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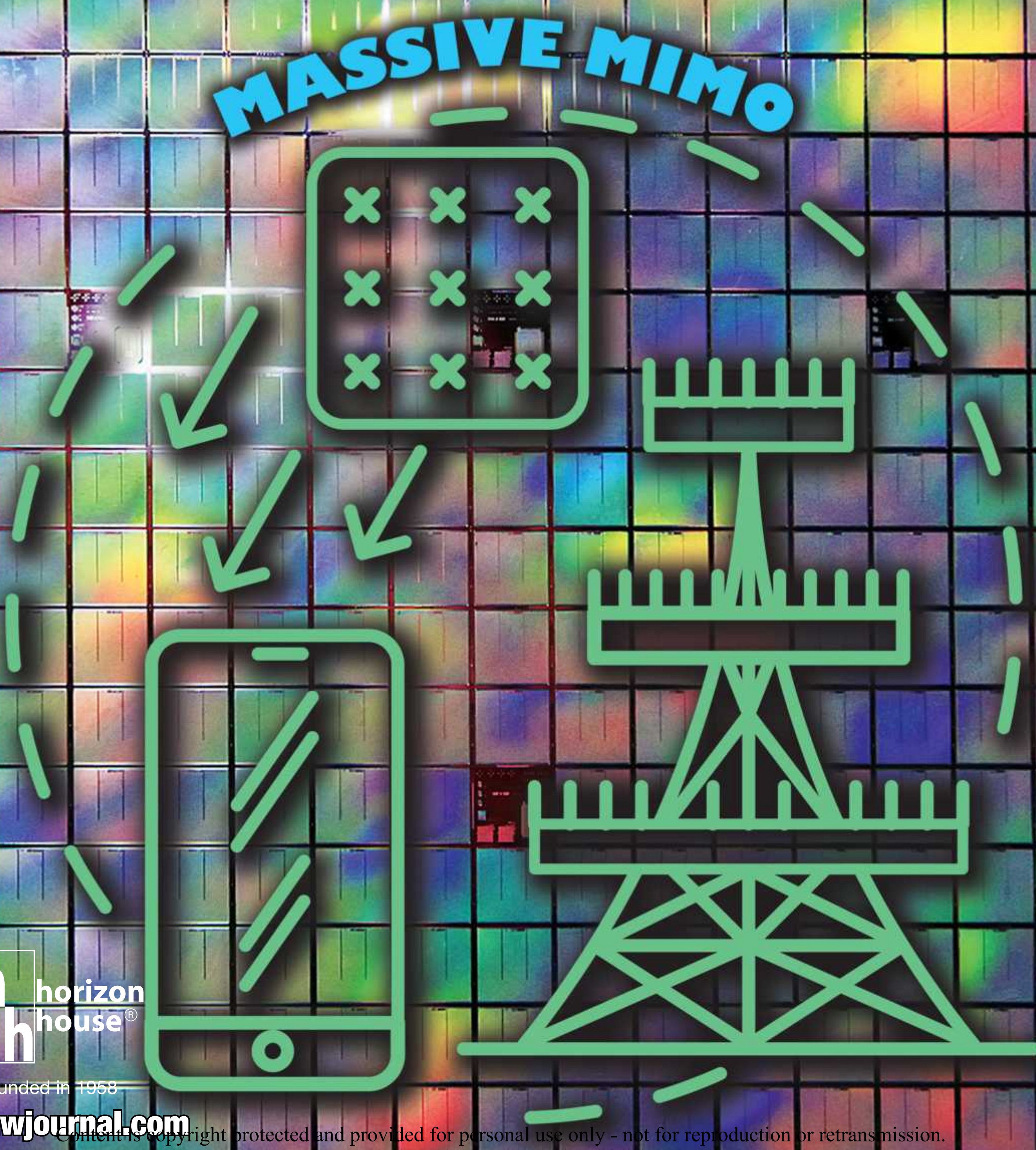

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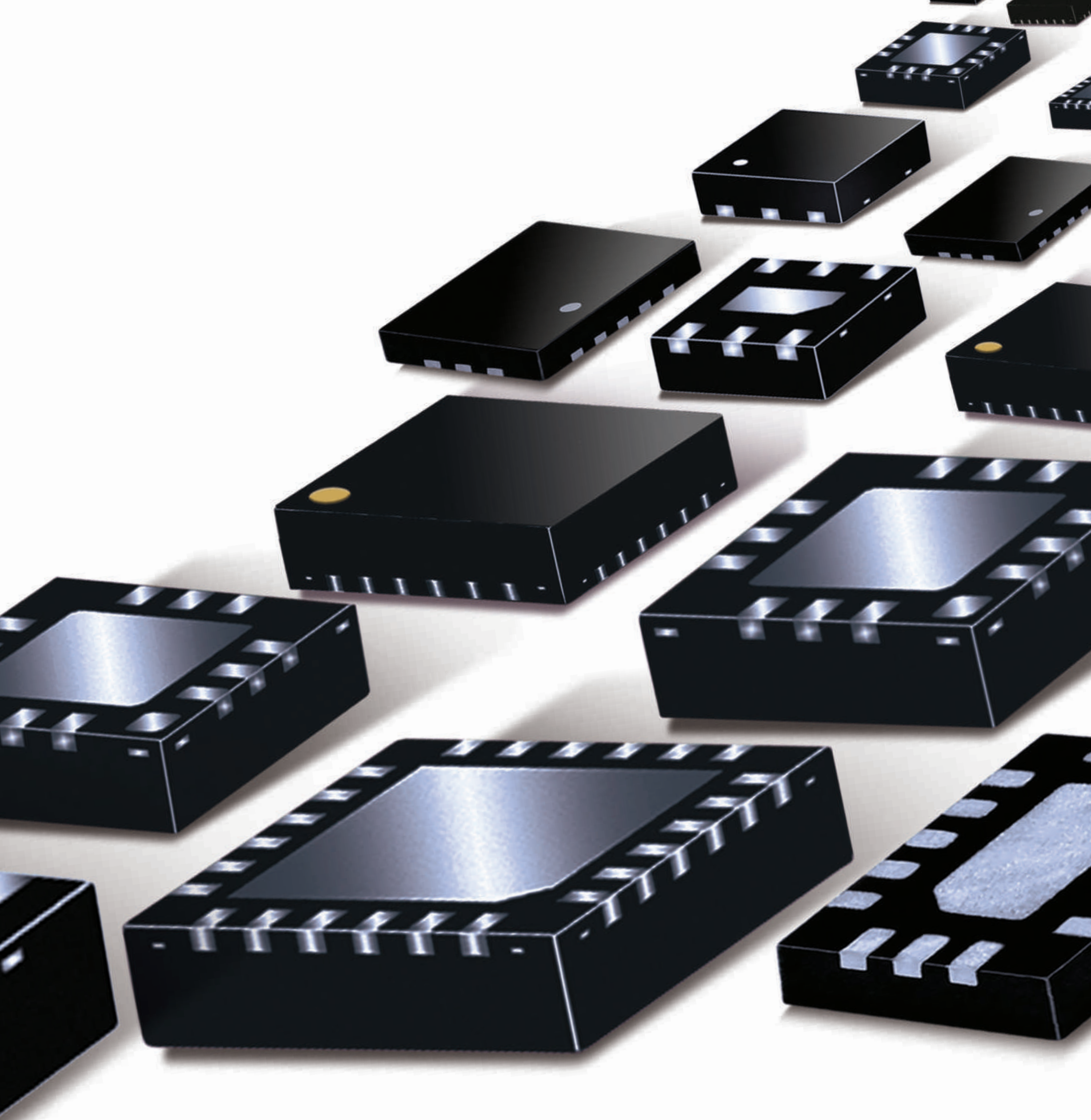


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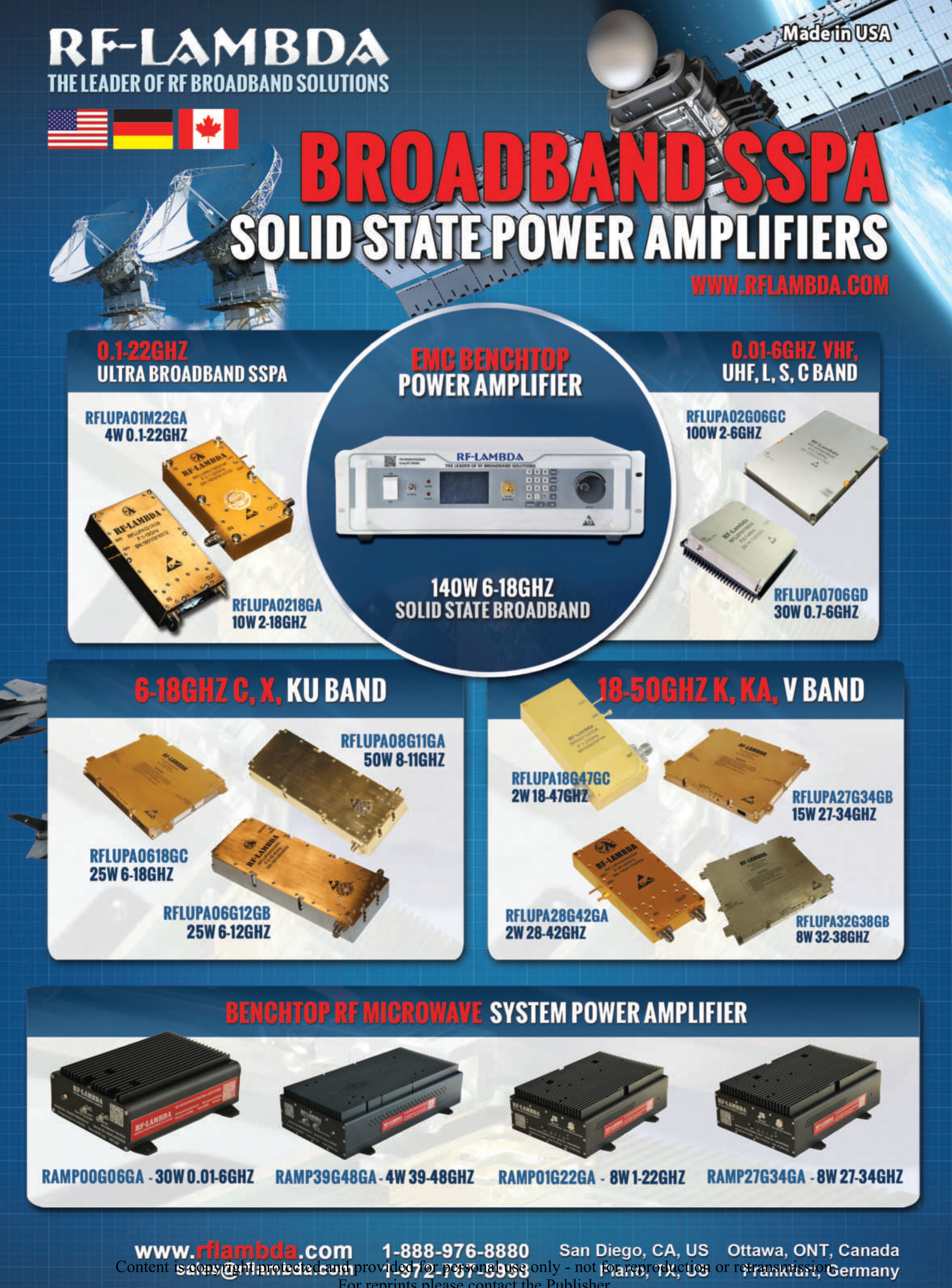
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Microwave Journal CONTENTS

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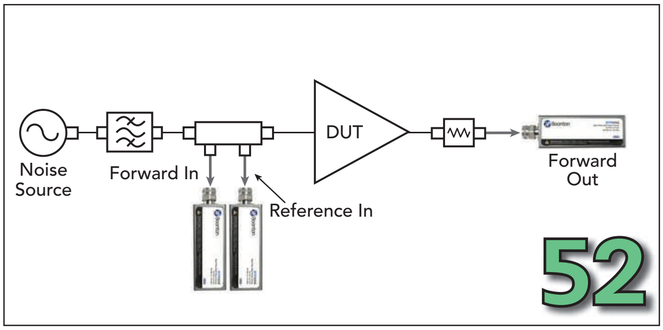

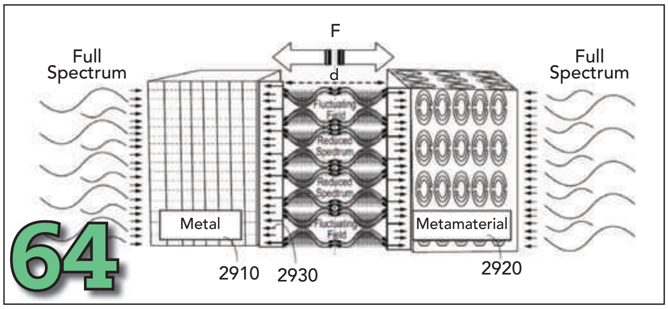

Cover Feature

22 **Semiconductor Trends in Sub-6 GHz 5G Networks**
Eric Higham, Strategy Analytics

Application Note

52 **A Better Approach to Measuring GaN PA Linearity**
Walt Strickler, Boonton Electronics, Paulo Correa and George Bollendorf, Empower RF Systems

Technical Feature

64 **A Microelectromechanical Switch with Metamaterial Contacts: Concepts and Technology Part II**
Shiban K. Koul and Chaitanya Mahajan, C.A.R.E, Indian Institute of Technology; Ajay K. Poddar and Ulrich L. Rohde, Synergy Microwave

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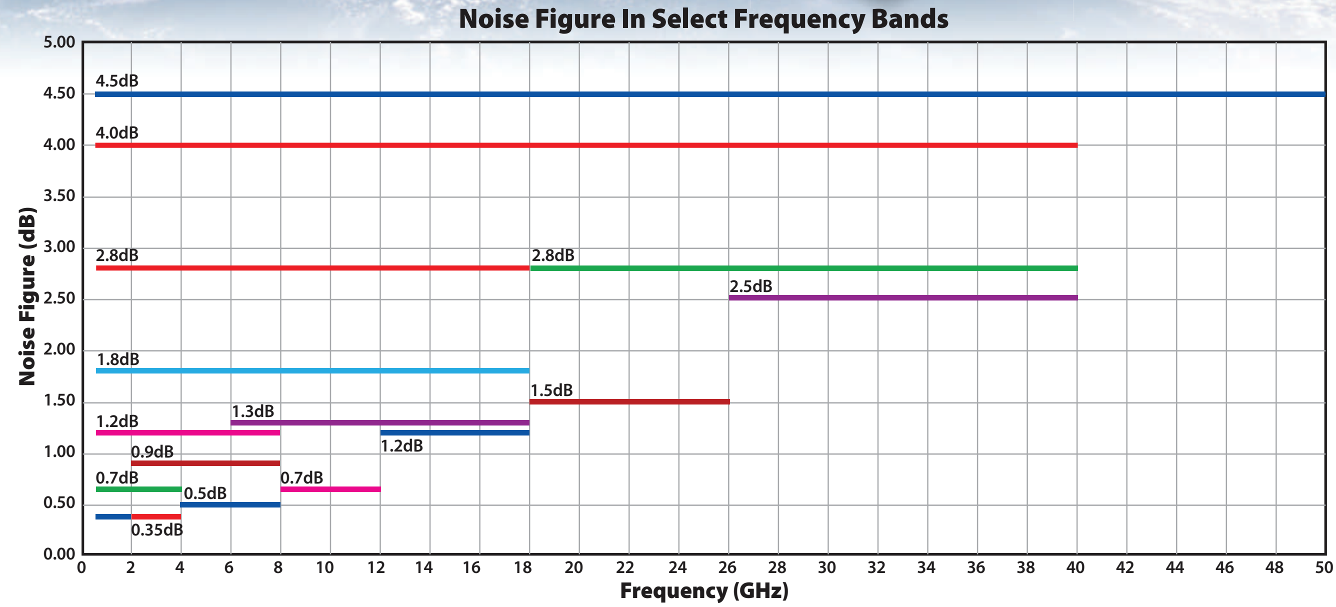
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Noise Figure (dB)
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2.8dB
2.8dB
2.5dB
1.8dB
1.5dB
1.3dB
1.2dB
1.2dB
0.9dB
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0.7dB
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CONTENTS

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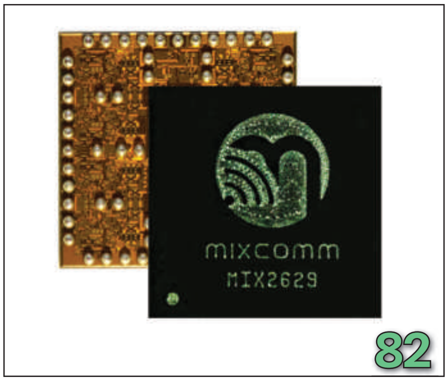

Product Feature

82 **Eight-Channel Front-End RFIC Claims New Record for 28 GHz Power, Efficiency and Integration**

MixComm Inc.

Departments

17 .... Mark Your Calendar
18 .... Coming Events
37 .... Defense News
41 .... Commercial Market
44 .... Around the Circuit
88 .... Web Update
90 .... New Products
102 .... Book End
104 .... Ad Index
104 .... Sales Reps
106 .... Fabs & Labs

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Semiconductor Trends in Sub-6 GHz 5G Networks

Eric Higham
Strategy Analytics, Boston, Mass.

Even before the COVID-19 virus emerged to challenge global supply chains, the RF and microwave semiconductor industry was facing significant headwinds. The cellular market, particularly mobile handsets, enables more than 50 percent of compound semiconductor revenue. This application has been a strong driver for the industry for more than a decade, but the engine is running out of steam. RF GaAs device revenue declined in 2019 and the culprit was a reduction in smartphone shipments. Despite this stumble, the future looks brighter for the compound semiconductor industry. The reason for this optimism is 5G networks and devices and this new standard is poised to become the growth engine for the entire semiconductor industry.

5G MARKET

Wireless operators have been deploying 5G networks and devices since 2019, so the three pillars of the 5G vision should be familiar. ***Figure 1*** shows a simple representation of the main tenets of the 5G vision, along with the features promised by these pillars. The challenge for operators and equipment manufacturers will be the timing and extent of the implementation of these pillars.

5G is an imprecise term in general usage. 5G can refer to the standalone or non-standalone version that makes use of the existing LTE core and signaling network. There are also the mmWave frequencies (also known as "FR2" or "high band") or sub-6 GHz frequencies (also known as "FR1" and comprised of "low band" and "mid-band"). The 3GPP industry standards body is working to codify 5G with ongoing work on Release 15 with Releases 16 and 17 scheduled for approval by the end of 2022 to address other aspects of 5G.

In addition to the ongoing development of technical standards, fundamental questions for the industry concern the business model for 5G. How will operators differentiate 5G networks from LTE networks? Will the 5G network address all or just a subset of the pillars and goals of the 5G vision?

SUB-6 GHZ 5G NETWORKS

Deploying a new generation of wireless networks is an expensive proposition and operators are working to identify and monetize 5G applications. While there is a substantial development effort aimed at addressing all three pillars of the 5G vision, the early 5G marketing messages focus more on the enhanced mobile broadband (eMBB) feature of 5G. Operators are competing based on network coverage and speed and this has implications for the sub-6 GHz network architectures and technologies.

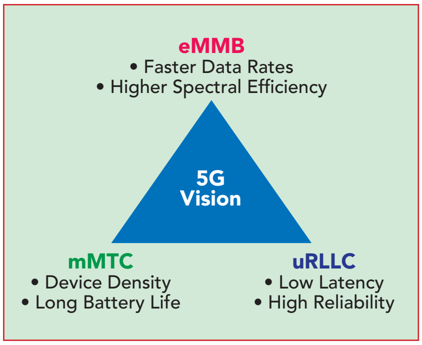
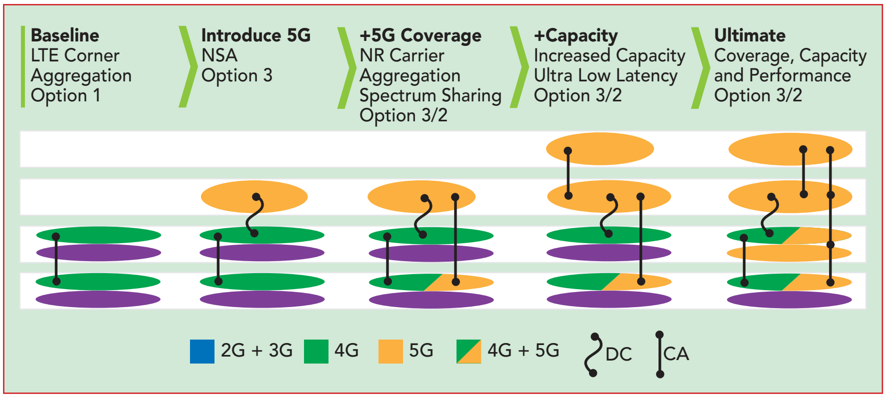
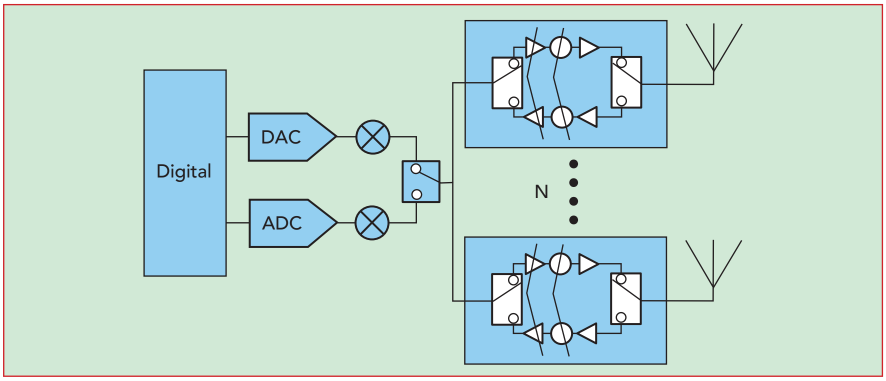


Fig. 1 The 5G Vision.



▲ Fig. 2 A Hybrid Network Evolution to 5G. *Source:* Ericsson.



▲ Fig. 3 Analog beamforming transceiver block diagram (source: Analog Devices, "Bits to Beams: RF Technology Evolution for 5G Millimeter Wave Radios").

CHALLENGES

If the criterion is speed, or capacity, sub-6 GHz 5G networks are at an immediate disadvantage. This is a byproduct of the Shannon-Hartley theorem, which describes the theoretical maximum data rate transmitted in a specific channel bandwidth:

$$C = B^*\log_2 (1+SNR)$$

where: C = channel capacity limit (bits/s), B = channel bandwidth (Hz) and SNR = signal to noise ratio.

Even as new sub-6 GHz frequency bands are being assigned globally, bandwidth is measured in the tens or hundreds of MHz in these bands. At mmWave frequencies, bandwidth is easily in the GHz range. This is a fundamental disadvantage for the sub-6 GHz networks compared to mmWave. ***Figure 2*** shows Ericsson's view of how to evolve an existing LTE network to 5G with best-in-class coverage, capacity and performance. This hybrid network incorporates existing 2G/3G/4G standards and bands, along with 5G sub-6 GHz and mmWave bands. The evolution starts with carrier aggregation (CA) at different LTE bands. The evolved network incorporates dual connectivity, where the downlink operates in a 5G sub-6 GHz band containing more channel bandwidth, while the uplink signal remains on the LTE network. Ultimately, the network evolves to incorporate various combinations of CA and dual connectivity in the sub-6 GHz and mmWave bands.

ADVANTAGES

Figure 2 shows a migration vision for an operator to upgrade their LTE networks to a full feature 5G network. This evolution involves multiple bands and standards, CA and dual connectivity, making implementation complex and costly. The sub-6 GHz portion of the network has channel bandwidth deficiencies and it increases the complexity of the hybrid network, but it provides many benefits for the 5G network.

A big benefit of the lower frequency bands is the signal propagation characteristics. The path loss for a transmitted signal increases with frequency by a factor $20\log_{10}(f)$. At the same distance, a signal at 28 GHz incurs 32 dB more loss than a

signal at 700 MHz. With fixed maximum transmit powers for the base station; this increased path loss at high frequency dramatically reduces the coverage area for the 28 GHz equipment. The sub-6 GHz signals also have lower building penetration losses than mmWave signals. This becomes an important consideration for a 5G network deploying in large urban areas.

Sub-6 GHz networks also provide a clear advantage in multiple input, multiple output (MIMO) techniques and massive MIMO antennas. MIMO relies on multiple transmitters and receivers at the base station and user terminal. Because the radiators are physically separate, transmitted signals follow different paths to the receivers. Using spatial diversity and multiplexing techniques, coupled with multiple data streams on a channel and multipath propagation allows for more robust (better signal to noise performance) signals and/or higher signal data rates.

This MIMO antenna architecture will be a mainstay of most 5G networks, because to a first approximation, a MIMO antenna increases the channel capacity shown in Equation 1 by a factor of n, where n equals the number of antenna radiator pairs. In earlier 3GPP releases, antenna structures were limited to an 8T/8R configuration, meaning eight transmitters and eight receivers. The term "massive MIMO" (mMIMO) is also imprecise, but it has come to mean a number of transceivers much greater than eight. In current 5G deployments, we are seeing mMIMO base stations and access points with up to 1,024 radiators per antenna.

