPGA fabric are eight integrated RF-class analog-to-digital and digital-to-analog converters with quad ARM Cortex-A53 and dual ARM Cortex-R5 processors. With these resources, along with 18 GB of SDRAM, LVDS connections for custom I/O and gigabit serial communications, both air and conduction-cooled versions and measuring only 2.5 in. x 4 in., the QuartzXM Model 6001 includes all of the circuitry to maximize the performance of the RFSoC in environments where SWaP are critical.

The QuartzXM 6001 is pre-loaded with a suite of Pentek IP modules that provide data capture and processing solutions for many common applications. Modules include direct memory access (DMA) engines, a DDR4 memory controller, test signal and metadata generators, data packing and flow control. IP for digital RF memory (DFRM), triggered waveform and radar chirp generation, triggered radar range gate engine, wideband real-time transient capture, flexible multi-mode data acquisition and extended decimation are pre-installed on the board.

The Model 6001 can be housed on the Pentek 3U VPX model 5950, or it can be deployed on a custom carrier. When deployed on the 5950, the QuartzXM can be used out-of-the-box with the built-in functions, requiring no FPGA development. When the QuartzXM is deployed on a custom carrier, developers will find the included IP cores a strong foundation for building custom applications. Pentek's complete design kit shortens the development cycle for customers building their own carriers.

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www.pentek.com

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CatalogUpdate

Products for Radar, EW and More

VENDOR**VIEW**

CPI Beverly Microwave Division (BMD) is the world's largest manufacturer of receiver protectors. CPI BMD designs and manufactures a broad range of RF and microwave products for radar, communications, electronic warfare (EW), medical and scientific applications. Their products are found in numerous radar systems operated by the U.S. military and militaries around the world. They also manufacture SSPAs, magnetrons, solid-state switches and integrated microwave assemblies, as well as TWTs, CFAs and pressure windows. Contact BMDMarketing@CPII.com for your high-power microwave components upgrades.

CPI Beverly Microwave Division
www.CPII.com/BMD

New Product Catalog

K&L Microwave designs and manufactures a full line of RF and microwave filters, duplexers and subassemblies, including ceramic, lumped element, cavity, waveguide and tunable filters. K&L supplies many of today's most significant military and homeland security electronics programs. Applications include space flight, radar, communications, guidance systems and mobile radio base stations, as well as air traffic communication and control. Visit their website to download the complete catalog or sections of interest.

K&L Microwave
www.klmicrowave.com

Q2 Product Guide

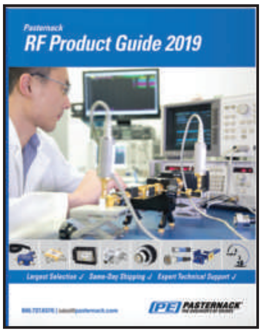
VENDOR**VIEW**

Mini-Circuits has been releasing new products to their catalog at a record pace, with over 250 new models in the first two quarters of 2018 alone. To help you stay up-to-date with recent additions to their catalog and find the best parts for your needs, this 48 page product guide provides a survey of their latest releases. Highlights include MMIC mixers, multipliers, attenuators, couplers and splitters up to 40 GHz and higher, connectorized passives up to 65 GHz, over 40 new MMIC die parts, new test & measurement devices up to 30 GHz and much more.

Mini-Circuits
www.minicircuits.com/WebStore/literature.html

New 2019 Product Guide

VENDOR**VIEW**



Pasternack, an industry-leading manufacturer and supplier of RF, microwave and mmWave products, has recently released their 2019 RF Product Guide. The company's latest 264 page catalog contains thousands of in-stock products including RF cable assemblies, RF amplifiers, an expanded portfolio of waveguide components, 60 GHz modules and systems, as well as hundreds of other active and passive RF components that are all available for same-day shipping worldwide.