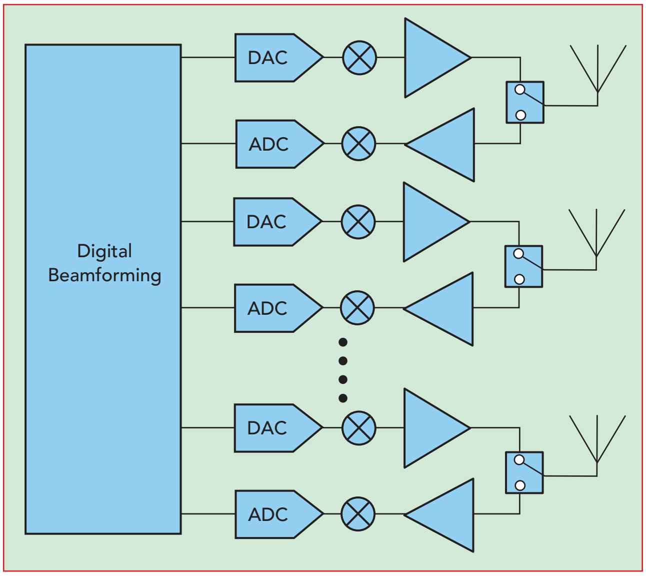


Fig. 4 **Digital beamforming transceiver block diagram (source: Analog Devices, "Bits to Beams: RF Technology Evolution for 5G Millimeter Wave Radios").**

The reality of mMIMO is different for sub-6 GHz and mmWave implementations and this leads to subtle differences in the architectures and design criteria. Because of longer wavelengths, the sub-6 GHz signals undergo more transmission reflection than mmWave signals. This means a richer multipath propagation environment to enable the advantages of MIMO. In addition, establishing and maintaining an optimized wireless link relies on knowing the channel state information. This involves processing and updating information on parameters like scattering, fading, path loss, blocking, etc. These quantities are more repeatable at the sub-6 GHz frequency range, providing a more favorable environment for signal propagation.

ARCHITECTURE

These mMIMO antennas allow beamforming and beam steering and this is another key enabler. LTE antennas are typically static, providing energy throughout a sector, but 5G antennas form beams that can be steered in azimuth and elevation. Driving multiple radiators with signals of the appropriate amplitude and phase will form a beam. Changing the phase and amplitude to that group of radiators enables the beam to be steered off antenna boresight.

There are three distinct methods of beamforming/beam steering, each having advantages and disadvantages. ***Figure 3*** is a representative block diagram for the RF front-end in an analog beamforming architecture. The advantage of this approach is simplicity, especially

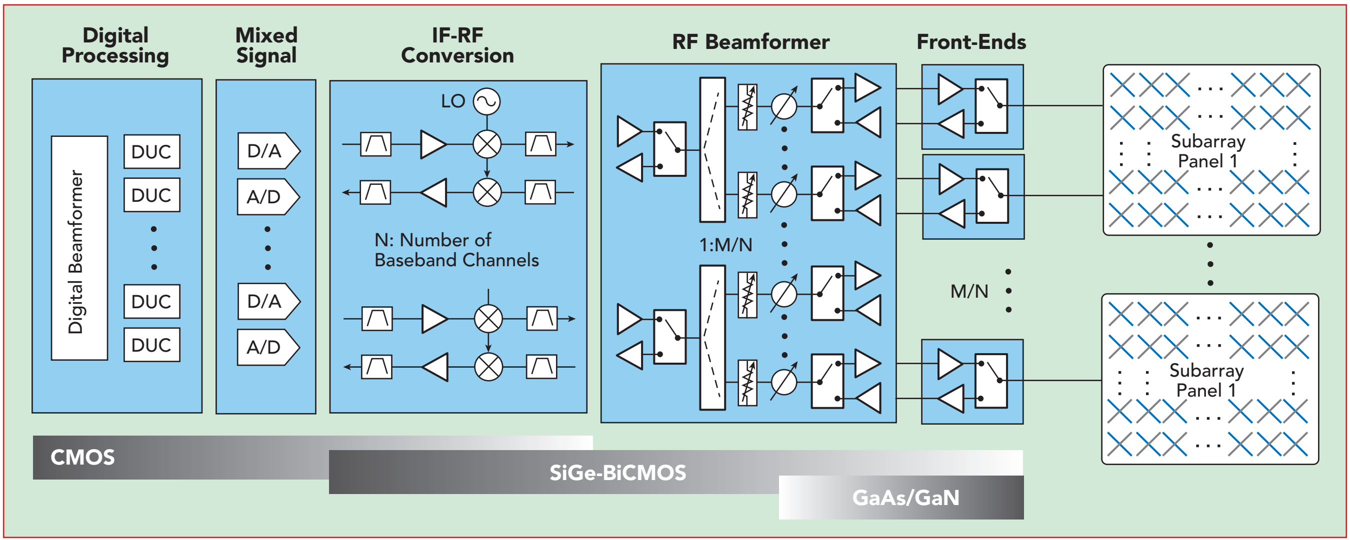


Fig. 5 **Hybrid beamforming transceiver block diagram (*Source:* Qorvo).**

in the digital section. The antenna beam can be steered by adjusting the phase shifters and attenuators. The disadvantage is that only one data stream feeds the antenna elements, limiting the data rate and flexibility of this architecture.

Figure 4 shows the other end of the capability spectrum. This simplified block diagram represents a digital beamforming architecture. In this approach, each antenna has a dedicated RF chain and depending on the system requirements, silicon processes can fabricate this entire RF chain. In this architecture, all the precoding, multiplexing, signal weighting, phase shifting, etc. happens in the digital domain. The number of beams from the antenna is variable, as is the number of elements making up a beam. These beams are all steerable and algorithms can synthesize a drive signal to get most any beam characteristic. This architecture is easily the most flexible with the highest capability. This architecture increases the digital chip content, and this may increase cost and power consumption. Despite these challenges, digital beamforming architectures are currently in use in sub-6 GHz bands. Because of the substantial increase in performance and capability, expect to see more digital beamforming in the future in both sub-6 GHz and mmWave frequency ranges.

In response to these challenges, wireless equipment manufacturers have developed the hybrid beamforming architecture shown in ***Figure 5*** as a compromise. This architecture incorporates the analog RF beamformer and front-end approach of the analog technique, along with the digital processing and independent data channels of the digital approach. The hybrid array will generate multiple beams, determined by the number of channels, but an RF chain drives a number of subarray “tiles,” rather than a single radiator. This compromise solution provides functionality closer to the digital architecture and complexity and power consumption closer to the analog architecture.

The hybrid and digital beamforming transceiver block diagrams illustrate why 5G deployments will become the new growth driver for the semiconductor market. More bands and mMIMO in the base station and more importantly, the handset implies a large increase in functional quantity. Each beam of the antenna requires a separate RF channel. The number of beams from an antenna depends on a variety of factors like the frequency range, the spatial multiplexing scheme, the number of users, etc., but we are seeing eight beams as a typical value in the early 5G deployments. This multiplicative effect of more beams and more RF content per sector times millions of 5G sectors has the semiconductor industry excited about the future.

BASE STATION SECTOR FORECASTS

Figure 5 illuminates another important topic for the semiconductor industry. As the diagram shows, there are several technology alternatives for this implementation. With cellular terminal sales flattening, 5G

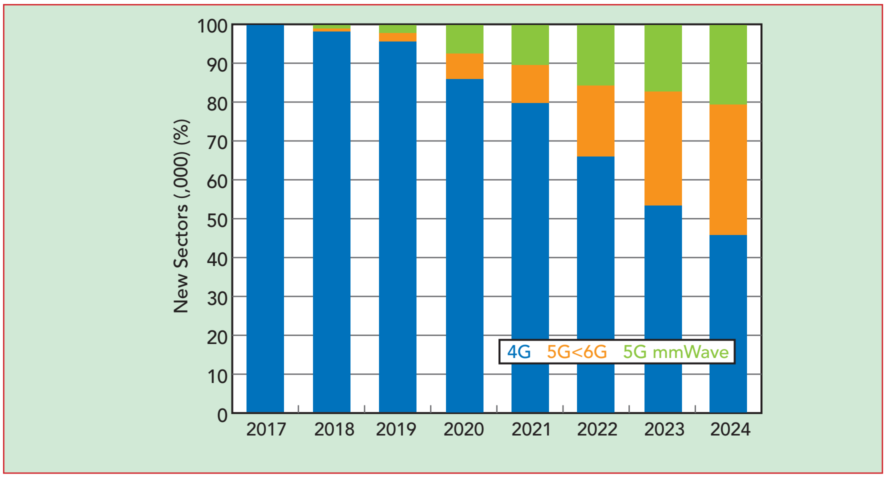
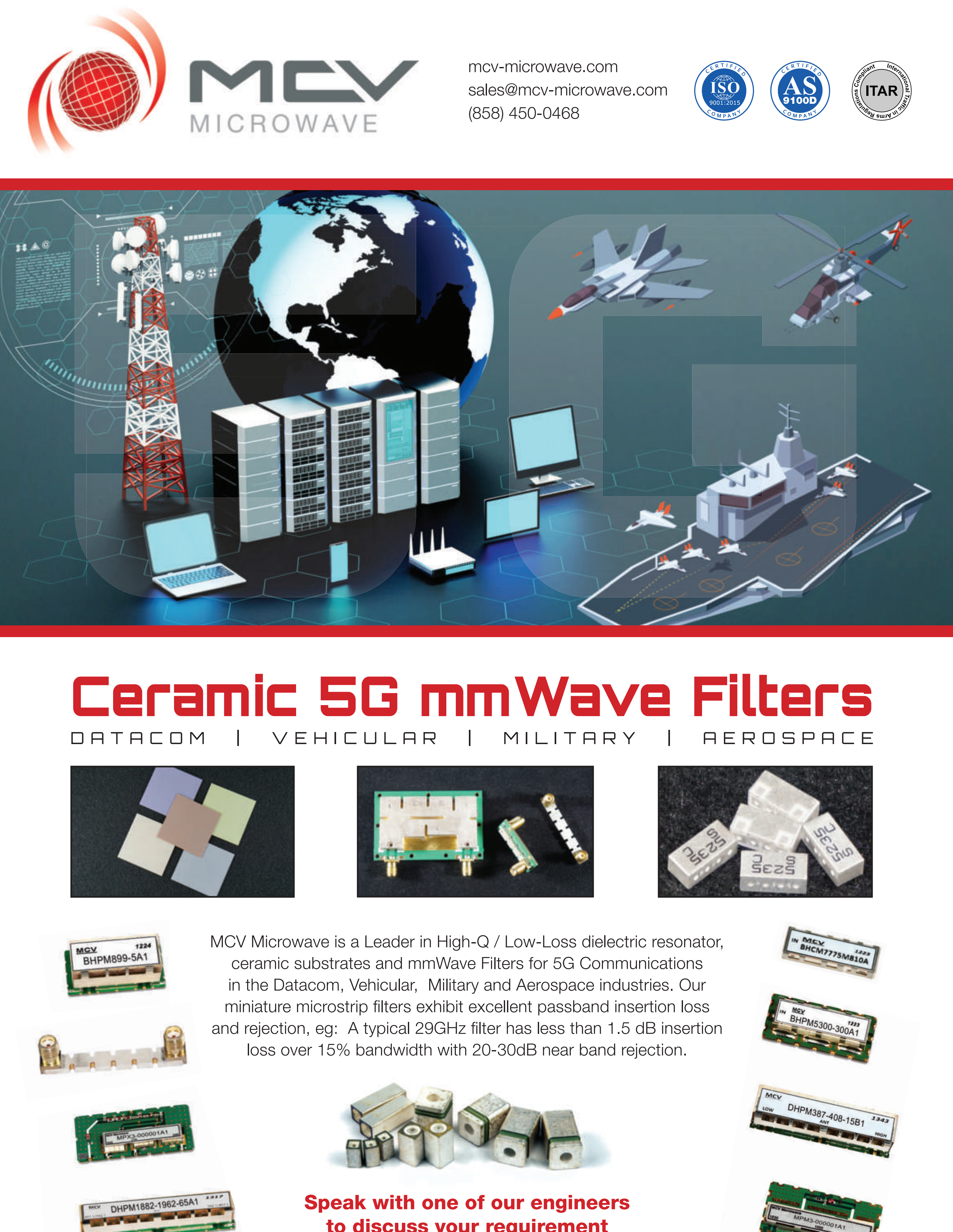


Fig. 6 Wireless base station sector forecast (*Source:* Strategy Analytics).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networks and devices are poised to become the most significant driver for the compound semiconductor market. The mix of sub-6 GHz and mmWave networks and devices, along with the relative shares of digital and beamforming architectures, will determine the growth trajectory for the various device technologies.

Figure 6 shows our forecast for new wireless base station sectors. Trends like remote radio heads, re-farming frequency ranges, adding capacity at existing sites, tower sharing, etc. make defining a "base station" increasingly difficult. To try to normalize these factors, we segment the base station market by sectors, where a sector contains all the electronics required to provide service to a pre-determined coverage area. With this definition, a conventional omni-directional macro cell will have three (or more) sectors, while a low power indoor cell may have only one sector. The other very important disclaimer is that we assembled these forecasts based on 2019 year-end data, without factoring in the effects of COVID-19 on global demand and the supply chain. Since this is an unfolding story, we are monitoring the effects of COVID-19 and we will update forecasts as trends become clearer.

The forecast shows some interesting trends, including the importance of the sub-6 GHz 5G segment to the wireless infrastructure market. The emergence of 5G does not foretell the end of 4G. The NSA versions of 5G will use existing 4G core infrastructure. Since it will take some time for 5G to become ubiquitous, the 4G network will evolve to provide 5G users with a robust experience during times when 5G coverage is not available. The first 5G network deployments were in the mmWave bands in the U.S. These deployments were primarily fixed wireless access applications, using a proprietary Verizon specification. These networks provided high speed "last mile" access to expand FiOS network coverage. We are forecasting that mmWave 5G networks will soon support mobility.

mmWave base station sectors will increase, but more slowly than the sub-6 GHz base station sectors. mmWave signals present many challenges, but for this forecast, the most important one is the smaller coverage footprint. With the small coverage area, it is very unlikely that operators will be able to approach ubiquitous coverage within the forecast period. As shown in the diagram of Figure 2, the most likely 5G network will be a hybrid of mmWave cells for high data rate capability, coupled with sub-6 GHz cells to maximize coverage area.

Growth of sub-6 GHz base station sectors tells a different story. The sub-6 GHz 5G bands are close to existing cellular bands. Incorporating these bands into networks and devices has not been a daunting challenge and initial network deployments accommodate mobility. Operators are deploying macro cells to establish coverage and then adding lower power small cells to improve coverage and capacity. This deployment model will drive fast growth in the sub-6 GHz segment, although the number of new sectors deployed in 2024 will be less than the number of new 4G sectors deployed. Our pre-COVID-19 sector estimate has the total market reaching nearly 10 million new sectors per year in 2024.

TECHNOLOGY SHARE FORECASTS

The estimated growth trajectory of 5G base stations sectors, coupled with the architectures discussed

TABLE 1

QUALITATIVE COMPARISON OF LDMOS AND GAAS

Characteristic	LDMOS	GaN
Frequency	✗	✔
Instantaneous Bandwidth	✗	✔
Efficiency	✗	✔
Power Density	✗	✔
Operating Temperature	✗	✔
Parasitic Capacitance	✗	✔
Resistance	✗	✔
Operating Voltage	✗	✔
Package Size	✗	✔
Robustness	✔	✔
Reliability	✔	✔
Cost	✔	✗

earlier influence the technology share. As wireless networks have evolved to 4G, the transceiver functional technologies have changed. Silicon IC technology has moved out toward the antenna, capturing share from compound semiconductor technologies. The increasing functional share of silicon in the block diagram relegates compound semiconductors to the beamformer and front-end functions.

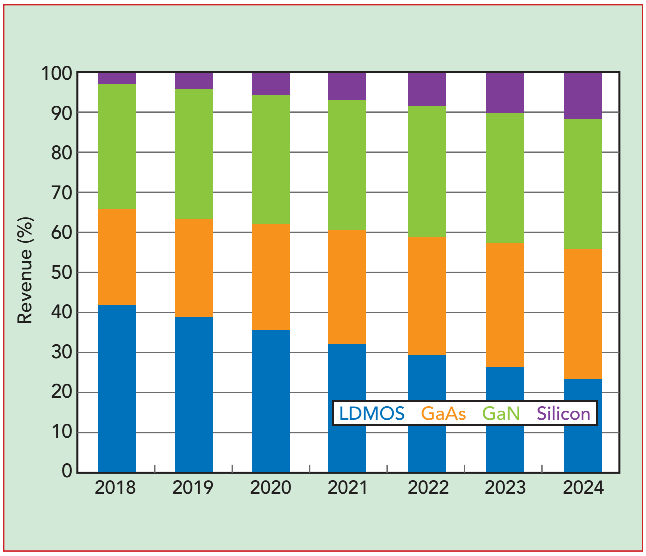
Within the front-end, the power technology transition is a major development that 5G will accelerate. Historically, Si-based laterally diffused metal oxide semiconductor (LDMOS) has been the dominant power technology. However, fueled by China's massive LTE deployments, GaN has become the fastest growing base station power technology. This trend will speed up as 5G networks with mMIMO antennas, wider bandwidths, higher operating frequencies, reduced DC power dissipation, etc. deploy more widely. ***Table 1*** shows a comparison of important performance characteristics.

The indications in Table 1 are anecdotal, qualitative and some comparisons may be a bit controversial, but the table gives a good visual indication of why GaN is quickly capturing share. Most of the green performance advantages result from GaN's wide bandgap device characteristics. Reliability was an early disadvantage of GaN, but the supply chain has done a very good job at improving GaN design and manufacturing processes to eliminate these reliability concerns. The rapid adoption of GaN in defense and base station applications is another testimonial to reliability.

Perhaps the most controversial entry in the table is cost. This has been the topic of many discussions with the industry and the picture is still not clear. LDMOS proponents maintain that equivalent GaN devices remain substantially higher in price. Proponents of GaN may dispute that, but even if they agree, they point to total cost of ownership advantages with GaN technology. The broad acceptance of GaN in base station applications indicates that there is a compelling price argument for GaN.

Silicon-based LDMOS has been an extraordinarily resilient technology. That ecosystem has introduced several new generations, each with incrementally better performance and price to delay the loss of market share. While the latest generation of LDMOS performs to 4 GHz to capture opportunities in the 3.5 GHz band that is becoming a global de-facto standard, LDMOS devices will not operate in mmWave bands. The growth of the mmWave base station segment will hasten the overall market share decline of LDMOS.

We estimate that GaN revenue in all base stations exceeded LDMOS revenue for the first time in 2019. However, LDMOS will continue to account for a significant share of the sub-6 GHz power revenue. ***Figure 7*** shows an estimate of the power device revenue for the sub-6 GHz portion of the base station market. Despite the interest in the mmWave portion of 5G, revenue in the sub-6 GHz segment is non-trivial. We estimate that this revenue will reach nearly $300 million by 2024. Silicon (CMOS, SiGe) has the fastest revenue growth



▲ Fig. 7 **Sub-6 GHz base station power revenue by technology (*Source:* Strategy Analytics).**

as sub-6 GHz base stations move to larger massive MIMO arrays that reduce the power amplifier transmit power. As operators seek to improve spectral efficiency to increase data rates with their limited channel bandwidths, the integration capabilities of silicon will be compelling.

Despite the integration benefits of silicon, GaN will account for the largest revenue in this segment. While the integration capability of silicon is compelling, the performance of GaN and the implications to operators for total cost of ownership are compelling. The advantages of GaN will allow this technology to capture a significant portion of the power revenue in the sub-6 GHz band. This revenue analysis includes driver amplifiers, largely the domain of GaAs devices in those applications where the entire RF chain is not integrated. The graph clearly shows that LDMOS revenue and share in this segment is shrinking. We do not expect it to disappear, but the technology is likely to find more use in niche applications in the future.

SUMMARY

Even before the COVID-19 outbreak, the compound semiconductor market was in the doldrums. Fortunately, 5G network and device deployments look to be the force that gets the market moving toward growth again. While mmWave frequencies offer some distinct advantages, the sub-6 GHz band offers the timeliest opportunities. The mix of frequency ranges and network architectures will determine the trajectory for compound semiconductor revenue growth, but we anticipate sub-6 GHz and mmWave 5G deployments will drive revenue in silicon IC, GaN, GaAs and LDMOS technologies.■

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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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New DARPA Contract to Disrupt the Future of Space

DARPA recently awarded Lockheed Martin a $5.8 million contract for the first phase of satellite integration on the Blackjack program.

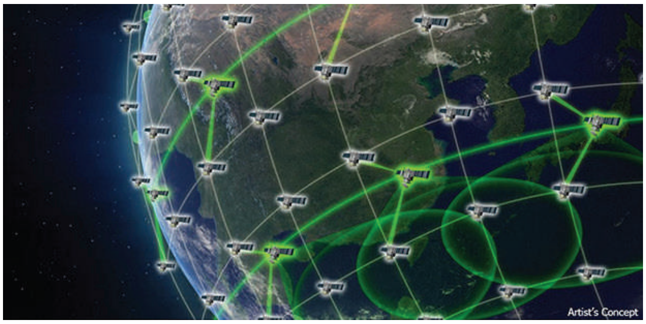
National Security Space (NSS) assets, critical to U.S. warfighting capabilities, traditionally reside in geosynchronous orbit to deliver persistent overhead access to any point on the globe. In the increasingly contested space environment, these exquisite, costly and monolithic systems have become vulnerable targets that would take years to replace if degraded or destroyed. DARPA's Blackjack program aims to develop and demonstrate the critical elements for a global high-speed network in low Earth orbit (LEO) that provides the Department of Defense with highly connected, resilient and persistent coverage.

Blackjack seeks to incorporate commercial sector advances in LEO, including design of LEO constellations intended for broadband internet service, of which the design and manufacturing could offer economies of scale previously unavailable. DARPA is interested in capitalizing on these advances to demonstrate military utility, emphasizing a commoditized bus and low-cost interchangeable payloads with short design cycles and frequent technology upgrades.

The key program objectives are:

- Develop payload and mission-level autonomy software and demonstrate autonomous orbital operations including on-orbit distributed decision processors.
- Develop and implement advanced commercial manufacturing for military payloads and the spacecraft bus.
- Demonstrate payloads in LEO to augment NSS assets. The driver will be to show LEO performance that is on par with current systems in geosynchronous orbit with the spacecraft combined bus, payload(s) and launch costs under $6 million per orbital node while the payloads meet size, weight and power constraints of the commercial bus.

Future phases of Blackjack are expected to include build, test and launch of a demonstration constellation in 2021-2022.

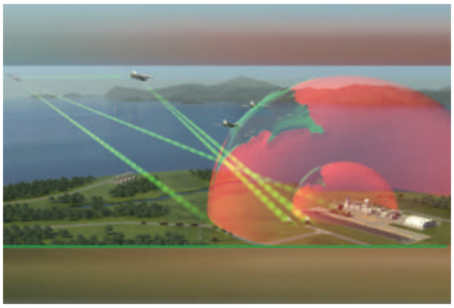


(Source: DARPA)

Electronic Shield for Air Forces

HENSOLDT has developed a modular airborne electronic combat system, Kalætron Attack. By neutralizing enemy fire control radars at different distances, it preserves freedom of movement for the air forces that deploy it and their allies, even when faced with state-of-the-art air defense systems. Kalætron Attack is a new addition to the Kalætron electronic warfare product family, which uses fully digitized hardware and artificial intelligence (AI) to detect radar-based threats to air forces in record time and neutralize them with targeted electronic countermeasures (ECM).

Due to its fully digital design, Kalætron Attack detects and identifies air defense positions very quickly over a wide frequency range. The unit uses AI techniques to recognize new threat patterns from a huge amount of collected pulses. This is especially important for identifying the latest air defense radar systems which cover an extremely wide frequency range or hop between frequencies in fractions of a second.



(Source: Hensoldt)

Kalætron Attack can be flexibly adjusted to changing threats using innovative antenna designs with active electronically scanned array technology, fully digital signal processing and AI algorithms. The Kalætron product family thus forms the basis for enabling fighter aircraft to not only take on an electronic combat role and perform escort jamming for aircraft units, but also to protect them from a great distance away through stand-off jamming. Experience from recent conflicts has shown that such equipment designed to counter the threat posed by the latest air defense systems will be essential for aircraft deployed in the future. With 'Kalaetron Attack' HENSOLDT as the German Sensor House provides a national answer to the LuWES program and contributes substantially to European defense cooperation programs such as Future Combat Air System. The German Air Force LuWES program stands for airborne action in the electromagnetic spectrum and includes three main elements—a stand-off jamming attack platform, an escort jamming platform and stand-in jamming system in the form of an unmanned airborne launched decoy.

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Navy Accepts Delivery of USS Zumwalt

The Navy recently accepted delivery of USS Zumwalt (DDG 1000), the lead ship of the Navy's next-generation of multi-mission surface combatants.

Following this delivery, the ship will transition from Combat Systems Activation to the next phase of developmental and integrated at-sea testing. This event marks a major milestone of the dual delivery approach for USS Zumwalt, which achieved Hull Mechanical & Electrical delivery from shipbuilder General Dynamics' Bath Iron Works in May 2016. Raytheon Integrated Defense Systems was the prime contractor for the Zumwalt Combat System and has lead activation and integration for Zumwalt class ships both in Bath, Maine, and San Diego, Calif.

With delivery, USS Zumwalt joins the U.S. Pacific Fleet battle force and remains assigned to Surface Development Squadron One. In addition to at-sea testing of the Zumwalt combat system, DDG 1000 will also operate as a key enabler in the acceleration of new warfighting capabilities and rapid development and validation of operational tactics, techniques and procedures.

The 610 foot wave-piercing tumblehome ship design provides a wide array of advancements. Employing an innovative and highly survivable Integrated Power System, DDG 1000 has the capacity to distribute 1,000 V of direct current across the ships' entirety, allowing for enhanced power capability for various operational requirements. Additionally, the shape of the superstructure and the arrangement of its antennas significantly reduce radar cross section, making the ship less visible to enemy radars.

"Every day the ship is at sea, the officers and crew learn more about her capability and can immediately inform the continued development of tactics, techniques and procedures to not only integrate Zumwalt into the fleet, but to advance the Navy's understanding of operations with a stealth destroyer," remarked the Commanding Officer of USS Zumwalt, Capt. Andrew Carlson. "After sailing over 9,000 miles and 100 days at sea in 2019, we are absolutely looking forward to more aggressive at-sea testing and validation of the combat systems leading to achievement of initial operational capability."

The USS Zumwalt is the first ship of the Zumwalt class destroyers. The USS Michael Monsoor (DDG 1001) is homeported in San Diego and is undergoing combat systems activation. The third and final ship of the class, the future USS Lyndon B. Johnson (DDG 1002), is under construction at BIW's shipyard in Bath, Maine.

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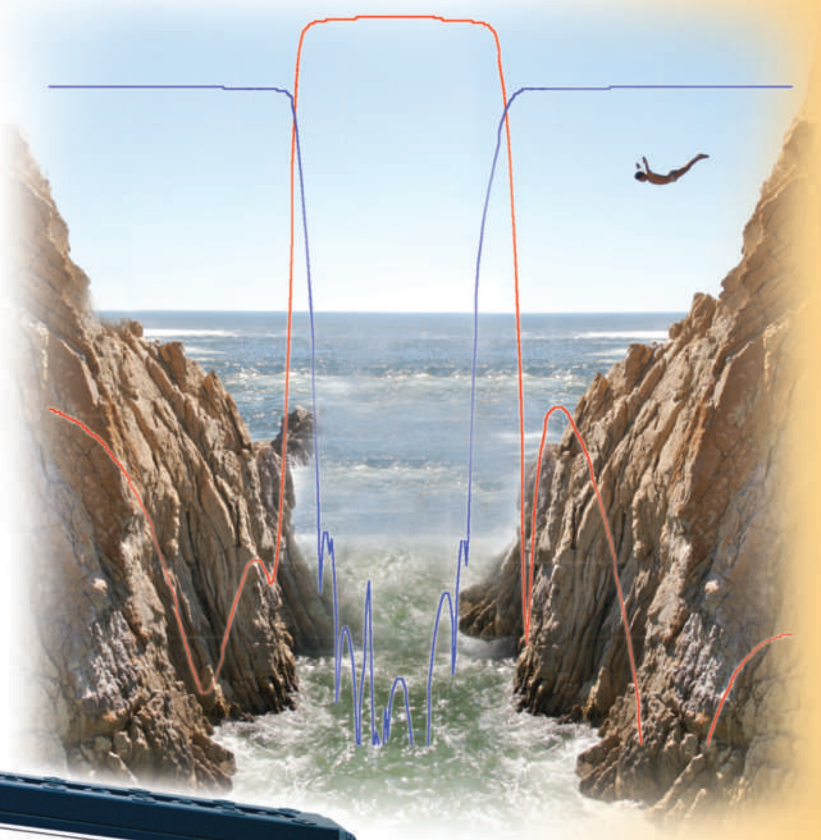

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Cliff Drubin, Associate Technical Editor

COVID-19 to Accelerate Adoption of New Technology

City governments are adjusting to a new reality, with COVID-19 driving urban resilience and digital transformation strategy agendas, according to ABI Research. This is reflected in the deployment of a range of technologies for new use cases during the current emergency:

- Drones–Communication and enforcement of social distancing rules; delivery of medical supplies
- New types of surveillance–AI-based remote temperature sensing (Kogniz Health)
- Autonomous freight–Autonomous last mile delivery (Beep, Navya, Nuro, Waymo, Postmates)
- Digital Twins–Holistic, transversal, real-time visibility for resources, assets and services (Siradel)
- Real-time dashboards (City of Boston) and data sharing including the use of smartphone data crowdsourcing for location tracking

"While many of the measures taken by city governments during COVID-19 are decided on the fly requiring high levels of improvisation, it has resulted in a rich laboratory type learning experience in terms of how to take advantage of the inherent flexibility of technologies to address emergency situations and challenges linked to demand-response management of assets and services," said Dominique Bonte, vice president of end markets at ABI Research. "This will have a lasting impact, coming out of COVID-19 during and after the drawn-out recovery period, in the form of a step change in how resilience is approached and generalized, allowing to prepare better for future calamities, a distinct silver lining on a very dark COVID-19 cloud."

At the same time cities are reaping the benefits of a digital only lifestyle in the form of the sudden adoption of e-Government services, e-Health and teleconsultation, remote work, online education and e-Commerce resulting in huge drops in traffic levels. These, in turn, are dramatically decreasing congestion, fatalities and air pollution. Importantly, post-COVID-19 traffic levels are expected to only reach between 80 and 90 percent of the pre-COVID-19 levels, as digital lifestyles take hold more permanently, driven by both public and private initiatives and incentives. The result will have lasting positive effects on the environment.

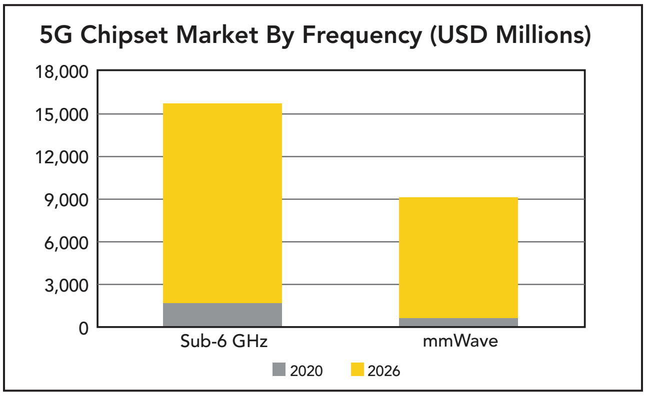
5G mmWave and Massive MIMO Market

It is expected that 5G will deliver more data to more devices with lower latency and higher consistency than previous-generation technologies. To adequately accommodate users, however, there is a need for larger bandwidth. Bandwidth is limited in the mobile frequency spectrum, hence, mmWave bands are being leveraged. mmWave technology offers several advantages such as high-speed data transfer, high resolution, low interference, small form factors, increased security and cost-effectiveness. Wavelengths are short, allowing many antenna elements to be placed in a compact, highly directive aperture. According to Associate Vice President of Semiconductor and Electronics at MarketsandMarkets, Sachin Garg, "mmWave is likely to play a key role to support burgeoning mobile data traffic growth. High data transfer rates offered by this spectrum, the growing involvement of various telecom service providers and favorable federal mandates are driving market growth."

5G mmWave is focused on deployments in existing dense urban markets. Indoor venues such as convention centers, concerts, malls, stadiums and indoor enterprises such as offices, shop floors and meeting rooms are challenged with limited network capacity. This presents a huge opportunity for mmWave in providing fixed wireless access in such crowded areas. mmWave's wider bandwidth and high spatial multiplexing gains allow mobile operators to provide gigabit, low latency connectivity to a large number of users.

Advancements have been made in RF silicon that allow a large number of RF chains to be supported in large antenna arrays. RFICs play an important role in network infrastructure, mainly in small cells and macrocells. They are also used for enabling radio-based communication. Companies such as Qualcomm, Intel, Huawei, Samsung, Anokiwave, Qorvo, Broadcom and Analog Devices are developing chipsets and chipset-based products for the 5G network infrastructure. The 5G mmWave chipset market is estimated at USD 0.4 billion in 2020 and is expected to reach USD 8.6 billion by 2026, at a CAGR of 53.1 percent between 2020 and 2026. The market includes RFICs, mmWave ICs and baseband ICs used in 5G devices and network infrastructure.

Massive MIMO will be a key enabler and foundational component of the fully functional 5G network. One of the key roles of the 5G network is to handle a huge in-



5G Chipset Market (Source: MarketsandMarkets)

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crease in data usage, and MIMO can help address this requirement. Densely packed 5G mmWave antenna arrays enable massive MIMO in small form factors. Large array gain overcomes low per-antenna SNR and shadowing. Joint capabilities of bandwidth at mmWave frequencies and high multiplexing gain achievable with massive antenna arrays can significantly raise user throughput, enhance spectral and energy efficiencies and increase mobile network capacity. The Massive MIMO market is estimated to be valued at USD 1.7 billion in 2020 and is projected to reach USD 20.9 billion by 2026, at a CAGR of 41.6 percent between 2020 and 2026.

6 GHz Will Provide Faster, Lower Latency and More Reliable Wi-Fi

The need for faster, more reliable, more efficient and more widespread Wi-Fi coverage is becoming increasingly vital in a world filled with more Wi-Fi devices at both ends of the performance spectrum, from high-throughput and low latency applications to battery-constrained IoT devices. ABI Research forecasts that Wi-Fi-enabled devices are set to increase from 3.3 billion annual unit shipments in 2019 to more than 4.6 billion by 2024, a growth that underscores the need for a more robust Wi-Fi network.

In its new whitepaper, The Future of Wi-Fi, ABI Research highlights that while the growing reach of Wi-Fi will be driven by several advancements, such as Wi-Fi 6 and Wi-Fi's expansion into the 60 GHz and sub-1 GHz bands through WiGig and HaLow, the most exciting and potentially transformative, change to the Wi-Fi landscape is the anticipated availability of 6 GHz spectrum over the next few years.

Currently, Wi-Fi faces several difficult challenges. Key among them are the growing demands being placed on Wi-Fi networks, leading to increased congestion, performance limitations, and reduced quality of service. Most Wi-Fi devices are using increasing amounts of data per device, including streaming high resolution music and videos, video calling, application and firmware updates, digital downloads, social networking, data-heavy web content and online gaming, among others.

"6 GHz not only brings about additional spectrum and higher throughputs, but essentially guarantees access to channels with no legacy, resulting in a corresponding improvement in latency and simplifying channel access. Wi-Fi 6E takes full advantage of what Wi-Fi 6 has to offer and can open new opportunities for Wi-Fi to better support 5G-class services reliant on high multi-gigabit throughput, low latency, high efficiency, broader coverage, and better mobility," said Andrew Zignani, principal analyst for Wi-Fi, Bluetooth and Wireless Connectivity at ABI Research.

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

After reaching a definitive agreement in January, **BAE Systems** has completed the acquisition of **Raytheon Technologies'** airborne tactical radios (ATR) business, based in Fort Wayne, Ind. and Largo, Fla. The ATR business designs, manufactures and supplies mission-critical communications systems to the U.S. Department of Defense, allied governments and large defense aircraft manufacturers, with secure, battle-proven communications solutions installed on a broad range of airborne platforms. The acquisition augments BAE Systems' portfolio in airborne communications with broad spectrum, multi-band and multi-channel radios featuring anti-jamming and encryption capabilities. The ATR business also brings complementary waveform expertise to BAE Systems' Electronic Systems Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance organization.

PCTEST Engineering Laboratory LLC, which recently became part of the **Element Materials Technology Group**, has acquired the latest 5G test solutions from **Rohde & Schwarz** for RF and RRM testing in the FR1 and FR2 frequency ranges. This acquisition includes the R&S TS8980 RF conformance test system, plus the R&S ATS1800C CATR based OTA test chamber. This investment will be instrumental in supporting Element's new Connected Technologies sector, with PCTEST's capabilities offering comprehensive wireless testing and certification services to device manufacturers. The R&S TS8980 provides the maximum test case coverage and **Global Certification Forum (GCF)**/PTRCB validation status for LTE RF and RRM 3GPP conformance and network operator supplemental tests.

COLLABORATIONS

Modelithics Inc. and **Mini-Circuits** have expanded their partnership by developing new high accuracy simulation models for several packaged Mini-Circuits amplifiers. In total, 14 new substrate amplifier models have been developed. These data-based models were extracted by performing broadband S-parameter and noise parameter measurements with a Keysight PNA-X vector network analyzer, as part of a Maury Microwave ultra-fast noise parameter measurement setup. Modelithics now offers over 68 models, representing over 130 individual Mini-Circuits components, that include amplifiers, filters and splitters, among others. All of the new amplifiers models are currently available for FREE for use within Keysight Technologies' PathWave Advanced Design System.

Test and measurement specialist **Rohde & Schwarz** and connectivity and sensor component manufacturer **TE Connectivity** cooperate on testing automotive Ethernet cables and connectors. The two companies have successfully tested a communication link, utilizing shielded twisted pair (STP) cables and TE's MATEnet data connector system, for compliance with the One-Pair Ethernet Alliance Technical Committee group 9 test specification for 1000BASE-T1. Automotive Ethernet is becoming the preferred solution for in-vehicle communications, offering to date speeds up to 10 Gbps.

ZTE Corporation announced that in partnership with **China Unicom**, ZTE has implemented the industry's first Tri-RAT dynamic spectrum sharing solution, SuperDSS, in the live network of the Henan Branch of China Unicom. The average throughput of SuperDSS in the same bandwidth has increased by 35 percent compared with that of LTE/NR DSS. SuperDSS can maintain 3G voice experience while greatly improving spectrum utilization efficiency. Therefore, SuperDSS offers an ideal solution to those operators who are eager to roll out 5G with limited spectrum resources.

COMSAT Inc. has ratified an agreement with **ABS** to enhance and strengthen the COMSAT global network. The addition of the ABS-3A satellite to the COMSAT Southbury, Conn. teleport services bolsters its reach throughout the Americas, Europe, North Africa and the Middle East to provide more resilient and robust connectivity solutions through its terrestrial fiber pathways. A 14.2M antenna delivering C-Band services and a 9M antenna, providing Ku-Band services, have been allocated to support the new partnership. As demand for data transmission increases globally the agreement focuses on providing multiple service options and strengthened satellite connectivity to deliver increased amounts of data, video, mobility and government applications between the U.S. and international markets.

GCF and **450 MHz Alliance** formalized a new partnership with the official signing of a Memorandum of Understanding that will see a GCF certification initiative extend to users of the 450 MHz band. The new collaboration means that global wireless carriers, equipment manufacturers and other device manufacturers in the IoT and machine-to-machine vertical markets can eventually have access to a program that provides a level of confidence in interoperability in this spectrum. 450 MHz Alliance works with members to grow momentum across the 450 MHz ecosystem, providing a simple entry for operators and manufacturers and unleashing the potential of the spectrum for cellular IoT applications on LTE networks.

NEW STARTS

RFMW announced a micro-site for customers and suppliers supporting solid-state RF energy technology. Magnetron tubes have dominated this market but have drawbacks with regards to degradation, reliability and power control. Solid-state RF solutions can be used to replace existing magnetron-based systems. Generally, magnetron replacement systems are made up of 1 KW

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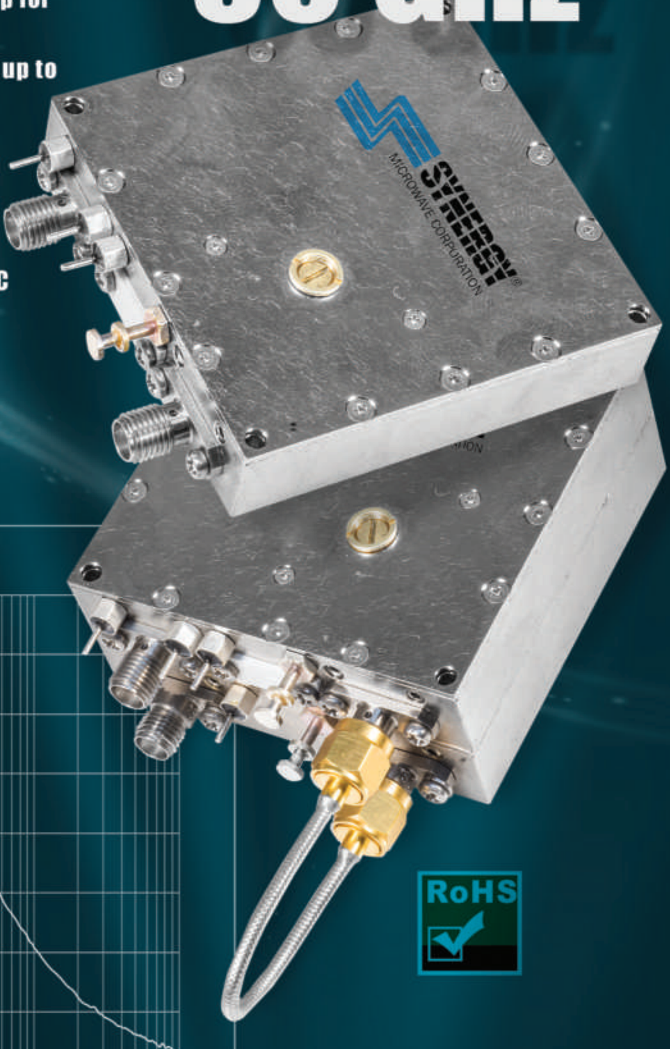

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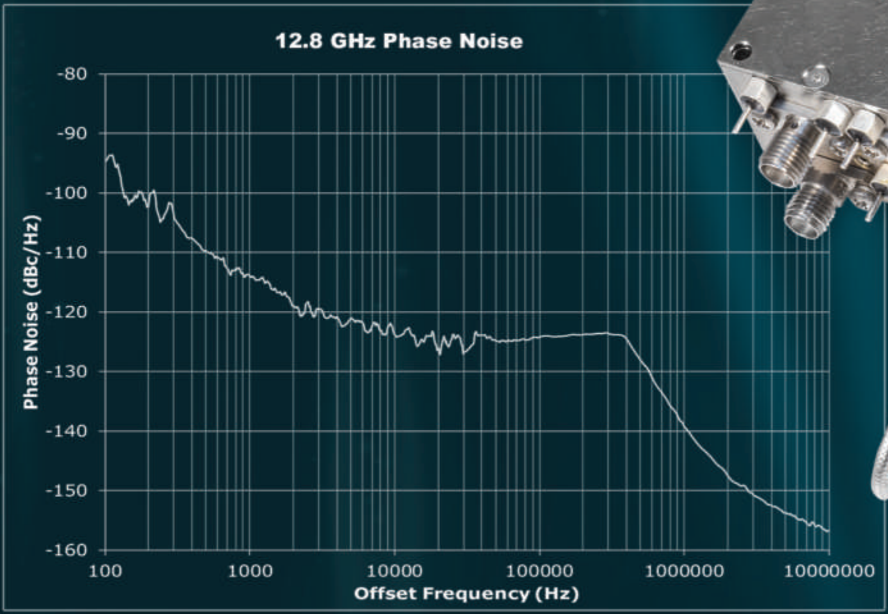

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modules, some systems can reach 50-60 KW at their final output. Solid-state RF energy offers a number of advantages including precise power/frequency/phase and PWM control, high-speed arc detection and shutdown, stability at all power levels, no degradation of power with age, improved reliability and the use of lower voltage power supplies.

ACHIEVEMENTS

Raytheon has recognized **G.T. Microwave Inc.** with an EPIC Supplier Excellence Award for their outstanding performance. EPIC Awards recognize a supplier's overall excellence in performance, innovation and collaboration for one or more Raytheon businesses. Only the highest performing suppliers are awarded this honor. G.T. Microwave is a veteran-owned, small business that designs and manufactures microwave integrated control components.

Infinite Electronics Inc. announced that it has received the 2019 Supplier Excellence Award from **Raytheon Missiles and Defense** for superior supplier performance. Raytheon Technologies' Legacy Integrated Defense Systems business (now Raytheon Missiles and Defense) instituted the annual Supplier Excellence Awards program to recognize suppliers who have provided outstanding service and partnership in exceeding customer requirements. Award candidates are judged on certain criteria, including overall quality and on-time delivery. Infinite Electronics was one of 36 companies recognized by Raytheon's legacy Integrated Defense Systems business for 3-Star honors.

Maury Microwave is excited to announce that it has been recognized by **Raytheon Integrated Defense Systems** as a recipient of its prestigious 3-Star award for supplier excellence. This award is proof of the dedication of their employees and their commitment to the company's value system with an emphasis on service mindset towards its customers.

Raytheon's Integrated Defense Systems business instituted the annual Supplier Excellence Awards program to recognize suppliers who have provided outstanding service and partnership in exceeding customer requirements. Award candidates are judged on certain criteria, including overall quality and on-time delivery. **RLC Electronics** was one of 86 companies recognized by Raytheon's Integrated Defense Systems business for 4-Star honors. This most recent recognition is the fifth time in the past six years that RLC has been awarded as a Top Supplier to Raytheon's Integrated Defense Systems business.

Anritsu Corp. President Hirokazu Hamada announced that Anritsu's New Radio RF Conformance Test System ME7873NR has achieved an industry-first validation for GCF certification of FR2 spurious emissions tests based on 3GPP specifications. The ME7873NR earned the world's first validation approval for spurious testing on GCF 5G NR FR2 non-standalone mode at the CAG#62 meeting in April. To attain this achievement and enable GCF certification for spurious emissions testing, Anritsu made numerous technical contributions to RAN5 to accelerate the development of test specifications defined in 3GPP TS 38.521.

Experts in wireless connectivity testing, **Microwave Vision Group**, has announced substantial interest in its innovative new StarWave system, with the first sale confirmed just a few weeks after launching the technology to market. Despite challenging global conditions caused by the coronavirus pandemic, the launch of this new era 5G mmWave OTA testing technology has been particularly well received by the telecommunications industry. The first system was sold post-launch in the U.S. and will be used to test 5G connected handsets, tablets and laptops.

ThinKom Solutions Inc. recently completed a series of interoperability tests that demonstrated the compatibility of its core antenna technology with a low-Earth orbit (LEO) satellite network. The tests took place during the first quarter of 2020, using commercially available airborne-certified hardware, including a ThinKom Ku3030 phased-array antenna subsystem and a Gogo radome, adaptor plate and power amplifier that together comprise the "2Ku" aero satcom terminal. The 2Ku terminal demonstrated rapid acquisition and tracking of LEO satellites and provided continuous connectivity over all operationally relevant elevation angles.

T-Mobile U.S. Inc. announced several important milestones for standalone architecture (SA) 5G. These achievements, using the Un-carrier's newly built 5G core, bring T-Mobile closer to taking its nationwide 5G network to the next level. In tech terms, SA 5G will eliminate the need for a mid-band LTE anchor, cutting out some of the limitations experienced today. Simply stated, it is the future of 5G. SA will allow 5G to reach its full potential by increasing coverage and laying a foundation for game-changing applications that can utilize blazing fast speeds, real-time responses and massive connectivity.

Rohde & Schwarz has announced the installation of an AI-based RF test system for digital TV compliance test in Vietnam. The system consists of the R&S BTC Broadcast Test Center and RFSpark AutoTester. The R&S BTC Broadcast Test Center is a reference signal generator featuring analysis functions and automated tests for audio, video and multimedia applications. It is a unique combination of outstanding technical features and a modular, flexible design to meet the highest demands and latest transmission technologies.

CONTRACTS

Science Applications International Corp. (SAIC) has been awarded a multiple award, indefinite delivery, indefinite quantity contract from the **U.S. Naval Sea Systems Command** with a ceiling value of $982 million to provide products and services within the unmanned surface vehicle family of systems. The contract carries a five-year period of performance and may extend to 10 years, if all options are exercised.

Around the **Circuit**

Elbit Systems Ltd. announced that it was awarded a contract valued at approximately $103 million to supply comprehensive electronic warfare (EW) suites for an Air Force of an Asian country. The contract will be performed over a three-year period and includes long-term integrated logistic support. Under the contract, Elbit Systems will fit the customer's helicopters with complete EW suites, including countermeasure systems. The EW suites will provide the helicopters with advanced protection to achieve the customer's operational requirements.