Pasternack
www.pasternack.com

Automotive Solutions Guide

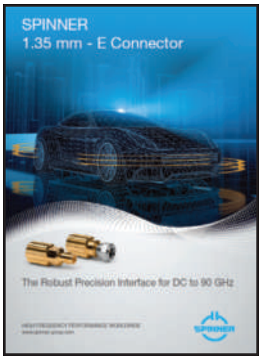
VENDOR**VIEW**

Groundbreaking, in-vehicle technologies and rapidly changing standards are being adopted at a pace previously unheard of in the automotive industry. With Skyworks as your partner, there is no need to worry. Their innovative portfolio takes seamless connectivity in today's cars to the next level—making the driving experience increasingly smarter and safer. By leveraging their leadership and expertise in wireless to deliver cutting edge communication technologies such as 5G NR for cellular, vehicle-to-vehicle (V2V) communication and 802.11ax Wi-Fi to new vehicles, Skyworks can help you elevate the driver experience.

Skyworks Solutions Inc.
www.skyworksinc.com

New E Connector Brochure

VENDOR**VIEW**



As the market for mmWave sensors for self-driving vehicles expands, the demand for proper RF connections in testing environments is also growing. The E Connector is ideal for making high performance RF measurements in the E-Band without being held up by fragile 1.00 mm coaxial connectors or wasting time reassembling WR 10 waveguides. SPINNER designed the new 1.35 mm E Connector to close the gap between the 1.85 mm and 1.00 mm coaxial connectors.

SPINNER GmbH
www.spinner-group.com

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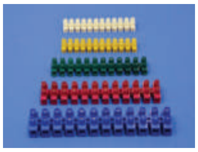
COMPONENTS

"Jelly Bean" PA Series



BlockMaster Electronics introduces a new addition to its popular "Jelly Beans®" line of colorful terminal blocks. The new EuroStyle PA Series features nylon terminal blocks in multiple colors for ease in identifying terminations and preventing costly field wiring mistakes. Low voltage and line voltage connections can easily be mixed up, especially by inexperienced installers. In addition to color coding, BlockMaster offers screen printing to mark alphanumeric characters on its PA Series terminal blocks to further simplify field wiring.

BlockMaster Electronics
www.blockmaster.com

Ku-Band Full Band Isolator

VENDORVIEW

Exceed Microwave has enhanced their ISO-W-12500-5000-75, which is a WR75 full band isolator with excellent return loss and isolation across the entire passband. It also has very low insertion loss of < 0.2 dB with great return loss of 20 dB and isolation across the entire WR75 frequency band.

Exceed Microwave
www.exceedmicrowave.com

USB-Controlled Programmable Attenuator

JFW Industries introduced their newest USB-controlled programmable RF attenuator. The 50P-2068 is adjustable from 0 to 31 dB in 1 dB increments and operates from 100 MHz to 18 GHz. A simple USB interface allows for easy programming and the included software can be used to control multiple JFW USB-components at once. Managed .Net 4.0 libraries and Python 3 support is also available.

JFW Industries Inc.
www.jfwindustries.com

mmWave Isolators

VENDORVIEW

MECA Electronics' latest new product offering, 37 to 40 GHz isolators optimized for excellent performance across a segment of the Ka-Band in addition to existing (K- and Ku-Bands) models covering 18 to 26.5, 27 to 31 and 26.5 to 40 GHz with 2.92 mm interfaces. Also available are couplers, power dividers, attenuators, terminations and bias tees and DC blocks. Their rugged construction makes them ideal for telecommunications, aerospace and test equipment systems. Made in the U.S. with 36 month warranty.

MECA Electronics
www.e-MECA.com

Coaxial DC Block Covers 10 MHz to 50 GHz

VENDORVIEW

Mini-Circuits' BLK-V54+ is a coaxial DC block supporting a wide range of applications from 10 MHz to 50 GHz including 5G systems, Ka-Band SATCOM, test & measurement and more. This model provides 0.5 dB insertion loss with flat response across the entire band, 23 dB return loss, RF input power handling up to 1 W and DC voltage handling up to 100 V. The unit features 2.4 mm male to 2.4 mm female connectors and cones hosed in a rugged, stainless steel body, measuring only 0.36 in. × 0.87 in.

Mini-Circuits
www.minicircuits.com

VSAT Terminals

Norsat MarineLink™ COM series of maritime VSAT terminals provide reliable SATCOM for military, commercial and recreational maritime applications across the oceans. With a 2048 kb/s downlink and 512 kb/s uplink, the three axis operating platform and 360 degree high speed tracking design ensures a reliable link in even the most rugged conditions. With its simple setup and pre-programmed satellite almanac, users with minimal training can have a MarineLink system up and transmitting in just a matter of minutes.