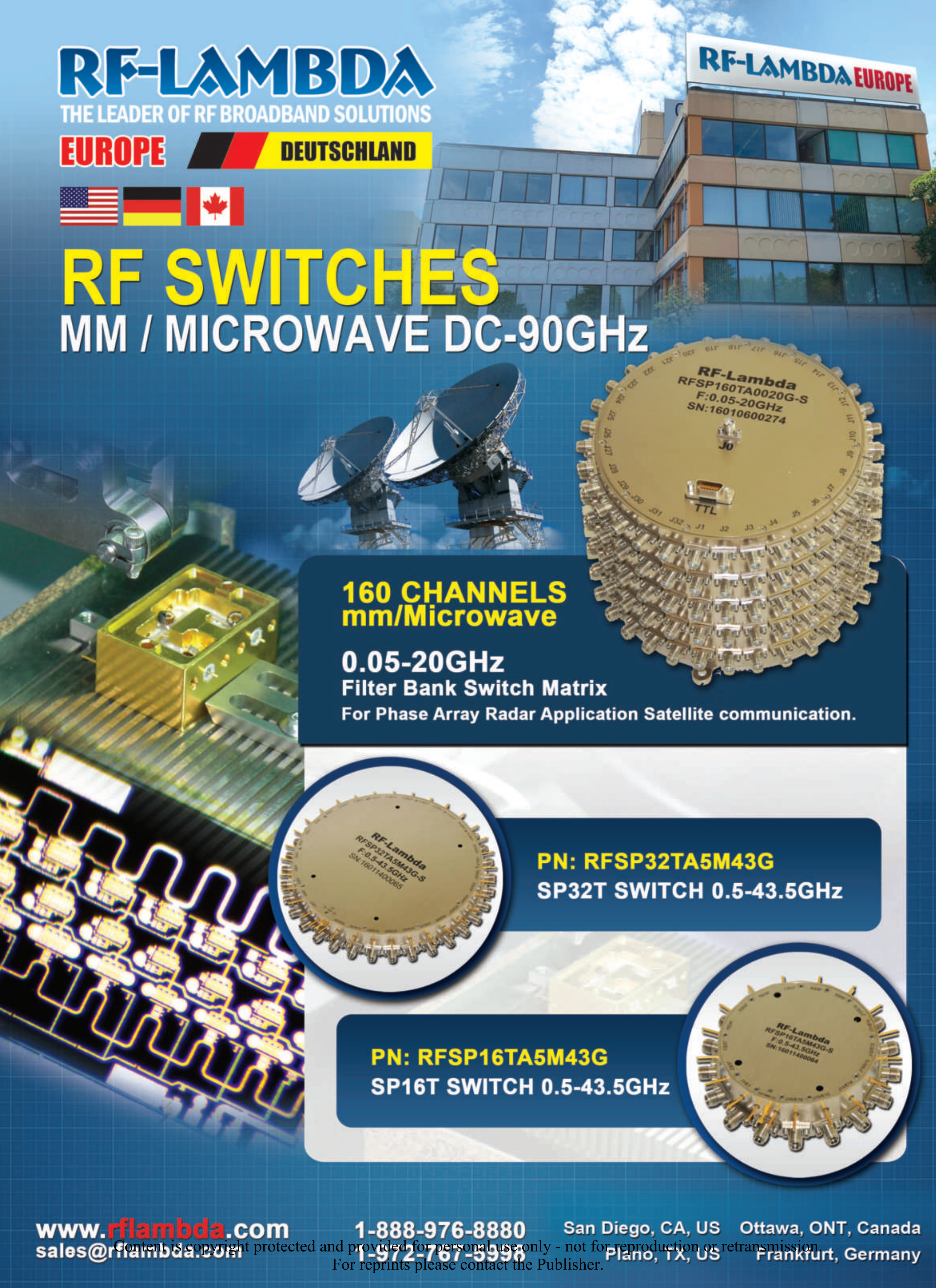
L3Harris Technologies has received a third low-rate initial production (LRIP) order valued at $95 million by the **U.S. Army** under the handheld, manpack and small form-fit (HMS) IDIQ contract to bring AN/PRC-158 multi-channel radios to the battlefield. This LRIP will be followed by an operational test that will inform a full rate production decision for the AN/PRC-158 and other HMS products. The IDIQ contract includes a five-year base and an additional five-year option with a ceiling of $12.7 billion. The Army expects to purchase approximately 65,000 HMS manpack radios under the IDIQ.

CACI International Inc. announced that it has been awarded a five-year task order, with a ceiling value of $63 million, to upgrade **U.S. Army** infrastructure across the U.S. Indo-Pacific Command, including providing continued enterprise support for the relocation of the Army's garrison at Yongsan, Seoul, South Korea, to Camp Humphreys.

Teledyne Brown Engineering Inc., a division of Teledyne Technologies Inc., was recently awarded a contract with a $40 million ceiling for production of automated radioxenon concentrator and spectrometer production units and spares for the **U.S. Air Force**. This sole source hybrid indefinite-delivery/indefinite quantity contract will provide multiple radioxenon sampler systems for nuclear test monitoring requirements of the U.S. Atomic Energy Detection System network for the verification of international treaties.

FLIR Systems Inc. announced it has won an additional $20.6 million contract from the **U.S. Army** to deliver its FLIR Black Hornet® 3 Personal Reconnaissance Systems. The advanced nano-unmanned aerial vehicles will support platoon- and small unit-level surveillance and reconnaissance capabilities as part of the Army's Soldier Borne Sensor (SBS) program. In January 2019, the U.S. Army awarded FLIR an initial $39.7 million contract for Black Hornet 3's to support the SBS program. The company is currently delivering those systems for fielding across the force.

Comtech Telecommunications Corp. announced that during its second quarter of fiscal 2020, its Santa Clara, Calif.-based subsidiary, Comtech Xicom Technology Inc., which is part of Comtech's Commercial Solutions segment, received a contract valued at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PEOPLE


▲ *William Nevius*

Anokiwave Inc. announced the appointment of **William "Bill" Nevius** as vice president and general manager of its Aerospace and Defense Portfolio. In this role, Nevius will lead the company's strategic defense accounts and build upon the long history of successful partnerships in the community to expand its reach into the market with enabling technology for SATCOM, RADAR, EW, COMMS and space applications. This appointment comes at a strategic time for Anokiwave with tremendous opportunities for growth in this market by leveraging the advances of mmWave commercial off the shelf Silicon commercial technologies into aerospace and defense systems.

REP APPOINTMENTS

RFMW announced a Global distribution agreement with **KCB Solutions** effective immediately. Under the agreement, RFMW will support KCB's product offering with a focus on their standard RF and microwave components portfolio including attenuators, switches and amplifiers.

Richardson RFPD, an Arrow Electronics company, announced that it has entered into a distribution agreement with **Cartesiam SAS**. Cartesiam is the market leader in artificial intelligence solutions for standard Cortex-M microcontrollers and has recently announced the availability of NanoEdge AI Studio, the first integrated development environment that enables rapid and easy creation of machine learning algorithms for Arm Cortex-M microcontrollers.

PLACES

Keysight Technologies Inc. has opened a new Regulatory Test Laboratory in Penang, Malaysia, to deliver accredited electromagnetic compatibility testing services for manufacturers of electronic devices and mission-critical industries across wireless communications, IoT, automotive, healthcare and medical applications. The Penang facility is the next world-class compliance and testing facility established by Keysight to offer expertise, knowledge, efficiency, capacity and exceptional customer service including calibration and testing services.


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INVITED PAPER

A Better Approach to Measuring GaN PA Linearity

Walt Strickler
Boonton Electronics, Parsippany, N.J.
Paulo Correa and George Bollendorf
Empower RF Systems, Inglewood, Calif.

GaN amplifier linearity is measured using three techniques: intermodulation distortion, noise power ratio and crest factor (CF). The CF method proves to be more relevant to actual operating conditions, while demonstrating the advantages of greater accuracy, simplicity and lower cost.

GaN devices continue to be key elements in many radar, electronic warfare, satellite and terrestrial communication systems. They offer several advantages.[1] For example, GaN has a high breakdown field due to a large bandgap that enables GaN devices to operate at higher voltages. Combined with a high saturation velocity and correspondingly large charge capability, GaN devices are ideal for high power applications. Add to this excellent thermal conductivity, and it is easy to see why applications for GaN devices continue to grow. In a recent study, Yole Développement expects the GaN industry to grow with a 23 percent compound annual growth rate between 2017 and 2023, driven by telecom and defense applications.[2]

Some of the most popular GaN devices are wideband RF power amplifiers (PA). Amplifiers are described by multiple characteristics including gain, frequency response or bandwidth, power output, linearity, efficiency and noise figure. Two key characteristics often used to describe the quality of an amplifier are linearity and efficiency. The relative importance of these two attributes depends on the application. For example, in a satellite-based system, efficiency may be more important, as limited power is available. In terrestrial wireless communications, the relative importance may be more balanced. Communication systems, such as those based on 5G standards, use wideband modulation with significant linearity requirements. In addition, because of the amount of base stations needed to support these systems, attention to power efficiency is required to manage operating expenses. Unfortunately, the output power levels to maintain amplifier linearity are often well below the levels needed for maximum efficiency.

MEASURING LINEARITY

This article focuses on the applications where amplifier linearity is the critical attribute. ***Figure 1*** illustrates typical amplifier behavior. Linearity is measured by increasing input power and observing output power until the amplifier enters compression. Often, amplifier linearity is specified as the input power level where the corresponding output power is 1 dB lower than the theoretical linear response, often designated as P_{1dB}. Historically, this has been considered the point where amplifiers operate most efficiently.

With the simultaneous need for linearity and efficiency, it is crucial to optimize the input back-off. Too much back-off sacrifices ef-


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ficiency and causes the amplifier to be oversized to reach the required output power and more expensive; too little causes increasing compression and signal degradation. Therefore, measuring amplifier linearity accurately under realistic operating conditions is important to GaN amplifier designers.

Of the ways to measure and express amplifier linearity, three common methods are: 1) intermodulation distortion (IMD), 2) noise power ratio (NPR) and 3) CF or peak-to-average power ratio. ***Table 1*** compares measurements made with the three approaches. Using a Noisecom noise source or a two-tone source, a signal is applied to the amplifier, with the input power starting at -25 dBm and increasing in 1 dB steps until reaching -15 dBm. Reductions in gain, CF, NPR and the difference between the intermodulation products and carrier signals all indicate an amplifier is nonlinear. All three measurements show that as the input power increases, the amplifier compresses the signal and operates nonlinearly; however, only the CF method clearly reveals the amount of compression. The three measurements show the amplifier starts compressing when the average input power is approximately -20 dBm. Although the gain begins reducing at around -20 dBm, even at -15 dBm, the gain is reduced by less than 1 dB. In contrast, the other linearity measurements show more significant compression of the peak power. For example, the CF decreases by more than 3 dB.

Compression measurements only using average power are not sufficient to identify significant impairments for signals with high CFs, such as the OFDM signals used in 5G and Wi-Fi communication. Comparing the three linearity measurements shows clear advantages to the CF approach:

- **Clearer indication of meaningful signal compression**—Conventional, average power compression measurements do not reflect the signal impairment occurring in wideband communication signals.
- **Lower cost**—The CF approach uses low-cost noise sources and wideband USB peak power sensors. Test systems using spectrum analyzers can cost multiples of the price of a USB sensor, and an analog signal generator adds expense.
- **Simpler, less error prone**—Spectrum analyzers can be complex to configure and the results may be difficult to interpret.
- **Higher accuracy**—The uncertainty of a power sensor measurement is usually in the tenths of a dB, while spectrum analyzers and signal generators are typically 1 to 2 dB.

Using the complementary cumulative distribution function (CCDF) of the CF adds the probability of occurrence to the measurement. CF measurements provide a single value based on a calculation from the highest single peak power value in a population of measurement samples. However, if this peak only occurs once out of a million samples, it may not present a problem during actual use. Quantifying the degree of peak impairment using CCDF can provide the value of CF that occurs with a specific probability—0.1 percent or one in 1,000 samples, for example—which is helpful when considering the effects of amplifier compression on bit-error-rate or error vector magnitude.

The following sections examine these three methods for measuring amplifier linearity.

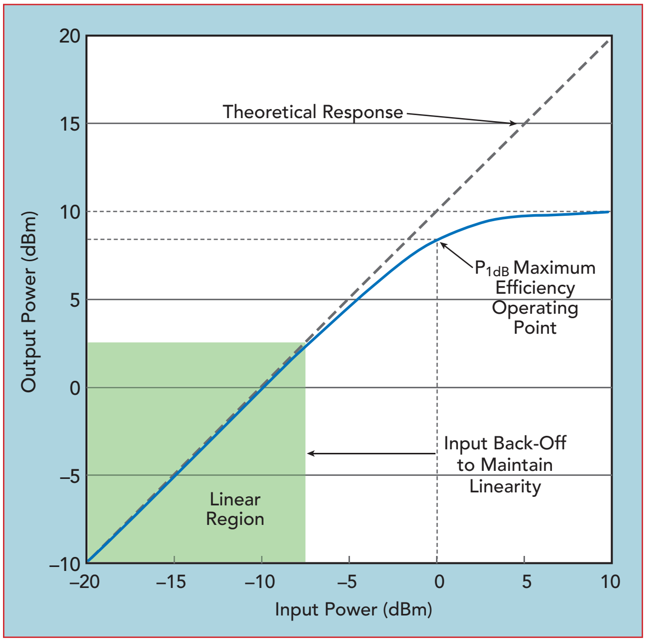

Fig. 1 Typical amplifier power transfer characteristic.

TABLE 1

COMPARISON OF LINEARITY MEASUREMENT METHODS

Average Input Power (dBm)	Average Output Power (dBm)	Gain (dB)	Peak Output Power (dBm)	Output Crest Factor (dB)	NPR (dB)	Third Order IMD (dBc)
–25	–19.7	5.3	–8.8	10.9	38.4	60
–24	–18.6	5.4	–7.8	10.8	39.3	58.5
–23	–17.8	5.2	–7	10.8	39.9	57.2
–22	–16.8	5.2	–6.5	10.3	40.1	55
–21	–15.8	5.2	–5.8	10	39.2	54
–20	–14.7	5.3	–5.3	9.4	36.2	53
–19	–14.1	4.9	–5.2	8.9	33.8	50
–18	–13	5	–4.9	8.1	29.8	47
–17	–12.1	4.9	–4.6	7.5	26.1	45
–16	–11.1	4.9	–4.3	6.8	22.9	42
–15	–10.4	4.6	–4.3	6.1	20.8	34

IMD or Third-Order Intercept

When an amplifier goes into compression, it becomes nonlinear and produces signal harmonics which can mix and generate intermodulation products. The second-, third- and higher-order harmonics are usually outside of the amplifier's

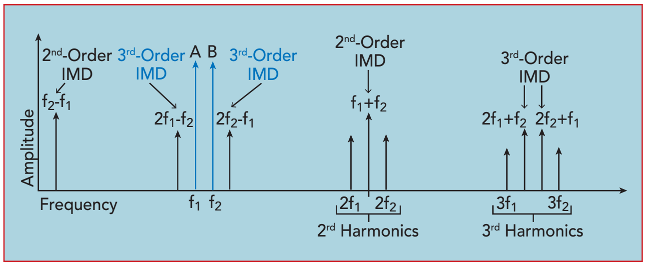

Fig. 2 IMD products for equal amplitude tones A and B.

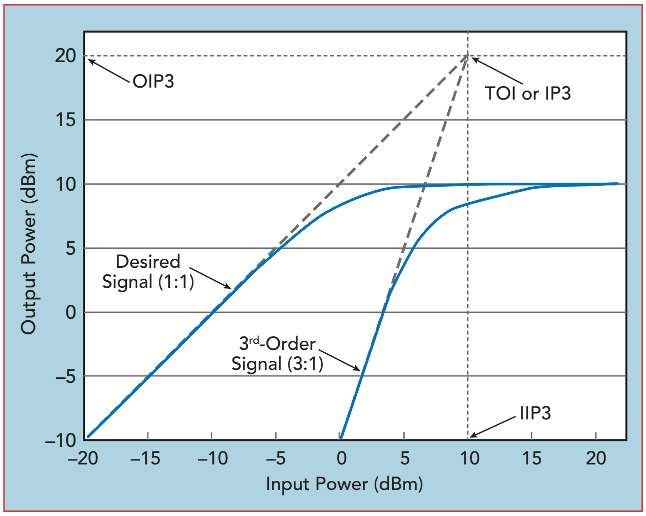

Fig. 3 Calculation of TOI point (OIP3).

bandwidth and are easy to filter. However, some of the intermodulation products are close to the intended signals and can cause IMD.

Figure 2 illustrates the intermodulation products generated from two equal amplitude tones, designated A and B. Because of their proximity to the intended signals, amplifier manufacturers are concerned with the amplitude of the third-order products and often specify a third-order intercept or IP3 value. To determine this value, the amplitude of the third-order products is plotted as shown in ***Figure 3***. The third-order products increase at a rate of 3× the desired signal, and the intersection of the theoretical extensions of the fundamental and third-order power levels is called the third-order intercept point, denoted as TOI or IP3. The higher the IP3 value, the better the linearity and the lower the IMD. To determine the TOI, a signal generator provides the two tones, and a spectrum analyzer or vector network analyzer (VNA) measures the desired signal and third-order products.

A disadvantage of this approach is the measurement uses only two tones, while, in practice, the signal provided to the amplifier often has significantly more tones. For example, an LTE-A signal with five component carriers has 6,000 effective subcarriers or tones; a 5G NR signal may have 3,300. Two CW tones do not represent the dynamic loading that an amplifier experiences in operation. The CF is only 3 dB for a two-tone signal, yet can approach 15 dB for a 5G signal; the power supply and thermal effects would be much different with just two tones versus a high count multi-tone or noise-like signal. Another consideration is the phase coherency between tones. If the relative phase among tones is random, the measurement may be different than with phase coherent tones. This is further complicated with LTE or 5G signals, where the physical layer is based on the orthogonality of the carriers.

NPR

Another measurement for quantifying amplifier linearity is NPR. Here, white noise is used to simulate a multi-tone carrier signal. An additive white Gaussian noise generator has a high CF and represents a wideband communication signal much better than a two-tone IMD stimulus. The noise is band-limited by a filter, to either the useful bandwidth of the amplifier or the bandwidth of the expected signal. The resulting signal is passed through a notch filter with a notch typically greater than 50 dB below the passband amplitude and a width of approximately 1 percent or less of the filtered noise bandwidth (see ***Figure 4a***).[3]

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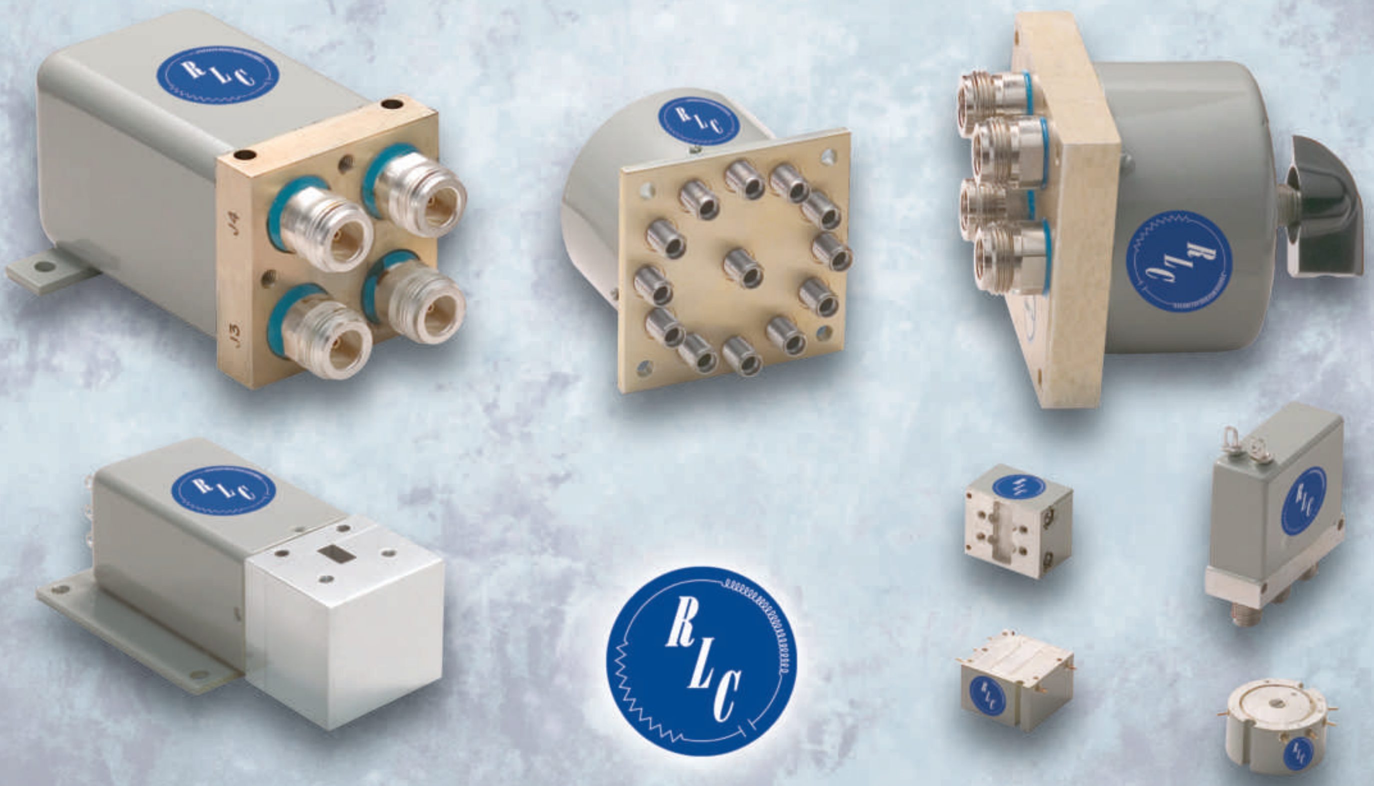

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This signal is applied to the input of the amplifier, and the amplitude is increased to the point of nonlinearly. As discussed above, in the nonlinear region, the multiple tones mix to create intermodulation products. Because the noise signal is equivalent to many tones, the individual IMD products cannot be measured easily. Instead the aggregate power of the IMD products at the notch frequency is measured; as the products increase, the effective depth of the notch decreases. ***Figure 4b*** shows the input signal to the amplifier has a notch depth of 38.4 dB, and the depth of the notch in the amplified signal decreased to 36.2 dB, indicating the amplifier is in compression. Like two-tone IMD testing, NPR is typically measured with a spectrum analyzer or VNA. An added expense is a high quality filter with sufficient notch depth to observe the IMD products of interest.

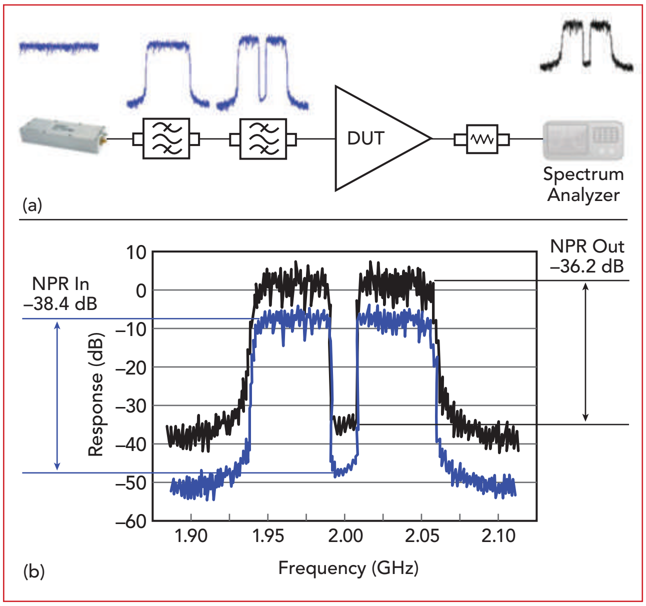

Fig. 4 **NPR test setup (a) and measurement (b).**

CF

The third approach for characterizing an amplifier's linearity is with a CF measurement. CF is the ratio of peak-to-average power. Like the NPR measurement, the amplifier input is band-limited noise to drive it with a signal approximating what an amplifier would see in actual use.

Using a directional coupler or signal splitter, the incident signal is measured with a wideband peak power sensor. The video bandwidth of the sensor, as well as the coupler or splitter, should be at least as wide as the bandwidth of the noise signal; otherwise, the measurement will be distorted (see ***Figure 5***). A second measurement is made at the output of the amplifier, including any attenuation needed to keep the signal in the measurement range of the sensor, and the CFs of the input and output signals are compared. If the output CF is less, the amplifier is compressing the signal's highest peaks. For the most accurate measurement, a third sensor can be used to determine if a portion of the input signal is reflected rather than amplified. By comparing the input and output average power, the amplifier's gain can be determined. ***Figure 6*** shows the test setup.

As previously noted, just monitoring gain changes with average power measurements does not give an accurate indication of amplifier linearity in operation. An average power gain reduction can be significantly smaller than the compression observed with a multi-tone signal.

BENEFITS OF CCDF

The CCDF can provide additional insight into amplifier performance. For each power level, the CCDF curve shows the amount of time the signal spends above the average power level. Equivalently, the CCDF curve displays the probability that the signal power will be

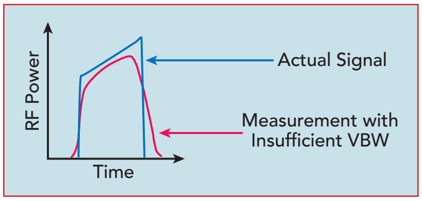

Fig. 5 **Incorrect peak power measurement from a sensor with insufficient bandwidth.**

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P3T-500M40G-60-T-55-292FF https://www.pmi-rf.com/product-details/p3t-500m40g-60-t-55-292ff	0.5 - 40	6	60	50 ns	+5 V @ 35 mA -5 V @ 15 mA	SP3T, Absorptive 1.0" x 1.0" x 0.5" 2.92mm (F)
P4T-100M50G-100-T-RD https://www.pmi-rf.com/product-details/p4t-100m50g-100-t-rd	0.1 - 50	5	100	50 ns	+5 V @ 154 mA -5 V @ 135 mA	SP4T, Absorptive 1.25" x 1.25" x 0.4" 2.4mm (F)
P5T-500M40G-60-T-55-292FF-5G40G https://www.pmi-rf.com/product-details/p5t-500m40g-60-t-55-292ff-5g40g	0.5 - 40	8	60	40 ns	+5 V @ 55 mA -5 V @ 45 mA	SP5T, Absorptive 1.25" x 1.25" x 0.4" 2.92mm (F)
P6T-2G18G-60-T-512-SFF-LV https://www.pmi-rf.com/product-details/p6t-2g18g-60-t-512-sff-lv	2 - 18	4	60	50 ns	+5 V @ 121 mA -12 V @ 33 mA	SP6T, Absorptive 1.5" x 2.0" x 0.4" SMA (F)
P7T-0R8G18G-60-T-SFF-SMC https://www.pmi-rf.com/product-details/p7t-0r8g18g-60-t-sff-smc	0.8 - 18	4.3	60	75 ns	+5 V @ 300 mA -5 V @ 100 mA	SP7T, Absorptive 1.5" x 1.5" x 0.7" SMA (F)
P8T-500M40G-50-T-55-292FF https://www.pmi-rf.com/product-details/p8t-500m40g-50-t-55-292ff-	0.5 - 40	10	50	50 ns	+5 V @ 300 mA -5V @ 50 mA	SP8T, Absorptive 4.0" x 1.5" x 0.4" 2.92mm (F)
P9T-500M40G-60-R-55-292FF-OPT1222 https://www.pmi-rf.com/product-details/p9t-500m40g-60-r-55-292ff-opt1222	0.5 - 40	6.5	60	100 ns	+5 V @ 450 mA -5 V @ 75 mA	SP9T, Reflective 4.5" x 1.5" x 0.4" 2.92mm (F)
P12T-0R5G18G-60-T-SFF https://www.pmi-rf.com/product-details/p12t-0r5g18g-60-t-sff	0.5 - 18	5	60	100 ns	+5 V @ 300 mA -5 V @ 100 mA	SP12T, Absorptive 6.0" x 2.0" x 0.4" SMA (F)
P16T-100M52G-100-T-DEC https://www.pmi-rf.com/product-details/p16t-100m52g-100-t-dec	0.1 - 52	18	100	100 ns	+5 V @ 1100 mA -12 V @ 720 mA	SP16T, Absorptive 8.0" x 3.0" x 0.67" 2.4mm (F)
P20T-7G18G-80-T-515-SFF-SP https://www.pmi-rf.com/product-details/p20t-7g18g-80-t-515-sff-sp	7 - 18	7.5	65	250 ns	+5 V @ 500 mA -15 V @ 200 mA	SP20T, Absorptive 4.0" x 4.0" x 0.63" SMA (F)
P32T-0R5G18G-60-T-SFF https://www.pmi-rf.com/product-details/p32t-0r5g18g-60-t-sff	0.5 - 18	9.5	60	100 ns	+5 V @ 1450 mA -5 V @ 200 mA	SP32T, Absorptive 8.0" x 3.5" x 1.0" SMA (F)


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P7T-0R8G18G-60-T-SFF-SMC


P8T-500M40G-50-T-55-292FF


P9T-500M40G-60-R-55-292FF-OPT1222


P12T-0R5G18G-60-T-SFF


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P20T-7G18G-80-T-515-SFF-SP

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above the average power. To illustrate, ***Figure 7*** shows the CCDFs for an amplifier with an average input power of -12.7 dBm, comparing the input (channel 1), output (channel 2) and ideal Gaussian signals. Approximately 0.01 percent of the time, the signal will have a CF of approximately 9 dB, and the input and output CFs match within 0.2 dB. When the input power is increased to -2.5 dBm, the CF at the output degrades significantly to 5.4 dB, indicating a substantial degree of compression (see ***Figure 8***).

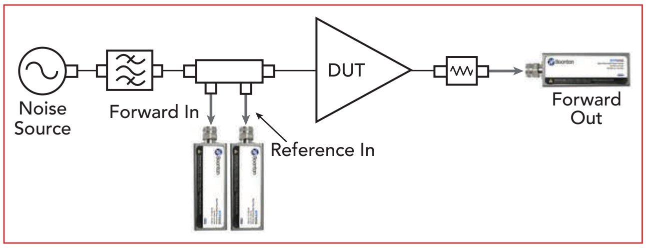

Fig. 6 **CF measurement setup.**

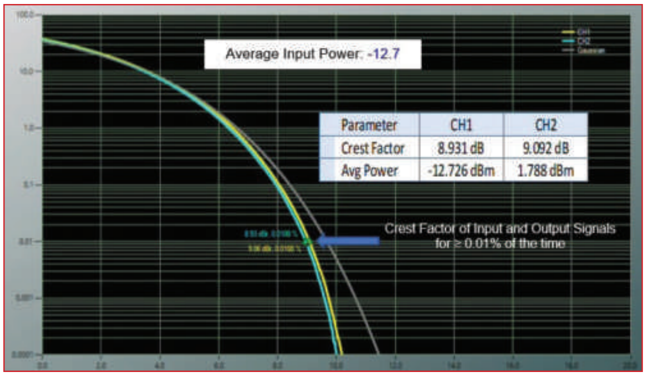

Fig. 7 **Amplifier CCDF for −12.7 dBm average input power.**

The additional information provided by using the CF and CCDF sheds light on the applicability of classes of amplifiers previously thought to be unacceptable for communications applications. For example, the Empower RF Systems model 2223 PA uses GaN on SiC in a class AB broadband amplifier. It has a wide frequency response from 500 MHz to 6 GHz, 53 dB gain and 150 W minimum output power. Its class AB design has very high efficiency, given its bandwidth, and is compact. This amplifier exemplifies a multi-mode amplifier, one capable of efficient "brute force" power and linear performance for communications or test applications. Traditional methods for measuring linearity will incorrectly characterize its linearity and suitability for transmitting digitally modulated waveforms.

Two linearity test methods were performed on the PA to determine P_{1dB}. The first used a CW signal, where the input power level was increased until 1 dB compression was measured and repeated at multiple frequencies across the band. The second method used CF for determining P_{1dB}, with a 64 QAM signal having a CF of 6.3 dB. To determine the 1 dB compression point using CF and CCDF, at each test frequency, the input power was increased until the measured output CF decreased 1 dB to 5.3 dB. ***Table 2*** compares the results of the two methods, showing the CW method gives a P_{1dB} compression point about 2 dB below the P_{1dB} measured with the CF method. The difference is because of transistor gain variation versus temperature. In most GaN HPAs, the gain per stage varies -0.012 dB/°C of junction temperature.

In a class AB amplifier, the transistor consumes more power as the output power increases, and as the junction temperature increases, transistor gain decreases. With a class A amplifier, one sees the opposite. For example, consider a class A amplifier with a CW input signal. When the output power is low, the transistor consumes the most power and junction temperatures are near maximum for the operating condition. As the output power increases, the junction temperature of the transistors reduces, resulting in gain expansion which extends the "apparent" compression point. However, when the same amplifier input is a modulated signal with a high CF, the device does not exhibit gain expansion since the transistor junction temperature correlates to the average power and remains high. This underscores the

best practice of stimulating an amplifier with a signal representing the actual signal it will see.

Examining the theory behind this phenomenon, the output power in a linear PA can be described by the equation:

$$P_{out}(\omega t) = \alpha + Gf(\omega t) \quad (1)$$

where f(ωt) is the input signal, α is a constant and G is the gain of the amplifier. For a GaN amplifier, G varies with temperature as described by:

$$\Delta G = -0.012\ dB/°C \times \text{Junction Thermal Resistance } (°C/W) \times \text{Dissipated Power } (W) \quad (2)$$

For a class AB amplifier, if the thermal resistance is 1°C/W and the power dissipation from small-signal to large-signal increases by 50 W, Equation 2 yields a gain reduction of 0.6 dB solely due to the increase in junction temperature. Conversely, when the same device operates in class A, the power dissipated decreases since a portion of the power goes into the load. Using the same gain equation, the resulting gain increases because the power dissipation is reduced. In both cases, this gain variation is not indicative of the true linearity of the PA, i.e., the linearity that changes the fidelity of the input signal. True linearity is assessed by measuring the compression of signal peaks relative to the average power.

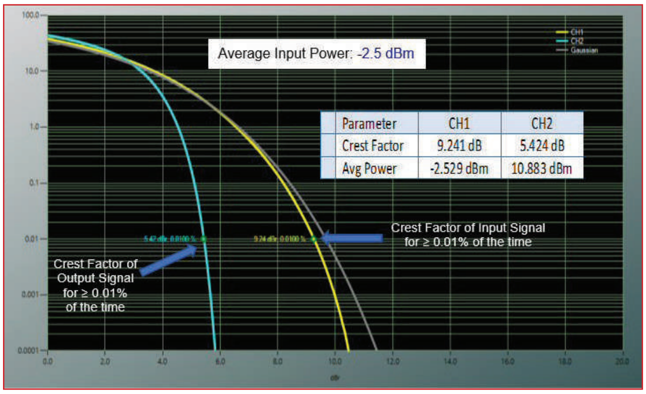

Fig. 8 Amplifier CCDF for −2.5 dBm average input power.

TABLE 2

CW vs. CF LINEARITY TEST METHODS FOR DETERMINING P_{1dB}

Frequency (MHz)	P_{1dB} CW (dBm)	P_{1dB} CF (dBm)
500	48.5	50.5
1000	49.0	51.6
1500	49.0	51.7
2000	47.9	51.8
2500	48.2	51.6
3000	46.5	49.1
3500	44.8	47.8
4000	46.0	47.2
4500	46.4	47.7
5000	47.0	48.4
5500	45.5	45.7
6000	45.8	45.1

CONCLUSION

Use of GaN technology will accelerate in the coming years, driven primarily by advances in commercial and military radar and the build-out of 5G networks. 5G has very demanding linearity requirements. Traditional tools for assessing amplifier linearity are no longer sufficient to predict real world performance. Compared to traditional tools, analyzing amplifier compression by measuring CF reduction combined with the statistical analysis offered by CCDFs provides a clearer and more accurate indication of signal compression. It is simpler, more accurate, less prone to errors and lower cost. This tool also provides insight into how amplifiers previously considered unsuitable for communications can be good alternatives to the amplifiers traditionally used.■

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INVITED PAPER

Editor's Note: In Part II, the authors look at a new way to reduce stiction effects in the Resistive MEMS switch (metal-to-metal contact) using an artificial engineered structure (metamaterial). As described in Part I (May issue), the combination of a primary shunt switch, DGS structures and secondary shunt switches, is shown to behave like a metamaterial. In addition to this design, metamaterial layers within the design of the switch contacts are proposed to reduce stiction issues in the MEMS switch. Part III of this series will be published in July.

A Microelectromechanical Switch with Metamaterial Contacts: Concepts and Technology Part II

Shiban K. Koul and Chaitanya Mahajan
C.A.R.E, Indian Institute of Technology, Delhi, India

Ajay K. Poddar and Ulrich L. Rohde
Synergy Microwave, N.J., U.S.

MEMS switches offer inexpensive, high performance solutions but reliability issues arising from stiction in MEMS switching devices can exclude the technology for high frequency applications.[1-9] In this article, a new MEMS Switch is reported using an artificial composite structure (or metamaterial) which can produce a repulsive Casimir force between metal and metamaterial structure realized by a high conductivity material.[2-5] This approach can resolve the stickiness problem, leading to new fabrication methods in next generation electro-mechanics linked to 5G and IoT applications.

CASIMIR EFFECT

The Casimir force originates from the interaction of surfaces with the surrounding electromagnetic spectrum and exhibits a dependence on the dielectric properties of the surfaces and the medium between the surfaces. Casimir forces between macroscopic surfaces have the same physical origin as atomic surface interactions and those between two atoms or molecules (van de Waals forces) because they originate from quantum fluctuations. In the case of two uncharged metal plates positioned closely to one another and in parallel, a force causing the two plates to move towards one another has been observed.[3] ***Figure 1*** shows the Casimir force 'F' on parallel plates kept in

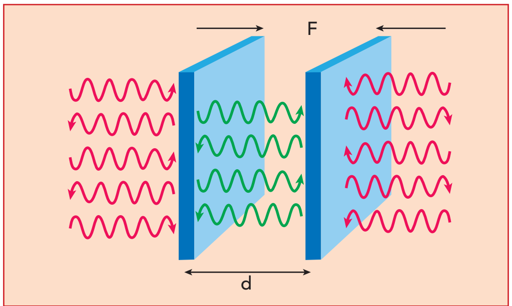


Fig. 1 Casimir force 'F' on parallel plate kept in vacuum.[3]

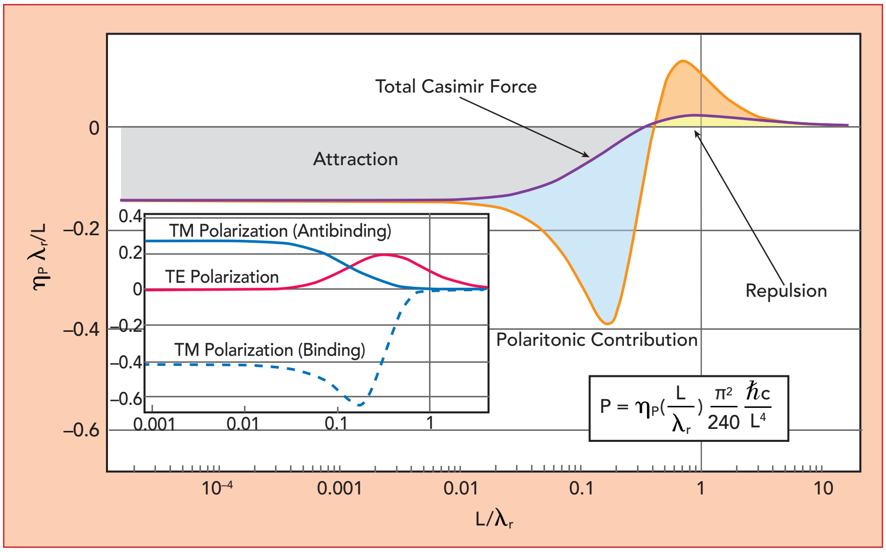


Fig. 2 Plots show the region of Casimir Force of attraction and repulsion.[4]

vacuum. The effective force is $F \propto A/d^4$, where A is the area of plate and d is the distance between the plates.[3]

The Casimir force is proportional to the effective permittivity of metal plates.[3,4] Therefore, by decreasing the effective permittivity on the metal planes, the Casimir force can be decreased. This can result in reduced forces preventing the plates from separating from one another, thus at least partially mitigating the stiction problem observed in MEMS switches.[2] ***Figure 2*** shows the polaritonic characteristics of the Casimir force of interaction that includes attraction and repulsion.[4]

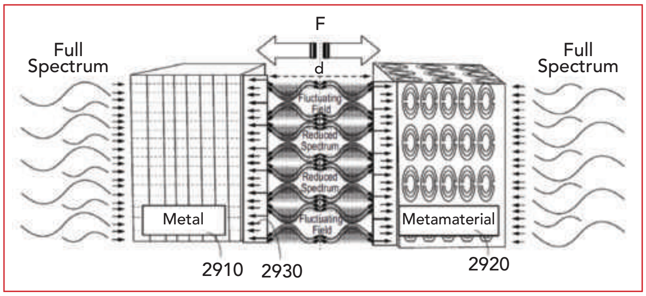


Fig. 3 Demonstration of the Casimir force in metamaterial structure.[2-5]

It is possible to reduce the likelihood of stiction by increasing the bias voltage applied to the switch as discussed in Part I of this article series (May issue). Alternatively, the electric field of the switch can be increased by distancing the top electrode from ground.[6] This can be accomplished, for example, by sandwiching the conductive layer (e.g., gold) between two dielectric layers (e.g., silicon oxynitride). Another alternative is to modify the beam to maximize its restoring force without having to increase the bias voltage. Increased restoring force is influenced by parameters such as increased plate size, shortened beam length or increased dielectric thickness. In addition to controlling the distance between the electrode and ground, and controlling the structural parameters of the switch contacts, it is also proposed in this article to weaken or reverse the forces applied to the switch contacts due to their proximity.

APPLICATION OF CASIMIR EFFECT IN MEMS SWITCHES

By reducing permittivity between plates, a repulsive force can be produced if the effective permittivity is sufficiently decreased, such as by engineered materials known as metamaterials.[7] Thus, generating a repulsive Casimir force can result in even less of a liability for the contacts to become "welded" together due to stiction. ***Figures 3*** and ***4*** illustrate the repulsive force, described as Casimir effect.[1-8] Figure 3 is a force diagram of an experimental setup, in which a plane of metal (2910) is positioned in parallel to a metama-

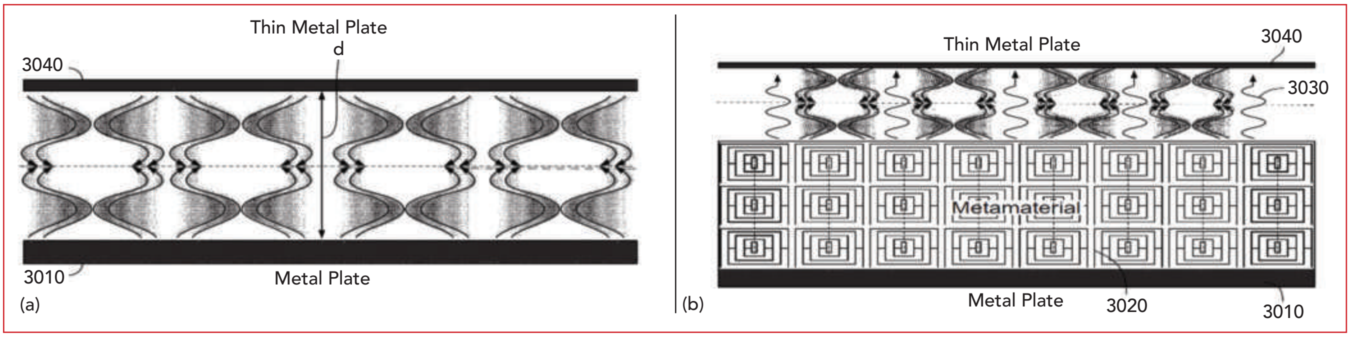


Fig. 4 Demonstration of the Casimir force in metal plates (a) and in metamaterial structure (b).[2,5]

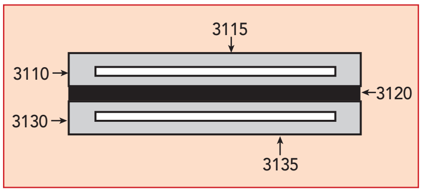


Fig. 5 Shows the metamaterial cell (three-layers composite structure): a first layer 3110 having permittivity $\varepsilon 1$, a second layer 3120 having permittivity $\varepsilon 2$ and a third layer 3130 having permittivity $\varepsilon 3$.[2]

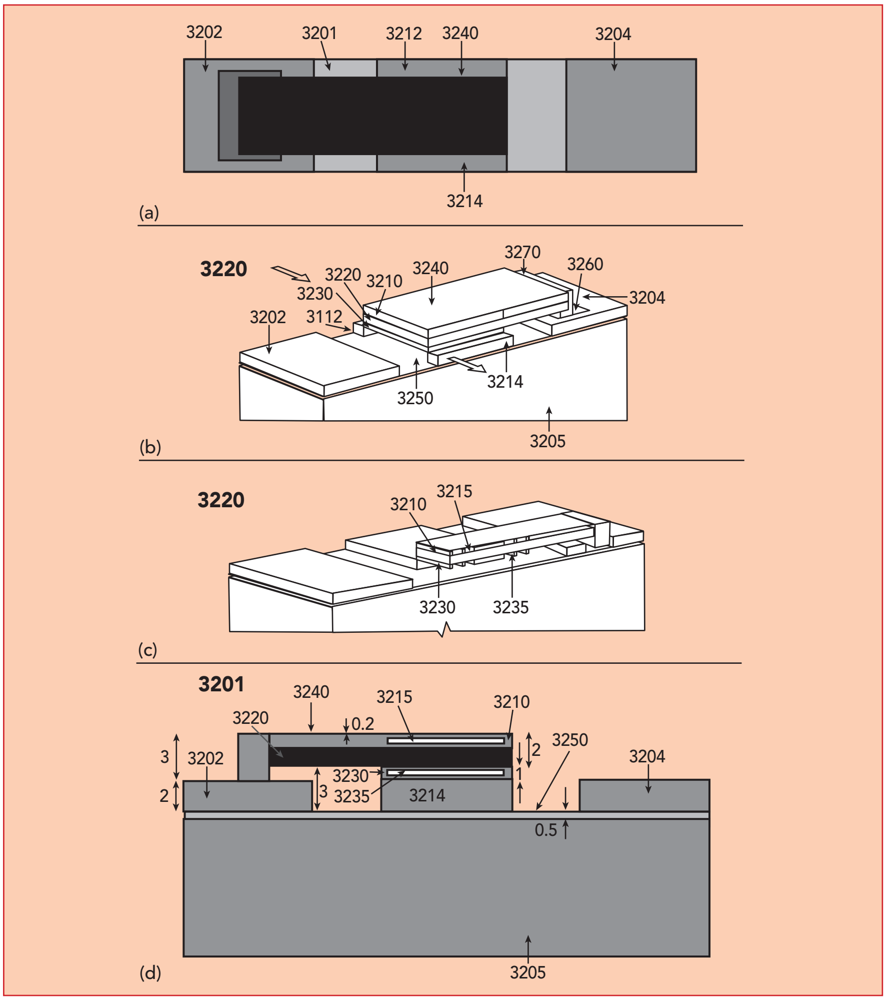
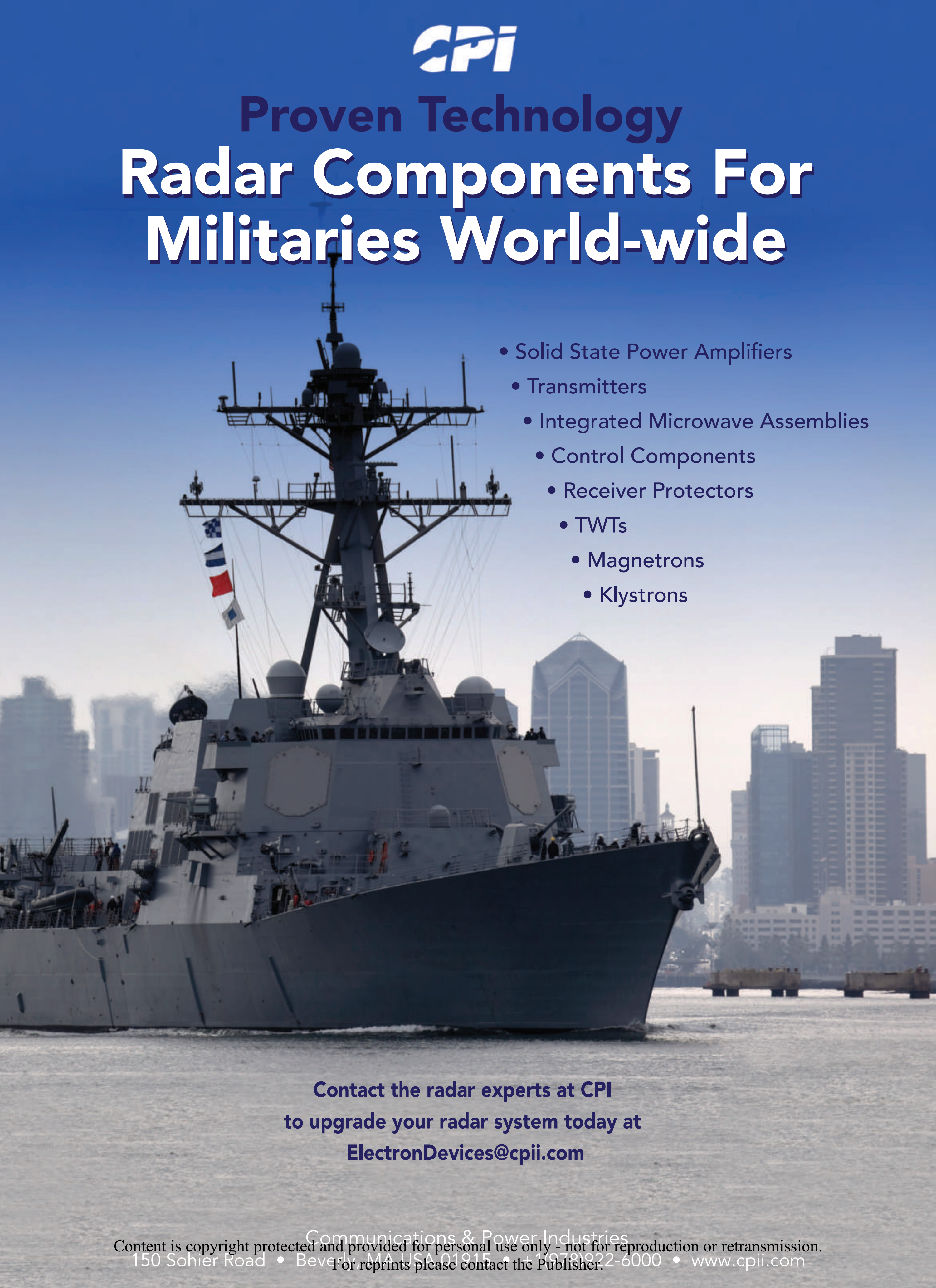


Fig. 6 An example MEMS switch incorporating metamaterial cells in order to provide a repulsive Casimir force between contacts of switch: (a) top-down view of the switch, (b) perspective view of the switch, (c) bisected cross-sectional perspective view of the switch and (d) side view of the switch in a closed position.

terial (2920). The metal and metamaterial are positioned apart from one another at a distance "d." The forces illustrated in the setup in Figure 3 are shown using arrows (2930). A force applied to the metal and metamaterial bring the two planes closer to one another. However, application of this force has been observed under the specific conditions of the experimental setup illustrated in Figure 4 to result in a second and opposite force "F" that causes the two planes to separate from one another. Figure 4 shows a typical example of a levitating mirror.[5] The repulsive Casimir force of the metamaterial may balance the weight of one of the mirrors, letting it levitate on the zero-point fluctuation.