Norsat International
www.norsat.com

Hi-Q/Low ESR Capacitors

Passive Plus Inc. now offers extended-values for the traditional NP0, Hi-Q 0505 (0.055 in. × 0.055)—now available up to 1000 pF. The 0505 has increased operational temperature up to 200°C. These parts exhibit low ESR/ESL, low noise, high self-resonance as well as ultra-stable performance over temperature. Used in wireless broadcasting equipment, mobile base stations, GPS, MRI and radar applications, these capacitors are offered in magnetic and non-magnetic terminations.

Passive Plus Inc.
www.passiveplus.com

Flexible Waveguides

Pasternack has introduced a new line of twistable and seamless flexible waveguides operating in the 5.85 to 50 GHz range and covering 10 frequency bands from WR-137 to WR-22. Typical applications include DAS systems, base stations, antennas and test instrumentation. Pasternack's newly released line of flexible waveguides is made up of 78 total models—39 seamless and 39 twistable. All models operate in the same wide range of frequencies, are available in lengths of 6 to 36 in. and with UG-style square/round cover and CPR-style flanges.

Pasternack
www.pasternack.com

SPDT Switch

VENDORVIEW

RFMW Ltd. announces design and sales support for a high-power, high isolation, symmetrical, SPDT switch from Aethercomm. The SSHPS 2.5-6.0-150 handles up to 150 W of CW RF power from 2500 to 6000 MHz for military and commercial communication systems. Mid-band insertion loss is typically < 1 dB while typical isolation is 53 dB. Maximum current draw from a +28 VDC supply is 300 mA. The SSHPS 2.5-6.0-150 offers 5 μs switching speed and is rated for temperature, altitude and shock under MIL-STD operating conditions.

RFMW Ltd.
www.rfmw.com

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New**Products**

Continuously Variable Coaxial Attenuators

RLC Electronics' continuously variable coaxial attenuators offer wide bandwidths up to 40 GHz for microwave applications where continuous adjustment of signal level is required with low insertion loss and good impedance matching. Unique mechanical packaging with a locking, non-translating shaft allows a compact assembly. The construction of the transmission line and shaped, proprietary lossy material give flat response over a wide range of attenuation. Units are available with locking screwdriver, panel mount or dial knob adjustment options.

RLC Electronics Inc.
www.rlcelectronics.com

Wideband Directional Coupler

The KBK-703S is a wideband directional coupler operating from 1 to 500 MHz. Product features include 11.25 dB coupling with excellent coupling flatness of ±0.6 dB across the band. The mainline loss is 0.8 dB (typ.)/1 dB (max.) and directivity of 25 dB (typ.)/20 dB (max.). This 1.25 in. square SMA connectorized package can handle up to 1 W of input power and operates over the temperature range of –55°C to +85°C. Other connector options are available.

Synergy Microwave Corp.
www.synergymwave.com

CABLES & CONNECTORS

High-Temp, Aerospace-Rated Ethernet Cables

MilesTek's high-temp cable assemblies feature FEP jackets that are rated for a wide temperature range of –55°C to +150°C and a double shielded cable with both 100 percent foil and 85 percent braid shields that provide maximum EMI and RFI protection. These cables are offered off-the-shelf in Cat6a, Cat5e and Cat5e slim construction versions and comply with all RoHS directives. Furthermore, the fire properties of these Ethernet cables meet FAR (Federal Aviation Regulation), Airbus and Boeing requirements.

MilesTek
www.milestek.com

AMPLIFIERS

GaN Solid-State Power Amplifier

Aethercomm model number SSPA 0.020-1.000-350 is a high-power, multi-decade bandwidth, GaN solid-state power amplifier. It is packaged in an enclosure that is optimized for airborne or ground applications that require survival in high performance shock and vibration environments. Nominal linear output power is 100 to 200 W but power levels at saturation of 300 to 400 W are typical from 100 to 900 MHz.