Figure 4a shows a first metal plate (3010) or mirror separated from a second metal plate (3040) or mirror by a distance "d." The two metal plates may be thought of as opposing contacts in a MEMS switch, and may be liable to become permanently stuck to one another at distances "d" that are sufficiently small. By contrast, Figure 4b shows a thin layer of metamaterial (3020) affixed to a surface of the first metal plate (3010) and positioned in between the metal plates (3010, 3040). A Casimir force (3030) is produced at the boundary between the metamaterial (3020) and the second metal plate (3040), thereby causing the second metal plate to further separate from the first metal plate by a distance "d." This additional separation may even counteract gravitational forces, and thus cause the second metal plate to levitate. As an example, the metamaterial could be made by split ring structure using gold foil.[4-7]

In the application of a MEMS switch structure, the switch may include a deflectable beam having a shorting bar positioned on a surface of the beam and aligned with the contact of the signal line. The shorting bar may be made of metal, such as a thin layer of gold foil. When the shorting bar touches the signal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line, the metal-to-metal contact surfaces may stick to one another in the form of strong adhesion. This adhesion causes undesirable stiction problems, which in turn may cause the switch to be electrically shorted, and it may take a considerable amount of force to separate the shorting bar from the signal line. The MEMS switch generally relies on stresses accumulating in the beam as a result of the beam's deflection in order to counteract the adhesive forces and to return the beam back to its at-rest or equilibrium position. This counteractive force, which is the sum of the stresses in the beam, is referred to as the restoring force that "restores" the beam to its at-rest position. However, this force is not always enough to counteract adhesive forces between the metal contacts. By providing a metamaterial structure between the metal contacts, the restoring force of the beam can be supplemented using the repulsive Casimir force generated when the shorting bar touches or comes within proximity to the signal line.

The Casimir force can be controlled by providing a permittivity gradient in the contact of the deflectable beam. The permittivity gradient can be provided by interfacing three layers of media in either decreasing or increasing order of permittivity. In ***Figure 5***, three layers of media are provided: a first layer (3110) having permittivity ε_1, a second layer (3120) having permittivity ε_2 and a third layer (3130) having permittivity ε_3. The first and third layers may be metal layers, and the second layer may be a dielectric layer. The layers may be interfaced such that either $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$ or $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$. This may be possible by providing one metal layer with positive permittivity and another metal layer with negative permittivity. For instance, the first layer may be made of gold and have an infinite permittivity, the second layer may be made of a dielectric (e.g., silicon mononitrate-SiN) having small but positive permittivity (e.g., 7) and the third layer may include a metamaterial unit cell (3135) and may have a zero or even negative permittivity. In other examples, the first layer can also include a metamaterial unit cell (3115) in order to acquire the desired permittivity.

EXAMPLE REPULSIVE CASIMIR FORCE INSPIRED RESISTIVE CONTACT MEMS SWITCH

Figure 6 shows an example MEMS switch incorporating metamaterial cells to provide a repulsive Casimir force between contacts of the switch. This metamaterial inspired MEMS switch is formed in a coplanar waveguide (3201) having two ground planes (3202 and 3204) formed above a substrate (3205). The ground planes are separated by a channel and a signal line (3210) that is formed lengthwise in the channel. The signal line includes an input port (3212) through which a signal is received (arrow in) and an output port through which the signal is transmitted (arrow out).

This MEMS switch includes a cantilevered beam that moves in and out of the plane of the coplanar waveguide in order to move in and out of contact with the signal line. The beam includes multiple layers. In Figure 6, from top to bottom, the layers include: a top layer (3420) of dielectric material, a first metal layer (3210), a dielectric layer (3220) and a second metal layer (3230). Each of the first and second metal layers may include a metamaterial device (3215 and 3235) encased within, as shown in the cross-sectional view of Figure 6c.

The top layer (3210) and first mater layer (3220) may be adapted to extend across the entire length of the beam, whereas the length of the sandwiched dielectric layer (3220) and second metal layer (3230) may be limited to the area above the signal line. Alternatively, the dielectric layer may extend the entire length of the beam while only the second metal layer may be limited to the area above the signal line (3210). The ground planes (3202 and 3204) and signal line ports (3212 and 3214) may be separated from the substrate (3205) by a thin layer of dielectric (3250), such as SiN or SiO_2.

Operation of the switch may be controlled by moving an anchor (3270) to which the beam is attached in and out of the plane of the coplanar waveguide (3201). In this case, the ground line (3202) may include a hole (3260) though which a post or anchor (3270) of the beam is positioned. Moving the post up and down can result in the contacts of the switch separating or contacting one another, respectively. Figure 6d shows the switch closed, with the contacts contacting one another.

In the example of Figure 6, the section of the coplanar waveguide shown may be about 100 μm, and the beam may have a width of about 75 μm. The anchor to which the beam is attached may have a length (in the direction of the beam length) of about 11.25 μm and a width of about 75 μm. The opening into which the beam is anchored may have a greater length and width, such as about 80 × 30 μm. The overall length of the waveguide (in the direction of the beam length) may be about 330 μm, whereby the ground planes and the signal lines may each have a width (also in the direction of the beam length) of about 75 μm, with 38 μm channels in between. The beam may have a length of about 140 μm (not including the length of the anchor).

The overall height of the beam when in the closed position may be about 5 μm, relative to the dielectric surface on which the ground planes and signal line are formed. Each of the ground planes and signal line may be 2 μm thick. The beam may then contribute an additional 3 μm to the height of the switch, whereby each of the metal layers (3210 and 3230) is about 1 μm thick and the dielectric layer sandwiched in between may also be about 1 μm. The top layer (3440) may add about 0.2 μm to the height of the switch. The metamaterial unit cells made of split rings[2-7] included in the second

metal layer (3230) and optionally in the first metal layer (3210).

Figure 7 illustrates an example, the metal layer (3310) with a first split ring (3322) having width L, and a second split ring (3324), formed in the layer (forming the rings may involve cutting out the rings from the layer). Each of the rings may be concentric and aligned so that the splits (3330) in the respective rings are positioned on opposing sides of the layer (3310). Each of the rings may have a uniform width W, and the splits may have a uniform width G. The rings may further be separated from one another by a uniform separation (3332) having width S. Different engineered structures may provide different metamaterial unit cells that can exhibit characteristics at the relevant band of frequencies for MEMS switch.[1-2]

Figures 8-10 show test results for transmission and reflection characteristics for a respective unit cell structure. The metamaterial cell shown in Figure 8 is included in a metal layer having a width equal to the width of the beam (3402). In this example, the unit cell is of transmission type at low frequencies, at about 300 GHz and again at about 470 GHz. The unit cell is of reflection type, with attenuation of the transmission exceeding that of the reflection, at about 150 GHz and again at about 300 GHz. Thus, the composite structure of Figure 8 is shown to exhibit metamaterial properties.

The composite structure (3501) shown in Figure 9 is

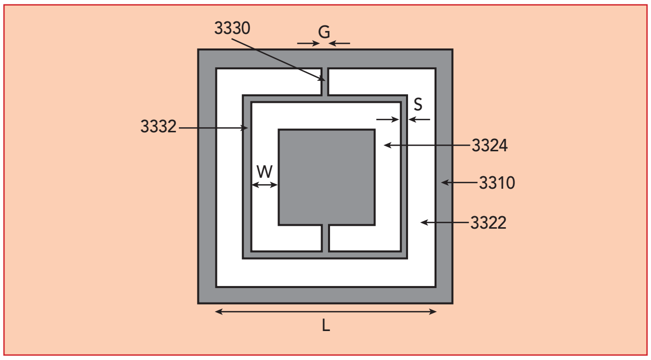

Fig. 7 The split ring configuration.

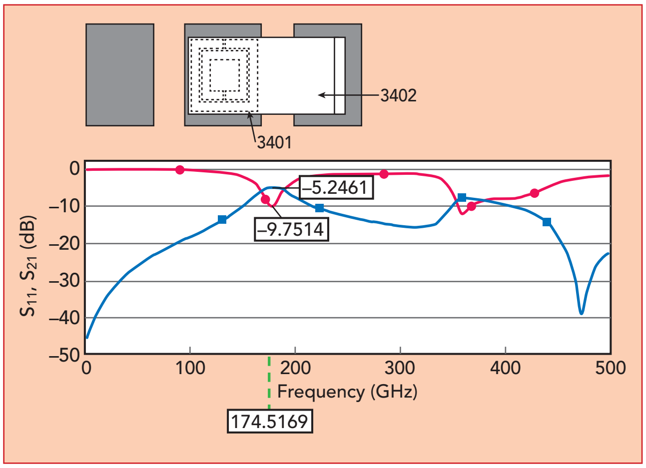

Fig. 8 The transmission and reflection characteristics of composite structure example #1.

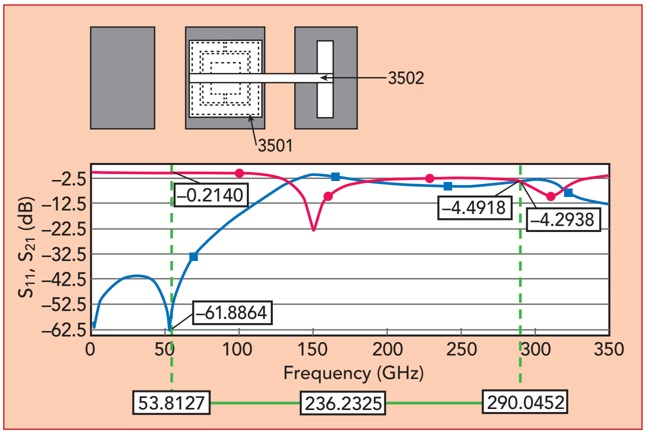

Fig. 9 The transmission and reflection characteristics of composite structure example #2.

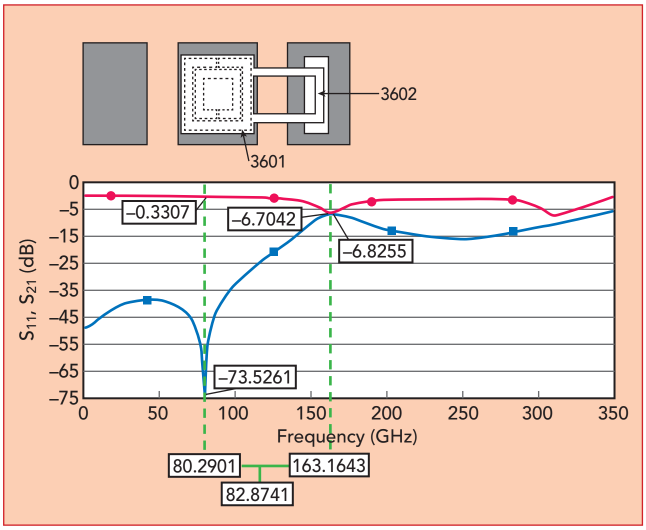

Fig. 10 The transmission and reflection characteristics of composite structure example #3.

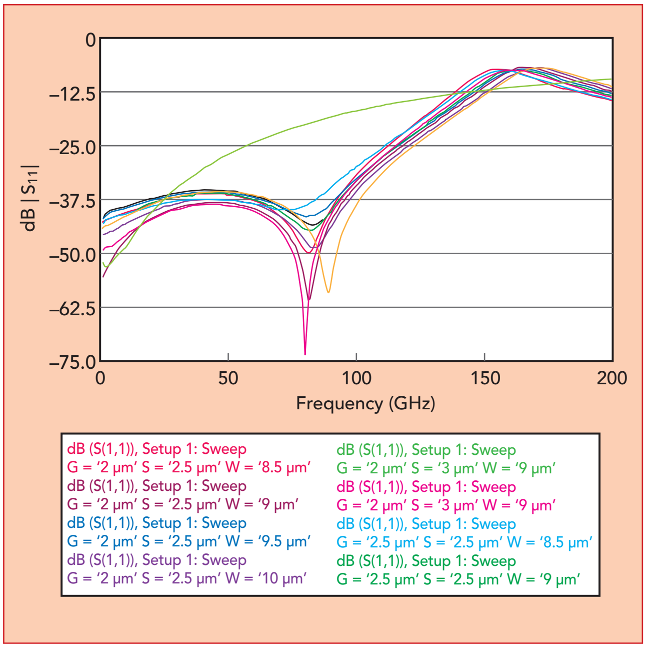

Fig. 11 Shows plots of reflection characteristics for a metamaterial cell with varying parameters G, S and W, given in Figure 7.

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Duty (%)	10
Dimension (mm)	250x150x28

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Eff (%)	40(typ)
Duty (%)	10
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included in a metal layer having a length equal to the width of the signal line, and further attached to a beam (3502) having a width much smaller than the width of the metal layer. In this example, the unit cell is shown to have transmission properties at about 54 GHz and reflection properties at about 150 GHz. Therefore, the composite structure of Figure 9 is also shown to exhibit metamaterial properties.

The composite structure (3601) of Figure 10 is included in a metal layer having a length equal to the width of the signal line, and further attached to a U-shaped beam (3602) having two branches each having width much smaller than the width of the metal layer. In this example, the unit cell is shown to have transmission properties at about 80 GHz and reflection properties at

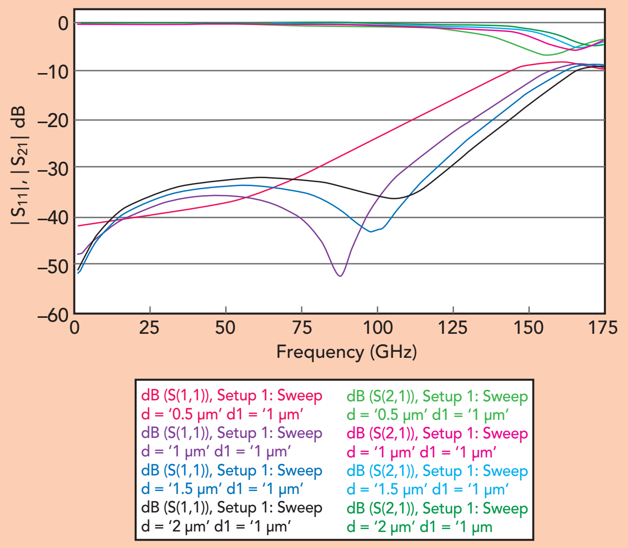

Fig. 12 **Shows plots of transmission and reflection characteristics of a switch for which the thickness of the second metal layer "d" (e.g., 3230 of Figure 6 varies between 0.5 µm through 2 µm).**

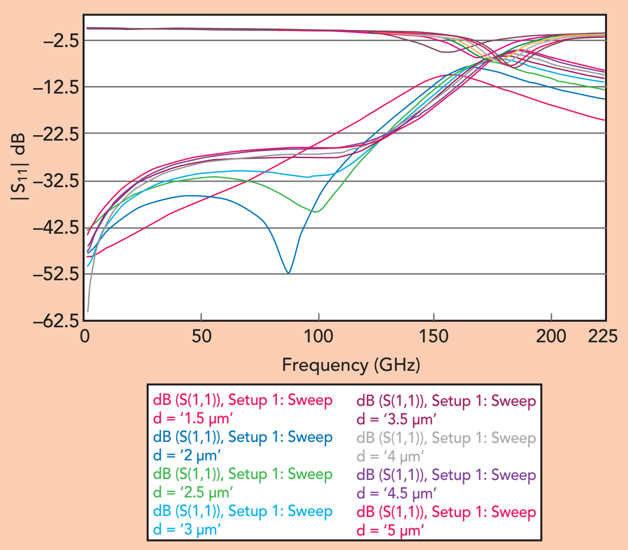

Fig. 13 **Shows plots of transmission and reflection characteristics of a switch for which the thickness of the second metal layer "d" (e.g., 3230 of Figure 6 varies between 1.5 µm through 5 µm).**

about 163 GHz. Therefore, the structure of Figure 10 is also shown to exhibit metamaterial properties, and these properties can be exhibited over a relatively narrow bandwidth of about 80 GHz.

Additionally, the parameters of the metamaterial cell structures can be varied to produce different transmission and reflection characteristics. For example, ***Figure 11*** provides a graph plotting reflection characteristic for a metamaterial cell having different parameters G, S and W (as defined in Figure 7). In Figure 11, it can be seen that the frequency at which reflection is most greatly attenuated, varied from about 80 to 90 GHz depending on G, S and W. For instance, where G is 2 µm, S is 3 µm and W is 9 µm, insertion loss drops to about 74 dB at 80 GHz. By comparison, other parameters of G, S and W yield a reflection of about -60 dB at about 90 GHz.

In addition to the use of variation of composite structure for the realization of metamaterial cell and cell structure parameters, the metal layers of the MEMS switch may also be formed with different parameters and dimensions as compared to those parameters and dimensions.

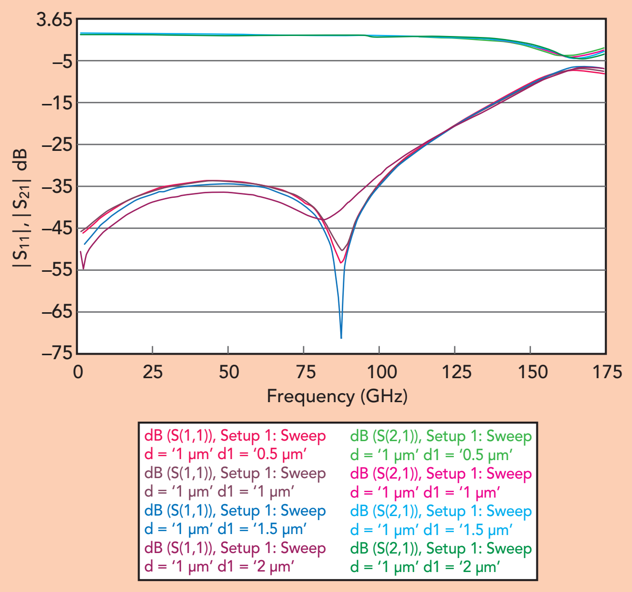

Fig. 14 **Shows the plot of transmission and reflection properties of a switch for which the thickness of the first metal layer "d1" (e.g., 3210 of Figs. 6 varies between 0.5 µm through 2 µm).**

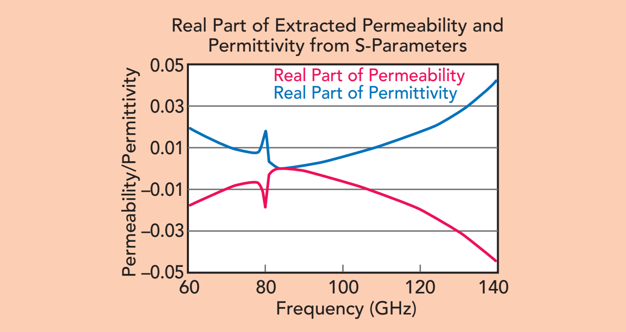

Fig. 15 **Shows the plot of permittivity extracted from the S-parameters of the composite structure in Figure 6.**

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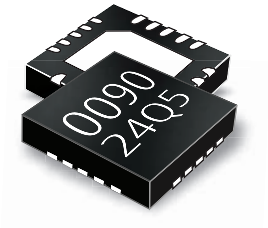

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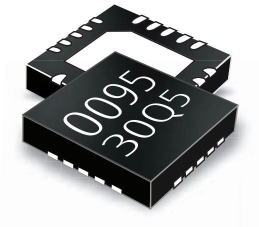

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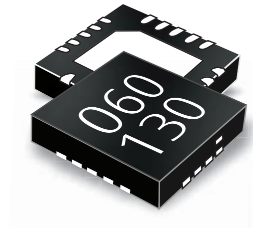

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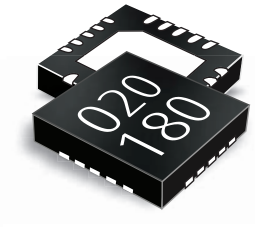

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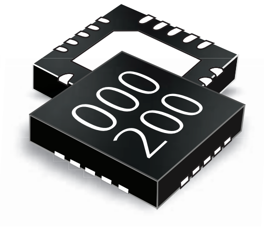

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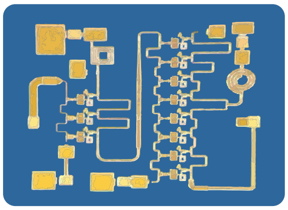

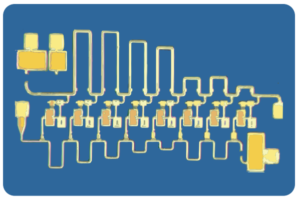

GaAs MMIC PAs

Model	Freq(GHz)	Gain(dB)	P1dB(dBm)	Psat(dBm)	Eff(%)	Vd(V)
AM003536WM-XX-R	0.01-3.5	23	35	36	20	20
AM002535MM-XX-R	0.03-2.5	24	34	35	25	20
AM012535MM-XX-R	0.03-2.5	20	33	33.5	20	20
AM009023WM-XX-R	0.05-9	21	21	23	20	12
AM008030WM-XX-R	0.05-10	18	30	31	20	12
AM012020WM-XX-R	0.1-2	30	16	17	8	8
AM011037WM-XX-R	0.2-1.0	31	37	37.5	40	8
AM103026MM-XX-R	0.9-3.2	22	25	26	10	14
AM132740MM-XX-R	1.3-2.7	26	38	39	30	14
AM142540MM-XX-R	1.4-1.8	25	39	40	35	14
AM153040WM-XX-R	1.4-3.4	18	37	38	30	12
AM143440WM-XX-R	1.5-1.8	20.5	38.5	39	35	12
AM143438WM-XX-R	1.5-1.8	20.5	37.5	38	30	12
AM153540WM-XX-R	1.5-3.5	18	39	39.5	35	14
AM183030WM-XX-R	1.6-3.3	30.5	30.5	31.5	20	8
AM183031WM-XX-R	1.6-3.3	31.5	31.5	32.5	25	8

GaN MMIC PAs

Model	Freq(GHz)	Gain(db)	Psat(dBm)	Eff(%)	Vd(V)
AM00010037WN-00-R	DC-10	13	37	25	28
AM00010037WN-SN-R	DC-10	13	37	23	28
AM003042WN-00-R	0.05-3	24	42	35	40
AM003042WN-XX-R	0.05-3	23	42	33	40
AM206041WN-00-R	1.8-6.5	32	42	27	28
AM206041WN-SN-R	1.8-6.5	30	41	23	28
AM408041WN-00-R	3.75-8.25	33	42	27	28
AM408041WN-SN-R	3.75-8.25	31	41	23	28
AM07512041WN-00-R	7.75-12.25	28	42	27	28
AM07512041WN-SN-R	7.75-12.25	27	41	22	28
AM08012041WN-00-R	7.5-12	22	42	20	28
AM08012041WN-SN-R	7.5-12	21	41	20	28

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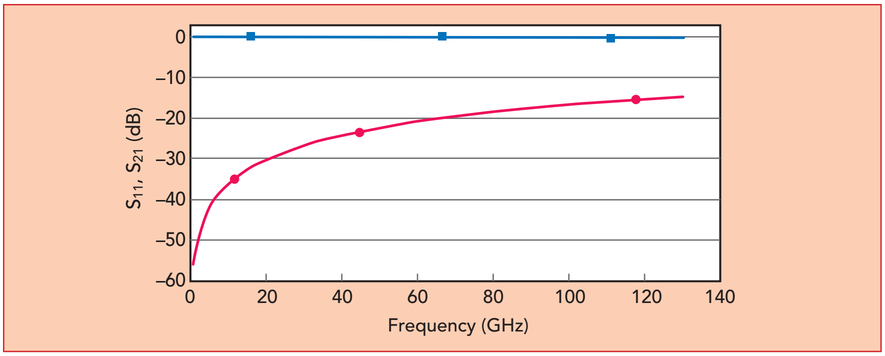
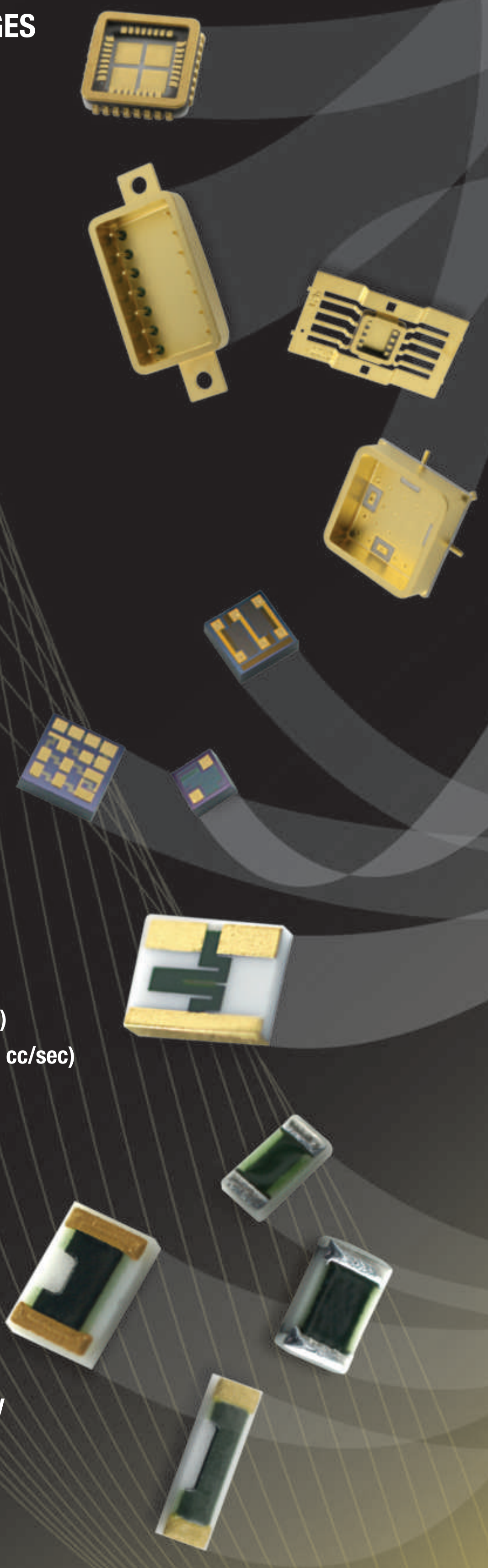


Fig. 16 Response of the MEMS switch.