Aethercomm
www.aethercomm.com

0.7 to 18 GHz CW Dual Band Amplifiers

VENDOR**VIEW**

AR put two of their state-of-the-art Class A CW amplifiers in a single chassis, and now you can go from 0.7 to 18 GHz with the reliability of solid-state designs and have freedom like never before. With up to 60 W in the first 0.7 to 6 GHz band split and up to 40 W output power in the 6 to 18 GHz split, AR put it together for you in one package that costs less, weighs less and takes up less space than two separate amplifiers.

AR RF/Microwave Instrumentation
www.arworld.us/html/ps-dual-band-amplifiers.asp

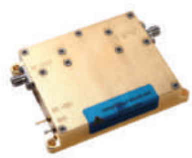
Wideband Solid-State Power Amplifier

COMTECH PST's latest innovation supports its customer's need for a VHF/UHF wideband high-power RF amplifier in a single LRU. This class AB linear design operates over the full 20 to 500 MHz frequency range and is ideal for use in research laboratories or where reliable and accurate linear power is required. The amplifier is robustly designed so that it can deliver exacting high power into high VSWR antenna loads, is electronically self-protected and supports multiple modulation schemes.

COMTECH PST
www.comtechpst.com

Solid-State Power Amplifier System

VENDOR**VIEW**

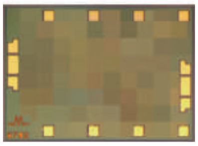


AMP2030-800 new best in class, state-of-the-art 800 MHz to 6 GHz, 800 W, 500 W, P1dB min. amplifier system. The amplifier features 59 dB min. gain, built-in VVA circuits for gain control local and remote with a GaN design for high-reliability and ruggedness. This system is suitable for all single channel modulation standards and any application requiring high-power and

New**Products**

wideband coverage such as TWTA replacements, EW, EMI/RFI general and specialized test equipment.
Exodus Advanced Communications
www.exoduscomm.com

Efficient, High-Power 20 to 55 GHz Amplifier



The AMM-6702 is a gamechanger. Featuring an ultra-wide 20 to 55 GHz bandwidth, over 25 dB gain and up to +23 dBm saturated output power with only a 0 dBm input, this GaAs MMIC amplifier consumes a mere 570 mW. High linearity broadband mmWave mixers such as the company's MM1-1850S require high-power broadband LO driver amplifiers, but these amps were largely absent from the market at frequencies above 40 GHz—until now.
Marki Microwave
www.markimicrowave.com

Microwave and mmWave LNAs

Norden Millimeter announced the addition of new wideband and narrowband microwave and mmWave LNAs. Pictured is an 18 to 44 GHz LNA providing a noise figure of 4.5 dB max, 40 dB gain and 15 dBm P1dB over the entire band. Norden has also released several LNA models which provide a noise figure of 1.3 dB max over the 17 to 21 GHz band. The LNAs have applications for 5G test stations and commercial airborne internet.
Norden Millimeter
www.nordengroup.com

Low Noise Amplifier

VENDORVIEW

PMI Model No. PEC-53-12-10-15-SFF is a 1 to 2 GHz Low Noise Amplifier which provides a minimum gain of 53 dB while maintaining a max gain flatness of ±0.75 dB. The noise figure is 3.5 dB max and offers a minimum OP1dB of +5 dBm. The unit is supplied with SMA female connectors.
Planar Monolithics Industries Inc.
www.pmi-rf.com

Amplifiers

The RFenable value line of amplifiers offers solid performance with respect to output power, thermal management and reliability. The amplifiers are designed for continious operation and all come with options for connectors in the front or back of the unit, as well as options for integrated bidirectional power couplers to allow external monitoring of power.
RFenable
www.rfenable.com

Power Amplifier Evaluation Boards

Richardson RFPD Inc. announced the availability and full design support capabilities for two new evaluation boards from GaN Systems Inc. The new power amplifiers are designed for the growing wireless charging market and feature GaN technology that enables smaller, lighter, lower-cost and more efficient power systems. The 100 W power amplifier (GSWP100W-EVBPA) is ideal for applications in the consumer market, including items such as laptop computers, recreational drones, domestic assistant robots, power tools and fast-charging of multiple smart phones.
Richardson RFPD
www.richardsonrfpd.com

L-Band Dual Bi-Directional Amplifier

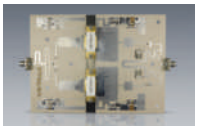
Triad RF has shipped their latest L-Band Dual Bi-Directional Amplifier (BDA), the TTRM1081D. This unit is compatible with all military and commercial radios and provides over 25 W of RF power across 1.3 to 1.4 GHz. Made specifically for MIMO radios,

providing 2 radio and 2 antenna ports, each providing 5 W of 64-QAM power or 20 W of BPSK power. The BDA operates off a single +28 V supply and provides 25 dB of Tx gain and 11 dB of Rx gain in both channels.
Triad RF Systems
www.triadrf.com

SOURCES

RF Power Module/Pallet

VENDORVIEW



Integra Technologies has released IGNP1011L2400, a new RF power module/pallet designed to solve various SWaP-C challenges in high performance L-Band avionic systems. IGNP1011L2400 is a high-power GaN on SiC RF power module/pallet that has been designed specifically for IFF/SSR systems operating under either Mode S ELM or standard Mode S pulse conditions, supplying a minimum of 2200 W of peak output power, with typically > 16 dB of gain and 57 percent efficiency and operates from a 50 V supply voltage.
Integra Technologies
www.integratech.com

Equivalent Temperature Compensated Crystal Oscillators

The Pletronics OeXO® Series OCXO-equivalent temperature compensated crystal oscillators is an optimal hybrid of a high performance TCXO with OCXO characteristics that meets the demands for today's high speed data transmission networks and testing equipment. The OeD4281-25.0MHz is manufactured to provide precise slave/holdover reference frequency in Ethernet physical link (BITS/SSU) or line timed (SDH/SONET) equipment. This oscillator is also ideal for use in synchronous Ethernet line cards utilized in 5G/mobile backhaul, test equipment, base stations, telecom transmission and switching equipment.
Pletronics Inc.
www.Pletronics.com

ANTENNAS

Horn Antenna Assembly

VENDORVIEW

Model SAF-6039031340-141-S1-122-DP is a dual polarized, WR-12 scalar feed horn antenna assembly that covers several popular 5G bands in the frequency range of 60 to 90 GHz. The antenna features an integrated orthomode transducer (OMT) that provides high port isolation and cross-polarization cancellation and a broadband scalar horn that provides low sidelobe levels. The OMT enables the antenna to separate a circular or elliptical polarized waveform into two linear, orthogonal waveforms or vice versa.
SAGE Millimeter
www.sagemillimeter.com

TEST & MEASUREMENT

Coaxial RF Probes

Fairview Microwave Inc. has recently expanded their line of RF coaxial probes into the 40 GHz frequency range for use in high speed communications, microwave components and networking applications. Fairview Microwave's expanded line of coaxial RF probes now includes four models that deliver 10 dB maximum return loss over a broad frequency range of DC to 40 GHz.
Fairview Microwave Inc.
www.fairviewmicrowave.com

Production, Wafer Fab & Testing Equipment

VENDORVIEW

SemiGen Inc. announced that after moving into their new state-of-the-art facility, they have made an additional capital investment of over a half million dollars in new production, wafer fab and testing equipment to support customer demand. The new equipment consists of improvements across their entire service platform and includes a new Mycronic MY300 pick and place system, two new Westbond wire bonders, a new Centrotherm eutectic vacuum chamber, new HTOL/HTRB ovens, as well as a new Disco DAD3220 dicing saw.
SemiGen Inc.
www.semigen.net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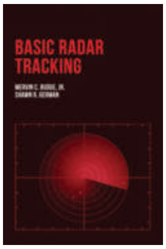
• Countless networking opportunities
• Special focus on startup companies with the first ever Startup pavilion, Startup panel session and Next Top Startup competition



Basic Radar Tracking

Mervin C. Budge, Jr.,
Shawn German

ISBN: 978-1-63081-335-2
360 pages

$149/£119

> “The text provides a detailed mathematical underpinning for virtually all radar tracking methods and techniques with examples and simulation results to solidify the concepts. While written as a textbook, it can easily be used as a reference for the experienced practitioner.”
>
> *—Jay Loomis, Ph.D.*
> *Senior Research Scientist*
> *University of Alabama Huntsville*

Detailed closed-loop bandwidth and transient response approach is a subject rarely found in current literature. This innovative resource offers practical explanations of closed-loop radar tracking techniques in range, Doppler and angle tracking. To address analog closed loop trackers, a review of basic control theory and modeling is included. In addition, control theory, radar receivers, signal processors and circuitry and algorithms necessary to form the signals needed in a tracker are presented. Digital trackers and multiple target tracking are also covered, focusing on g-h and g-h-k filters.