Figure 12 is a plot of both transmission and reflection properties of a switch where the thickness of the second metal layer "d" (e.g., 3230 of Figure 6) varies between 0.5 μm and 2 μm. ***Figure 13*** is a plot of transmission and reflection properties of a switch where the thickness of the sandwiched dielectric layer (e.g., 3220 of Fig. 6) varies between 1.5 μm and 5 μm. ***Figure 14*** is a plot of transmission and reflection properties of a switch where the thickness of the first metal layer "d1" (e.g., 3210 of Fig. 6) varies between 0.5 μm and 2 μm. The transmission properties of the various MEMS switches are largely similar in each of these conditions, although the frequency at which the transmission attenuates varies between about 160 and 180 GHz, and the reflection properties of the switch vary mainly between 60 and 150 GHz.

Using the transmission and reflection data, permeability and permittivity of the metamaterial cells can be extracted using parameter extraction procedures.[6] The parameter extraction is shown in ***Figure 15***. The composite structure exhibits near zero permittivity and permeability at a band of frequencies centered around 85 GHz. Therefore, these structures would produce a repulsive Casimir force around the band of frequencies ranging from about 60 to 130 GHz.

Figures 16 and ***17*** further demonstrate the overall response of the MEMS switch in each of its ON and OFF states, respectively. In Figure 16, when the switch is OFF, and thus not passing the transmitted signal between input and output ports, the reflection characteristics are shown to be just slightly less than 0 dB even at frequencies of up to 130 GHz, the transmission characteristics are between about -20 dB and -15 dB between operating frequencies of about 60 to 130 GHz. In Figure 17, when the switch is ON, and thus passing the transmitted signal between input and output ports, the reflection characteristics are as low as about -73.5 dB at 80 GHz with the transmission characteristics as high as -0.33 dB while the reflection and transmission characteristics at 163 GHz are both about -6.75 dB.



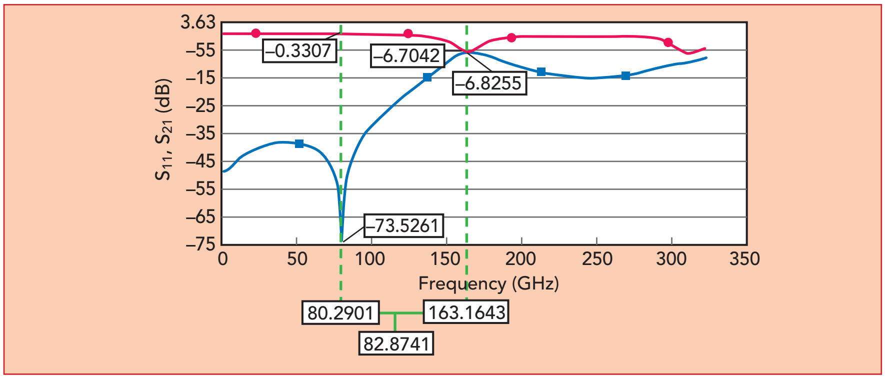


Fig. 17 Response of the MEMS switch.

The examples of Figures 6 through 17 demonstrate the possibility of incorporating metamaterial structures into a high frequency resistive MEMS switch in order to reduce the effects of stiction.[1-2]

CONCLUSION

In this article (Part II), the principle of repulsive Casimir force is applied to improve stiction of the resistive contact MEMS switch. This approach can be similarly applied to capacitive contact MEMS switches. As with the resistive switch, a sandwich of metal and dielectric layers used to achieve the desired permittivity interface, such as having a gold layer with infinite permittivity, a dielectric layer with positive but low permittivity and a metamaterial layer with a permittivity in the range of about zero or less. Unlike the example switches here, in the capacitive switch, the metamaterial layer can be used as part of the signal line contact instead of as part of the beam contact and will be covered in Part III (coming in the July issue).■

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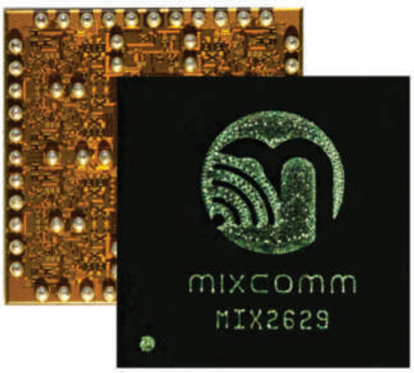


Eight-Channel Front-End RFIC Claims New Record for 28 GHz Power, Efficiency and Integration

MixComm, Inc.
Chatham, N.J.

mmWave 5G networks have great potential and are needed to provide capacity beyond the existing LTE and sub-6 GHz networks. The substantial investments made by carriers to license the mmWave spectrum in recent auctions is evidence of this need and carriers' intentions. However, the effective use of this spectrum is not straightforward. At these frequencies, obstacles in the signal path—trees, rainfall and even a user's hand—can cause significant attenuation. In addition, initial mmWave deployments have underdelivered due to insufficient output power, resulting in limited range and high thermal budgets, reducing reliability and increasing system costs.

RF-SOI based mmWave phased array systems can help address these challenges, especially compared to existing complementary metal-oxide semiconductor (CMOS) or SiGe solutions. RF-SOI process technology has three key advantages:

1. Transistors, substrate and the back-end provide improved RF performance.
2. SOI's n-FET has lower parasitics than

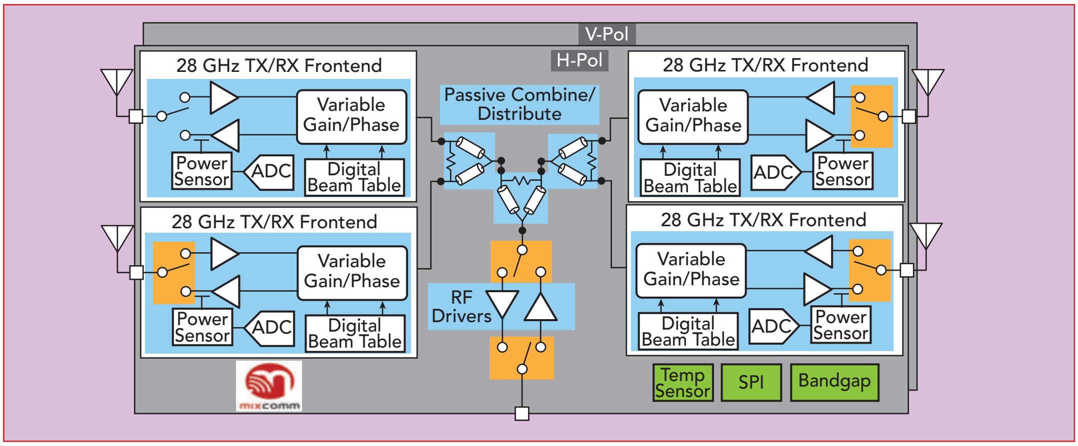
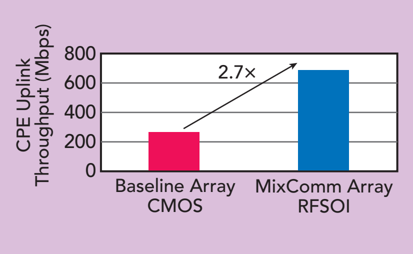


Fig. 1 MixComm SUMMIT 2629 block diagram.



▲ Fig. 2 Median CPE uplink throughput for a baseline bulk CMOS CPE array vs. a MixComm CPE array fabricated with GlobalFoundries' 45 nm RF-SOI.

bulk CMOS, enabling higher performance: GlobalFoundries' 45RFSOI achieves approximately 40 percent higher f_{max} than bulk CMOS.

3. Stacked RF-SOI transistors enable 10x higher output power and 2× to 5× higher efficiency.

In March, MixComm announced its first production IC, the SUMMIT 2629™, an eight-channel RF front-end for 28 GHz, 5G phased array antenna systems fabricated in RF-SOI. The SUMMIT 2629 was designed to address the challenges constraining 5G mmWave performance by:

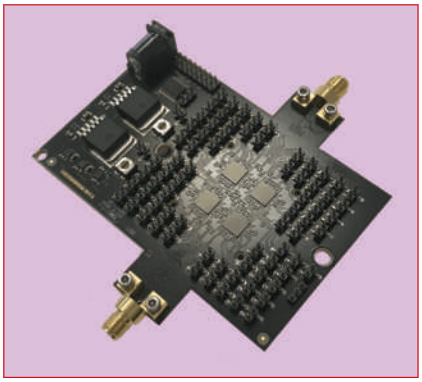
- Extending the link range to decrease infrastructure costs and improve customer satisfaction.
- Reducing power consumption and thermal dissipation.
- Reducing antenna array complexity and overall RF front-end cost.

Operating from 26.5 to 29.5 GHz, the SUMMIT 2629 RFIC integrates power amplifiers (PA), low noise amplifiers, T/R switching, beamformers with beam table memory, calibration, gain control and temperature and power telemetry with a high speed system peripheral interface (SPI) for control. A single SUMMIT 2629 provides two sets of four channels for two antenna polarizations—a total of eight channels per RFIC (see ***Figure 1***).

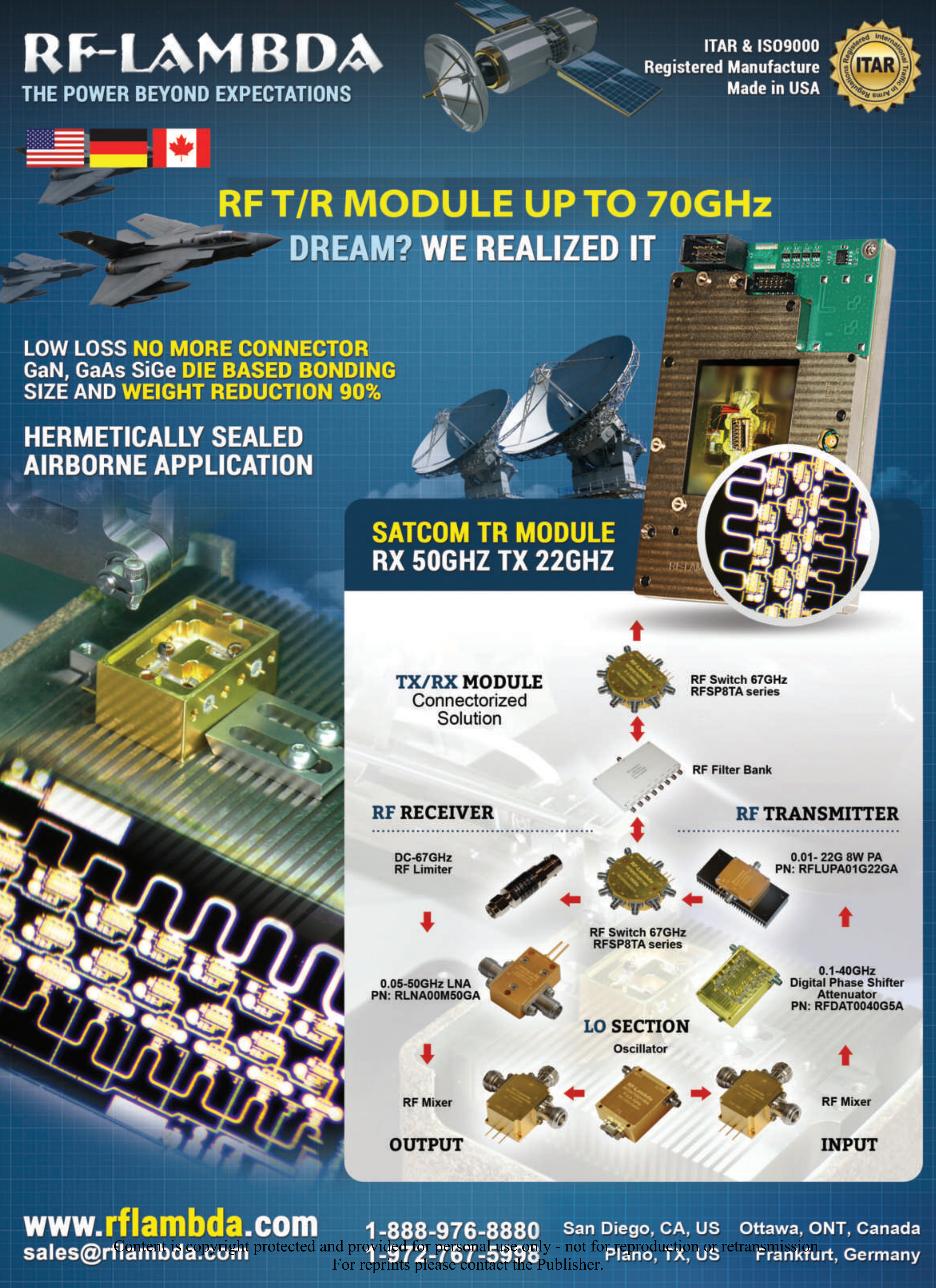
Combining MixComm's unique circuit architecture with the RF-SOI process capabilities, the SUMMIT 2629 on-chip PAs achieve high power and high efficiency, more than twice the efficiency of competing CMOS solutions. To maintain efficiency and dynamic range, the T/R switches are very low loss, and the receive amplifier has a low noise figure. Beam steering is accomplished using six-bit phase shifters with 360-degree coverage and 16 dB gain adjustment in 0.5 dB steps.

The SUMMIT 2629 offers additional capabilities to enhance performance, control and reliability:

- Fully calibrated for gain and phase matching among multiple RFICs.
- Extensive on-chip temperature



▲ Fig. 3 Taoglas smart antenna subsystem using four MixComm Summit 2629 ICs.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RF Switch 67GHz
RFSP8TA series
0.05-50GHz LNA
PN: RLNA00M50GA
0.1-40GHz
Digital Phase Shifter
Attenuator
PN: RFDAT0040G5A
LO SECTION
Oscillator
RF Mixer
RF Mixer
OUTPUT
INPUT
www.rflambda.com
sales@rflambda.com
1-888-976-8880
1-972-767-5998
San Diego, CA, US
Plano, TX, US
Ottawa, ONT, Canada
Frankfurt, Germany

and power sensing.

- On-chip gain control for temperature compensation.
- High speed SPI with large on-chip beam table storage memory.

With its high output power and excellent efficiency, the SUMMIT 2629 is well suited for 5G infrastructure applications, such as gNodeB, customer premises equipment (CPE) and repeaters. The higher output power per PA enables significantly superior link budgets, enabling a 2.7× increase in throughput rate (see ***Figure 2***). The figure compares the median CPE uplink throughput of a CPE array using a bulk CMOS-based front-end with an array using MixComm's 45 nm RF-SOI RFICs, both with equal numbers of antennas.

The SUMMIT 2629 is fabricated on GlobalFoundries' 45RFSOI process, a 45 nm, partially-depleted SOI technology codeveloped with DARPA to enable mmWave innovation and commercial applications. Since 2008, the 45RFSOI process has been running in high volume at multiple GlobalFoundries' fabs, evolving to incorporate enhancements improving RF performance. GlobalFoundries is providing turnkey manufacturing of the SUMMIT 2629, from wafer fab through wafer-level chip-scale packaging (WLCSP) and RF testing at the mmWave operating frequencies. SUMMIT 2629's WLCSP is compatible with assembly onto low-cost PCBs, which are used for 5G antenna arrays.

The first antenna array to use the SUMMIT 2629 is the Taoglas KHA16.23C smart antenna subsystem (see ***Figure 3***). The KHA16.23C is a proprietary 2D antenna array with 16 elements integrated into a multilayer PCB that contains four Summit 2629 ICs. The PCB has several layers for power optimization and thermal control, digital control and the RF feed—all in footprint of 53 mm × 84 mm. The antenna subsystem is scalable up to 1024 element arrays, depending on device implementation.

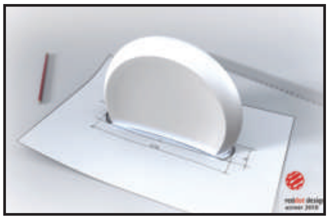
Although a relatively new company, founded in 2017, MixComm has a substantial legacy and head-start in RF-SOI and mmWave solutions. The company's expertise leverages the pioneering work of Harish Krishnaswamy at Columbia University's COSMIC lab, who cofounded MixComm and serves as chief technology officer. For more than 10 years, members of the COSMIC lab team were key performers on programs such as DARPA's Efficient Linearized All-Silicon Transmitter ICs, which proved the unique modeling, circuit design and architectures that MixComm is using to optimize RF-SOI for mmWave applications. The SUMMIT 2629 is the first family of mmWave devices which will cover the 5G mmWave bands.

Sample quantities of MixComm's SUMMIT 2629 and Taoglas KHA16.23C will be available through Richardson RFPD.

MixComm, Inc.,
Chatham, N.J.,
www.mixcomm-inc.com,
www.richardsonrfpd.com/Supplier/Index/Mixcomm,
info@mixcomm-inc.com


JOIN US IN ATLANTA FOR IMS2021

SENCITY® Occhio DAS Antenna Video



The HUBER+SUHNER SENCITY Occhio DAS (Distributed Antenna System) or small cell antenna for indoor use, offers the operator 5G coverage, a simple, time-saving installation process and an attractive industry preferred design with a small form factor. Thanks to its multiband capability between 1.7 to 6 GHz and 2 × 2/4 × 4 MIMO configurations it supports today's and future wireless applications. Watch how the awarded antenna has been designed and get in touch if you are interested in learning more.

HUBER+SUHNER

www.youtube.com/watch?v=DKTSv7QGVuw

New Product Catalog and Space Brochure

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

K&L Microwave

www.klmicrowave.com

New Website Launched

VENDORVIEW

L-com has recently launched a new and improved ecommerce website that includes an improved look and feel (UI & UX), new and improved site navigation and search capabilities to help customers find the right products faster and mobile optimization to make finding and buying products easy on any device. Other enhancements including a quick one page checkout, custom cable configurators and a library of helpful technical resources. L-com's new website features thousands of wired and wireless connectivity products that are in-stock and available for same-day shipping.

L-com

www.l-com.com

Modelithics® Launches New Product Line

VENDORVIEW

Modelithics® recently acquired the ProbePoints™ substrate fixture assets from Jmicro Technology. This acquisition includes test fixtures and probing accessory products for the RF/microwave and electrical test of advanced semiconductor devices and packaging products. Also included is the popular ProbePoint alumina substrate fixtures that allow devices without ground-signal-ground probe pads to be tested with RF wafer probes. Modelithics now also offers its own standard and custom microwave and mmWave test fixtures and calibration standards alongside the Jmicro ProbePoint fixture products.

Modelithics, Inc.

www.modelithics.com/home/fixtures

RFMW Creates Resource for RF Energy Technology

VENDORVIEW

RFMW announces a microsite for customers and suppliers supporting solid-state RF energy technology in popular frequency bands of 433 MHz, 915 MHz, 2.45 GHz and 5.8 GHz. Solutions include signal generators, phase shifters, splitters, combiners, power amplifiers, circulators/isolators, terminations, cables and connectors. The site offers different entry levels including components, pallets and modules depending on customer preference.

RFMW

https://bit.ly/3beUSRA

Spectratime mRO-50-New Low SWaP-C Miniaturized Rb Oscillator

The new Spectratime mRO-50 meets core telecom, military and critical infrastructure requirements to provide better holdover and higher stability than standard oscillators with same level of power consumption and volume. The clock design, based on the "classical" rubidium clock heritage at Orolia, has been adapted for low power (0.36 W at 3.3 V) and size (51 cc). The atomic clock provides a signal at the convenient frequency of 10 MHz meeting the performances of the atomic transition.

Orolia

https://www.orolia.com/

Web&VideoUpdate

New 10GbE-based Spectrum Analyzer From Signal Hound

This new video highlights the SM200C—Signal Hound's third-generation 20 GHz spectrum analyzer. This device maintains the dynamic range, phase noise, 1 THz/s sweep speed and 100 kHz to 20 GHz tuning range that made the SM200B so popular, but now includes a full 160 MHz IBW available for calibrated I/Q data streaming, plus device control via 10 GbE SFP+ connection. No longer limited by the length of a cable, the SM200C is perfect for secure environments where USB is prohibited.

Signal Hound
https://youtu.be/Xp87XagAGG8

TowerJazz Announces New Brand Identity

TowerJazz has announced a new brand identity that will include updates to the company's brand name, vision, mission, values, logo, tagline, website and graphic design approach. The rebranding process is aligned with a strategic roadmap to provide the highest value analog semiconductor solutions, supported by a focus on being a long-term trusted partner with a positive and sustainable impact on the world through innovative analog technologies and manufacturing solutions.

TowerJazz
www.towerjazz.com

Gore Launches New Online Microwave/RF Assembly Builder

W. L. Gore & Associates has launched its updated GORE® Microwave/RF Assembly Builder, a step-by-step tool that allows the user to configure and request a quote for an assembly with a variety of connector and cable options, assembly lengths and frequencies. The updated online tool features enhancements that allow users to design a cable from their desktop, tablet or mobile phone. In today's predominantly remote-work environment, these added features make it possible to design GORE® Microwave/RF Assemblies with ease, from anywhere, anytime and from any device.

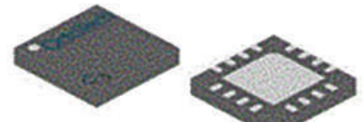
W. L. Gore & Associates
https://www.gore.com

NEW PRODUCTS

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

COMPONENTS

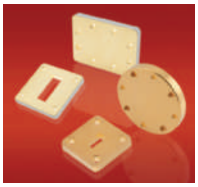
2.4 GHz Front End Module



The 8TR8201 is an RFIC for 802.15.4 ZigBee™/Thread, BLE and proprietary ISM wireless systems for Bluetooth and ZigBee Applications. It consists of an integrated power amplifier, low noise amplifier, SPDT Tx/Rx switch and an SPDT antenna switch.

Berex
www.berex.com

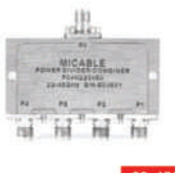
Waveguide Shorts and Shims
VENDORVIEW



Fairview Microwave Inc. has launched a new series of waveguide shorts and shims that are ideal for use in test and instrumentation, wireless communication, satellite communication and radar applications. Fairview's new line of waveguide shorts and shims includes 36 models offered in waveguide sizes ranging from WR-430 to WR-10. This new line is ideal for use in RF test and measurement applications and provides superior RF performance. Waveguide shims and shorts, or shorting plates, are commonly included in calibration kits and they are used in calibration applications.

Fairview Microwave Inc.
www.fairviewmicrowave.com

23-45 GHz Four Way Power Divider/Combiner



P04N230450 is a four-way power divider/combiner specially developed to cover whole 5G mmWave bands. It has 2.4 dB max insertion loss, 20 dB min isolation, 1.7: 1 max VSWR, ±0.5 dB max amplitude balance and ±6° max phase balance. The input power as the power divider is 20 W average. As combiner, it can stand for 5 W average input power. The size is 51.7 × 25.4 × 12.7 mm, the operating temperatures -54 to +85°C.

Fuzhou MIcable Electronic Technology Co., Ltd.
www.micable.cn

10-50 GHz Dual-Directional Coupler
VENDORVIEW

KRYTAR's Model 510050010 dual-directional coupler lends itself to designs and test and measurement applications in mmWave and 5G markets. Within a broadband frequency range of 10 to 50 GHz performance ratings include nominal coupling of 10 dB, ±1.8 dB, frequency sensitivity is ±1 dB, insertion loss less than 3 dB, Directivity greater than 10 dB, maximum VSWR is 1.8. The coupler comes with 2.4 mm female connectors and measures just 2.24 in. (L) x 0.40 in. (W) x 0.62 in. (H).

KRYTAR
https://krytar.com/products/couplers/dual-directional-couplers/dual-directional-coupler-510050010/

Direct Replacement Coaxial Switches

Logus Microwave now offers the SPDT SEM Series to their list of direct replacement coaxial switches. The form, fit and function of this Logus series is your solution to replacing the legacy manufacturers series. DC to 18 GHz VSWR 1.5:1 max, insertion loss 0.5 max and isolation 60 dB min.