Readers learn techniques for modeling digital, closed-loop trackers. The radar circuitry/block diagrams necessary for range, Doppler and angle tracking are presented and described, with examples and simulations included. Factors such as noise and Swerling type fluctuations are taken into account. In addition to numerous worked examples, this approachable reference includes MATLAB® code associated with analysis, simulations and figures. The book contains solutions to practical problems, making it useful for both novice and advanced radar practitioners. Software will be available on the Artech House website at www.artechhouse.com.

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Sales Representatives

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Eastern and Central Time Zones
Jaime Leger
Northeast Reg. Sales Mgr.
(New England, New York, Eastern Canada)
685 Canton Street
Norwood, MA 02062
Tel: (781) 619-1942
FAX: (781) 769-5037
jleger@mwjournal.com

Michael Hallman
Associate Publisher
(NJ, Mid-Atlantic, Southeast, Midwest, TX)
4 Valley View Court
Middletown, MD 21769
Tel: (301) 371-8830
FAX: (301) 371-8832
mhallman@mwjournal.com

Pacific and Mountain Time Zones
Brian Landy
Western Reg. Sales Mgr.
(CA, AZ, OR, WA, ID, NV, UT, NM, CO, WY, MT, ND, SD, NE & Western Canada)
144 Segre Place
Santa Cruz, CA 95060
Tel: (831) 426-4143
FAX: (831) 515-5444
blandy@mwjournal.com

International Sales
Richard Vaughan
International Sales Manager
16 Sussex Street
London SW1V 4RW, England
Tel: +44 207 596 8742
FAX: +44 207 596 8749
rvaughan@horizonhouse.co.uk

Germany, Austria, and Switzerland (German-speaking)
WMS.Werbe- und Media Service
Brigitte Beranek
Gerhart-Hauptmann-Street 33, D-72574 Bad Urach
Germany
Tel: +49 7125 407 31 18
FAX: +49 7125 407 31 08
bberanek@horizonhouse.com

Korea
Young-Seoh Chinn
JES Media International
2nd Floor, ANA Bldg.
257-1, Myungil-Dong
Kangdong-Gu
Seoul, 134-070 Korea
Tel: +82 2 481-3411
FAX: +82 2 481-3414
yschinn@horizonhouse.com

China
Shenzhen
Michael Tsui
ACT International
Tel: 86-755-25988571
FAX: 86-755-25988567
michaelt@actintl.com.hk

Shanghai
Linda Li
ACT International
Tel: 86-021-62511200
lindal@actintl.com.hk

Beijing
Cecily Bian
ACT International
Tel: +86 135 5262 1310
cecilyb@actintl.com.hk

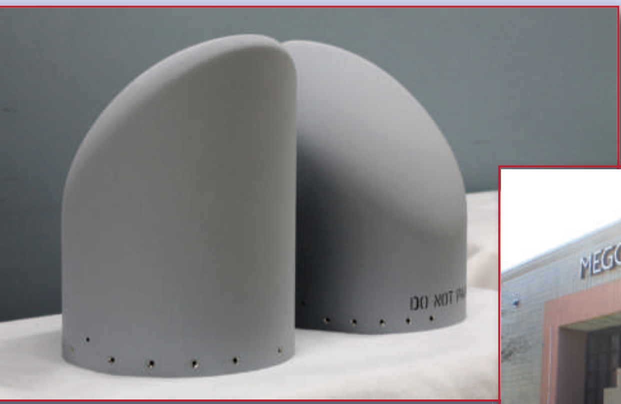
Hong Kong, Taiwan, Singapore
Mark Mak
ACT International
Tel: 852-28386298
markm@actintl.com.hk

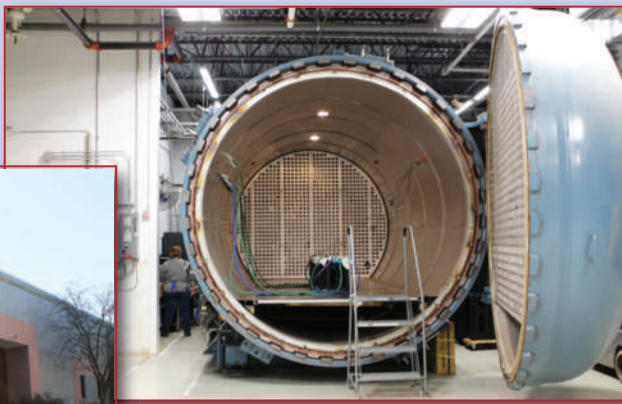
Japan
Katsuhiro Ishii
Ace Media Service Inc.
12-6, 4-Chome,
Nishiiko, Adachi-Ku
Tokyo 121-0824, Japan
Tel: +81 3 5691 3335
FAX: +81 3 5691 3336
amskatsu@dream.com

Ed Kiessling • Traffic Manager/Inside Sales • 685 Canton Street, Norwood, MA 02062 • Tel: (781) 619-1963 FAX: (781) 769-6178 • ekiessling@mwjournal.com

FABS and LABS

Designing the Invisible





Imagine being asked to design a product that is electromagnetically invisible, structurally impervious to the environment and mechanically rugged—yet with little mass. That is the daily challenge for the composite radome designers at Meggitt Baltimore, Inc. (MBI). A radome's purpose is to protect an antenna without perturbing the electrical performance of the antenna and overall system. It shields the antenna from the environment while also mating with the platform hosting the antenna, the airframe of a fighter, superstructure of a destroyer or trailer of a ground-based radar. Each platform adds unique environmental challenges, beginning with temperature, vibration and severe mechanical loads. Fighters fly faster than the speed of sound and withstand bird strikes, ships contend with the corrosive salt of the ocean and ground-based systems weather sand and dust, ice and snow.

To address these challenges, MBI brings more than 50 years' experience working with the chemistry of polymers and composites. This capability was born with Nurad, an antenna company formed in 1965. Nurad became part of Chelton Microwave, then Cobham. Meggitt acquired the composite radome capability from Cobham in late 2015, a high-tech complement to Meggitt's broad composites capability. Today, MBI focuses on the design, manufacturing and repair of radomes and composite related antennas. The business primarily serves the defense market and has quite a pedigree: products flying on the B-1B, F-15, F-16, EA-18G, P-8, C-130 aircraft and many others, with Boeing, Cobham, Harris, L3, Lockheed Martin and Northrop Grumman long-term customers. The business is not strictly defense though, as the team developed the radome for Gogo's 2Ku satellite in-flight internet service used by many commercial airlines.

MBI has a fully vertically integrated capability, with a staff of 80 occupying a 75,000 square foot facility that houses engineering and manufacturing. Designers use a suite of computer-aided design tools for electromagnetic, mechanical and thermal simulation. Manufacturing capabilities include 5-axis CNC machines, large autoclaves and the capability to apply high performance paints and coatings; MBI can access the capabilities of the 10+ other Meggitt Polymers and Composites sites, if required. Seven fully instrumented antenna ranges support evaluation and production testing and are also used by customers. The ranges include outside, compact and far-field anechoic chambers, enabling testing from UHF to 50 GHz, which is being extended to 100 GHz. These test ranges are available as a test service to MBI customers.

An antenna with a radome is an interdependent system. Successful development requires close collaboration between the customer and MBI technical teams. Once the specifications are defined, the composite radome design begins with electromagnetic simulation and creation of a flat sheet prototype for RF testing. The sequence proceeds to the mechanical design and fabrication of a form-fit prototype, tested with the antenna to compare the antenna's performance without the radome and with it. Extensive far-field electrical tests are performed during development, and the test sequence is simplified in production, usually just measuring the radome's S-parameters.

The Meggitt Baltimore business is healthy and growing, reflecting new development, production and spares orders. That is no surprise for a company with a successful 50+ year legacy designing the invisible.

www.meggittbaltimore.com