Logus Microwave
www.logus.com

Low-Loss Coupler

Maury Microwave announced the expansion of its low loss coupler product offering with new 3 to 67 GHz models. The LLC67-series of bidirectional couplers offer best-in-class unmatched performance including the industry's lowest insertion loss of 0.2 dB maximum at 20 GHz and 0.4 dB maximum at 67 GHz with high CW and pulsed power handling and excellent directivity over a broadband frequency range of 3 to 67 GHz with 1.85 mm connectors.

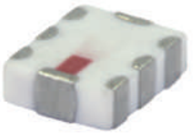
Maury Microwave
www.maurymw.com

Broadband Two-Way DC Blocking Power Divider
VENDORVIEW

MECA Electronics' latest new product offering is a two-way broadband DC blocking weatherproof divider. Blocking DC on all ports covering 0.600 to 6 GHz (DC802-2-3.300WWP) encompassing public safety through ISM bands. With typical performance of VSWR's of 1.25:1, isolation of 22 dB, insertion loss of 0.6 dB and exceptional amplitude and phase balance of 0.3 dB and 5° max. This is in addition to the family of two, four, eight and 16 way splitters in various connector styles and IP60 and 67/68 ratings. Made in the U.S., 36 month warranty.

MECA Electronics, Inc.
www.e-meca.com

Tiny LTCC Dual/Differential Low Pass Filter
VENDORVIEW



Mini-Circuits' DLFCV-1600+ is a dual low pass filter with a passband from DC to 1,600 MHz designed into a single 1210 ceramic package. This design allows customers to use a single unit in systems where two filters of the same passband are required, saving board space. The dual filter can also be used as a differential filter in differential circuits where interference and noise must be minimized. This model provides 1.5 dB passband insertion loss, 50 dB stopband rejection and RF input power handling up to 3 W (each filter). It supports a wide range of applications and is ideal for minimizing interference at amplifier inputs and ADC outputs.

Mini-Circuits
www.minicircuits.com

NewProducts

Double Ridge Waveguide Electromechanical Relay Switches

VENDORVIEW

Pasternack, an Infinite Electronics brand, has just launched a new series of double ridge waveguide electromechanical relay switches which perform over broader frequency bands, making them ideal for applications involved with electronic warfare, electronic countermeasures, microwave radio, VSAT, radar, test instrumentation and research and development. This comprehensive selection of 12 new double ridge waveguide electromechanical switch models is now available featuring broadband multi-octave frequency coverage spanning 6.5 to 40 GHz in SPDT and optional DPDT configurations.

Pasternack
www.pasternack.com

10-Bit Programmable Attenuator

VENDORVIEW

PMI Model No. DTA-2G18G-60-CD-1-OPT618-2 is a 6.0 to 18.0 GHz, 10-Bit programmable attenuator. Specifications include mean attenuation range: 60 dB;

minimum attenuation step: 0.06 dB; maximum insertion loss of 4.5 dB; flatness up to 20 dB: ±1.0 dB typ, 40 dB: ±1.25 dB typ, 60 dB: ±3.0 dB typ; ccuracy of attenuation of 0 to 20 dB: ±1.0 dB typ, 20 to 40 dB: ±1.5 dB typ, 40 to 60 dB: ±2.0 dB typ; and DC power supply +15 V at 100 mA max, -15 V at 100 mA max. Housing measures 2 × 1.81 × 0.88 in. with SMA female connectors and a 15-pin D-sub connector.

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

3 dB Quad Hybrid

Response Microwave Inc. is pleased to announce the availability of its new broadband 3 dB hybrid for use in telecom applications. The new RMHY3.1000-6000Sf covers the 1 to 6 GHz band offering typical electrical performance of 0.7 dB max insertion loss, VSWR of 1.25:1 max and minimum isolation of 20 dB. Unit is phase stable at ±5° and power handling is 50 W CW. Unit is operational over the -55° to +105° C range.

Response Microwave Inc.
www.responsemicrowave.com

Pickoff Tees

RLC Electronics manufactures Pickoff Tees, which offer excellent through-line insertion loss and pickoff stability rise times of <10 Pico-seconds (at 40 GHz). Units are offered in standard frequency ranges from DC-18 GHz, DC-26 GHz and DC-40 GHz, with the option to customize the Pickoff Insertion Loss value to meet customer specific requirements. The units provide extremely broadband signal monitoring in a very small package (0.54 × 0.39 × 0.32 in.). RLC offers both catalog options and customized options and can provide form factor drop-in replacement/obsolescence assistance as needed.

RLC Electronics Inc.
www.rlcelectronics.com

Planar X Series of RF Filters

VENDORVIEW

Smiths Interconnect announced the new Planar X Series of RF filter solutions with bandpass, bandstop, lowpass and highpass configurations up to 18 GHz (Ku-Band). It is part of an overarching initiative that entails the creation of first-class board level ceramic based thick film RF filters, designed and tested to support various application markets. The small footprint, light weight and surface mountable configuration allows for high volume pick and place applications and make Planar X Series ideal for SATCOM, radar and broadcasting industries.

Smiths Interconnect
www.smithsinterconnect.com

CABLES & CONNECTORS

PSM Connectors

The power sub-miniature (PSM) interface meets the increasing demand of cost effective, power demanding and weight sensitive aerospace applications. Especially developed for space flight, high altitude platforms and TVAC environments. Space qualified per MIL-PRF-39012 and ESCC 3402/08. The HUBER+SUHNER PSM connector system enables maximized performance on power handling while minimizing overall system weight and size. Multipaction breakdown and corona withstanding meet or exceed TNC interface level.

HUBER+SUHNER AG
www.hubersuhner.com

NewProducts

50 GHz SUCOFLEX® 550S Test Cables

Richardson RFPD Inc. announced the availability and full design support capabilities for a new family of test cables from HUBER+SUHNER. With a lifetime of more than 100,000 flex cycles, SUCOFLEX 550S is the latest addition to HUBER+SUHNER's SUCOFLEX 500 family and provides a range of benefits, including a high electrical performance with an enhanced mechanical design for durability. The longer service life also results in less testing downtime and improved cost efficiency.

Richardson RFPD Inc.
www.richardsonrfpd.com

Cable Assembly

Samtec announced a new flexible low loss cable assembly with performance up to 67 GHz. The RF047-A cable assembly, using 1.85 mm male and female connectors, operates to 67 GHz with a maximum VSWR of 1.4:1 or better. The connectors are solder clamp designs with fully captivated center contacts. The body components are passivated stainless steel with gold plated brass solder ferrule and beryllium copper contact. Other connector options offered include male and female 2.92 mm series, as well as male and female SMPM series.

Samtec Inc.
www.samtec.com

Precision Right Angle Adapters

Withwave's precision test adapters with right angle types are designed based on precision microwave interconnection technologies. These adapters are manufactured to precise microwave specifications and constructed with male and female gender on both sides. The precision microwave connector interfaces ensure an excellent microwave performance up to 40 GHz

Withwave Co. Ltd.
www.with-wave.com

AMPLIFIERS

1,000 W Amplifier

VENDORVIEW

Increased EMC test level requirements equate to two words: More. Power. AR RF's newest 1,000 W amplifier, the 1000A400, is used for radiated and conducted susceptibility testing, specifically for the increased test levels of composite aircraft in the frequency range of 10 kHz to 400 MHz. When utilized in conjunction with AR's accessories and antennas, the required conducted and radiated susceptibility test levels are easily reached.

AR RF/Microwave Instrumentation
www.arworld.us

Solid-State Power Amplifier Module

COMTECH PST introduced its latest development for the TWT replacement market covering the full 2,000 to 6,000 MHz band providing 75 W linear power in a small, compact, lightweight, ruggedized form factor, ideally suited for UAV, fixed wing, rotary wing applications. This SSPA features built in protection and monitoring circuits, low voltage prime power input, high efficiency and reliable solid-state technology. Unit will self-protect under fault conditions and automatically return to normal operation when fault conditions are removed. The SSPA module withstands and operates reliably in rugged and hostile environments.

COMTECH PST
www.comtechpst.com

X- & Ku-Band Solid-State Power Amplifiers

Kratos General Microwave's cutting-edge, field proven SSPAs are designed and built for the harshest environment conditions, including hostile temperatures, shock, vibration, moisture, altitudes and G-forces. The custom and off-the-shelf SSPAs in X-Band and Ku-Bands utilize the latest GaN and GaAs technologies and provide high power density in a compact footprint to meet critical space and weight requirements in high frequencies. All of our SSPAs can be supplied to meet the most stringent environmental requirements.

Kratos General Microwave
www.kratosmed.com

Power Transistor for Accelerator Applications

The IE13550D is a 550 W, CW, GaN SiC power transistor operating in the frequency range of 1,295 to 1,305 MHz. This transistor is designed for commercial scale laser, linear and particle accelerator applications. The IE13550D achieves an exceptional drain efficiency of 80 percent, at a power gain of 15 dB with low power dissipation. This device is internally matched and has a compact size of 20.6 × 9.8 × 3.77 mm. Other product features include excellent thermal stability and ruggedness enabling longer mean time between failure.

RFHIC Corp.
www.rfhic.com

SOURCES

Ultra-Agile Signal Source

The APUASYN20 is a very compact and agile signal source up to 20 GHz. It combines fast switching speeds with good phase noise and signal quality. The single-channel unit is available as a mountable module or in a compact enclosure with display and front panel control. The multi-channel version APUASYN20-X is available in one to four channel configurations in a standard 1U 19" rack-mountable enclosure. For high phase coherence, RF channels are locked to a single reference source.

AnaPico Ltd.
www.anapico.com

4,512 MHz VCO

Crystek's CV-CO55CC-4512-4512 voltage controlled oscillator (VCO) operates at 4,512 MHz with a control voltage range of 0.3 to 4.7 V. This VCO features a typical phase noise of -105 dBc/Hz at 10 KHz offset and has excellent linearity. Output power is typically +4 dBm. Engineered and manufactured in the U.S., the model CV-CO55CC4512-4512 is packaged in the industry-standard 0.5 in. × 0.5 in. SMD package. Input voltage is 5 V, with a typ. current consumption of 28 mA. Pulling and pushing are minimized to 1 MHz and 1 MHz/V, respectively.

Crystek Corp.
www.crystek.com

HSM Series RF Synthesizer Modules

VENDORVIEW

The HSM Series RF Synthesizer Modules are high performance, non-PLL based CW sources that exhibit exceptional frequency/phase stability. The intentional lack of a PLL supports frequency switching speeds of as fast as <10 µs (fully settled) while offering phenomenal pulse generation waveforms. These compact, broadband signal sources have a field proven MTBF of >200k hours and are available in seven models covering 10 MHz to 1 GHz, 2 GHz, 3 GHz, 4 GHz, 6.7 GHz, 12.5 GHz and 20 GHz.

HOLZWORTH
www.holzworth.com

World's Smallest OCXO

VENDORVIEW

RFMW announced design and sales support for the world's smallest ASIC based oven controlled crystal oscillator (OCXO) from Rakon. The Rakon U8176LF 10MHz OCXO meets the stringent requirements of 5G remote radio head (RRH), small cell, optical network and microwave transmission system applications. Combined with Rakon's renowned, patented Mercury+™ ASIC with advanced SC-cut strip crystal technology, this device delivers excellent frequency stability (≤±20 ppb) in a miniature, 7× 5 mm package. Supporting frequencies from 10 to 50 MHz, phase noise is as low as -160 dBc/Hz.

RFMW
www.rfmw.com

40 GHz CW Signal Source

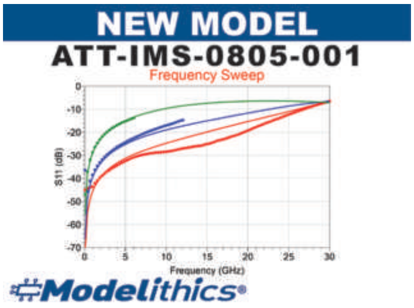
The SC5520A and SC5521A are part of our ultra-high frequency synthesizer series (UHFS) of signal sources. They boast a frequency tuning range of 160 MHz to 40 GHz stepping at 1 Hz resolution, and an amplitude range of -10 to +15 dBm typ with phase noise among the lowest in the market. These compact modules are ideal for system integration and appropriate for applications in communication transceivers, automotive radar and optics and as clocks in modern day digital data converters.

SignalCore
www.signalcore.com

SOFTWARE

Microwave Global Model

VENDORVIEW

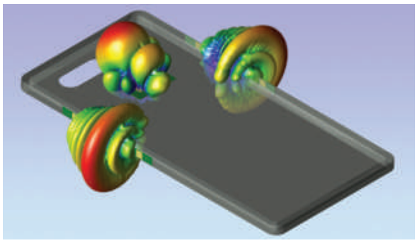


Modelithics has introduced a new equivalent circuit-based scalable microwave Global Model for International Manufacturing Services, Inc.'s IA3-0805WA thick film 400 mW surface mount attenuator family. The model is validated up to 30 GHz and features substrate, pad and part value scaling over the full range of the attenuator series, 1 to 30 dB. IMS is a sponsoring Modelithics Vendor Partner (MVP) and is sponsoring free 90-day trials of all available Modelithics IMS models by request and with approval.

Modelithics
www.Modelithics.com

XFdtd®

VENDORVIEW



Remcom has announced superposition simulation in the latest release of XFdtd®3D EM Simulation Software, enabling users to analyze antenna arrays and other multi-port devices. Leveraging the electromagnetic principle of superposition, XF can quickly analyze hundreds or thousands of port phase combinations when determining beam states for a 5G-enabled device design. This post-processing option provides interactive manipulation of the input signals that compute near fields, far fields, efficiencies and other results in real time.

Remcom
www.remcom.com

The program will contain the following activities and will feature both pre-recorded and live events:

IMS, RFIC and ARFTG Technical Sessions

IMS, RFIC and ARFTG Plenary Sessions

Technical Lectures

5G Summit

Panel Sessions

Three Minute Thesis

MicroApps

Industry Workshops

Virtual Exhibition

Visit ims-ieee.org to learn more!

Follow us on:

IEEE

#IMS2020

MTT-S

Microwave/RF Assembly Builder

W. L. Gore & Associates has launched its updated GORE®Microwave/RF Assembly Builder, a step-by-step tool that allows the user to configure and request a quote for an assembly with a variety of connector and cable options, assembly lengths and frequencies. The updated online tool features enhancements that allow users to design a cable from their desktop, tablet or mobile phone. In today's predominantly remote-work environment, these added features make it possible to design GORE®Microwave/RF Assemblies with ease, from anywhere, anytime and from any device.

W. L. Gore & Associates
www.gore.com

ANTENNAS

Choke Flange Feed Horn Antenna

SAH-7531141060-110-S1-100-DP is a dual polarized, WR-10 choke flange feed horn antenna assembly that operates from 75 to 110 GHz. The assembly 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.

Eravant
www.eravant.com

SENCITY Occhio Distributed Antenna System

The HUBER+SUHNER SENCITY Occhio DAS (distributed antenna system) or small cell antenna for indoor use, offers the operator 5G coverage, a simple, time-saving installation process and an attractive industry preferred design with a small form factor. Thanks to its multiband capability between 1.7 to 6 GHz and 2 x 2/4 x 4 MIMO configurations it supports today's and future wireless applications. See how the awarded antenna has been designed and get in touch if you are interested.

HUBER+SUHNER
www.hubersuhner.com/en/products/radio-frequency/antennas/das-ibc/sencity-occhio

TEST & MEASUREMENT

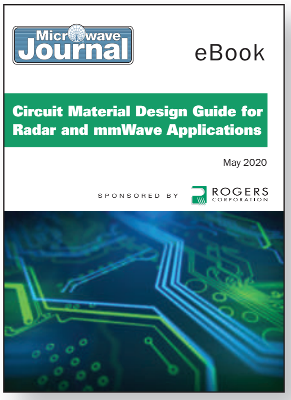
R&S FSW With Up to 8.3 GHz Internal Analysis Bandwidth

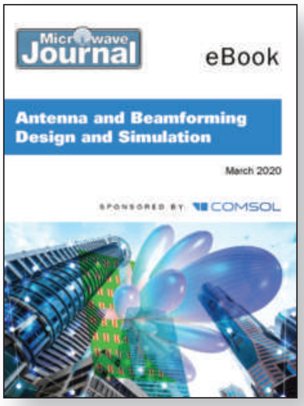
VENDORVIEW

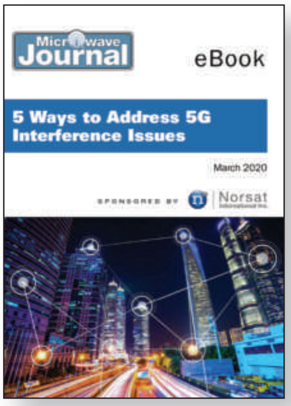
Rohde & Schwarz offers the R&S FSW high-end signal and spectrum analyzers with optional internal 4 GHz, 6.4 GHz and 8.3 GHz analysis bandwidth, providing unmatched dynamic range and sensitivity. Along with dedicated measurement applica-

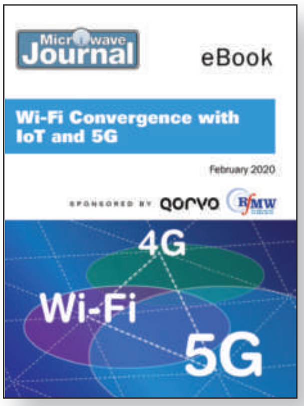
FEATURED eBooks

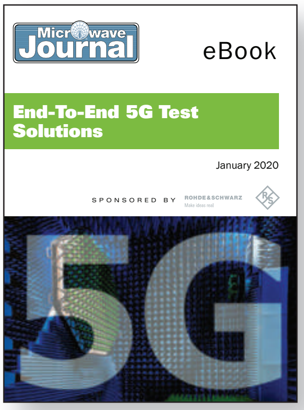
The information you need, from industry experts.

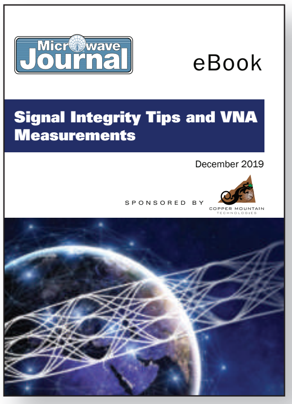


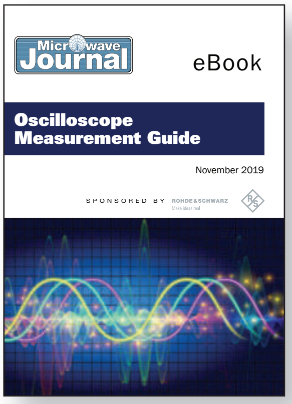












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Advertiser	Page No.
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American Technical Ceramics	55
Analog Devices	23, 65
Anokiwave	25
Antenom Antenna Technologies, Inc.	48
APMC 2020	103
AR RF/Microwave Instrumentation	43
Artech House	91, 102
Avtech Electrosystems	101
B&Z Technologies, LLC	11
Cadence Design Systems, Inc.	47
Cernex, Inc.	28
Ciao Wireless, Inc.	36
COMSOL, Inc.	15
CPI Beverly Microwave Division	69
dBm Corp, Inc.	78
Ducommun Labarge Technologies, Inc.	32
Eclipse MDI	92
EDI CON CHINA 2020	93
EDI CON ONLINE 2020	COV 3
Eravant (formerly SAGE Millimeter)	20-21
ET Industries	94
EuMW 2020	99
Fairview Microwave	66, 67
FormFactor	31
GGB Industries, Inc.	3
HASCO, Inc.	24
Herotek, Inc.	30
Holzworth Instrumentation	34
HYPERLABS INC.	61
IEEE MTT-S International Microwave Symposium 2020	97
IEEE MTT-S International Microwave Symposium 2021	87
K&L Microwave, Inc.	7
Koaxis, Inc.	80
Master Bond Inc.	101
MCV Microwave	29
MECA Electronics, Inc.	72
MIcable Inc.	73
Micro Lambda, LLC	58
Microwave Journal	48, 50, 89, 95, 100
Milliwave Silicon Solutions	86
Mini-Circuits	4-5, 16, 40 63, 81, 105
Mini-Systems, Inc.	79
Modelithics, Inc.	71
Networks International Corporation	6
Norden Millimeter Inc.	84
OML Inc.	53
Orolia Switzerland SA	51
Pasternack	8
Planar Monolithics Industries, Inc.	59
QML, Inc.	COV 2
Qorvo	33
Reactel, Incorporated	39
RF-Lambda	9, 49, 85
RFHIC	75
RFMW, Ltd.	13
Richardson RFPD	19, 42
RLC Electronics, Inc.	57
Rosenberger	27
Satellink, Inc.	101
Sector Microwave Industries, Inc.	101
SemiDice, Inc.	70
Signal Integrity Journal	98
Special Hermetic Products, Inc.	101
Synergy Microwave Corporation	45, 83
Taiyo Yuden Co., Ltd.	62
Weinschel Associates	56
Wenteq Microwave Corporation	101
Wenzel Associates, Inc.	60
Werlatone, Inc.	COV 4
West Bond Inc.	38
Z-Communications, Inc.	18

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ACT International
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Linda Li
ACT International
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Cecily Bian
ACT International
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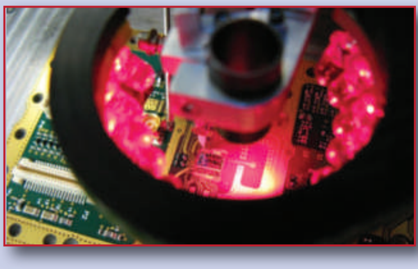
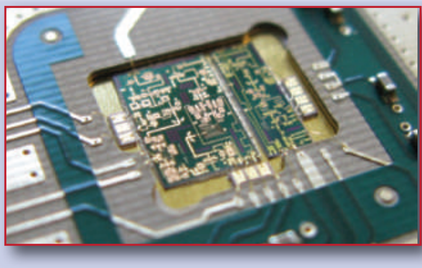
Filtronic Precision Hybrid Microelectronics Assembly and Test to 90 GHz

Having invested over U.S. $1.3 million in new equipment at the end of last year, and at the same time expanded its workforce, Filtronic has recently overseen a significant increase in the capacity of its manufacturing facility in Sedgefield, in the North-East of England. The 20,000-square-foot design and manufacturing center produces Filtronic's integrated E-Band transceiver modules in high volumes for mobile backhaul, products that are now seeing accelerating demand due to the roll-out of 5G globally. Over 500,000 transceiver modules and 700,000 filter products have been successfully deployed in the field. Of these, more than 40,000 have been E-band modules, including the company's flagship Orpheus and Morpheus II transceivers.

Filtronic is also seeing a significant increase in demand for its custom design and microelectronics assembly services, particularly at microwave and mmWave frequencies. These services enable clients around the world to commission their own product designs to be prototyped and manufactured in an automated factory in the U.K., with a world-class reputation for product quality and reliability.

The company's expertise has been accumulated during a heritage spanning more than four decades since it was first founded in 1977. Filtronic fosters a culture with a commitment to quality supported by Six Sigma, high levels of production automation, strict traceability and adherence to military standards. The Filtronic team is highly qualified, experienced and enjoys enviable levels of retention with an average length of service of over 14 years. Filtronic's aim is to provide a unique path to a low-risk, secure service to make products for applications including point-to-point radio links, phased array radars and security applications such as imaging.

The manufacturing and test area at Sedgefield includes 2,500 square feet of Class 100,000 clean rooms, and another 2,500 square feet of engineering development labs. Its production capability includes microwave and mmWave device packaging, sub-assembly manufacturing and test, specializing in mmWave projects up to 90 GHz and beyond. Filtronic also offers design services to fit customer's needs. The company's expertise is taking a project from concept to implementation. In all cases, from rapid prototyping to volume production, the appropriate design expertise and production engineering advice is readily available.

Filtronic's hybrid microelectronics assembly and test portfolio includes low-void die attach and precision component placement; fully automated wire and ribbon bonding with deep-access multi-level capability; skilled manual assembly; hermetic sealing; and automated test to 90 GHz. Proprietary air cavity packages can include mixed GaAs, GaN and Si die within a single package, and can perform at frequencies higher than 90 GHz. Particular attention is given to optimizing die attachment and heatsinking for power devices, and in minimizing wire-bond parasitics for products that operate at higher frequencies.

The precision hybrid microelectronics assembly facility has received significant positive feedback from its clients, including a major European defense manufacturer who singled out Filtronic's manufacturing expertise for a special commendation. The award cites Filtronic's effort and commitment in successfully delivering a large production run of transmit/receive modules as providing an "outstanding contribution" to its state-of-the-art radar system.

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C10526	Dual	700-6000	300	40	0.20	N Female	2.0 x 2.0 x 1.06
C10364	Dual	700-6000	500	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10614	Dual	700-6000	500	60	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10996	Dual	700-6000	700	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C11555	Dual	700-6000	1,000	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10695	Dual	700-6500	500	50	0.20	7/16-Female	2.15 x 2.0 x 1.36

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D11958	4-Way	600-6000	100	18 (PI*)	0.60	N-F / SMA-F	4.00 x 2.0 x 1.00
D11149	4-Way	700-6000	300	Non-Isolated	0.60	N-Female	4.35 x 3.9 x 1.15
D11832	2-Way	700-6000	500	Non-Isolated	0.60	7/16-Female	5.50 x 2.4 x 1.06
D10803	2-Way	700-6500	300	Non-Isolated	0.60	N-Female	5.50 x 2.4 x 1.06

(PI*) references Partial Isolation

90° Hybrid Couplers

Model	Type	Frequency (MHz)	Power (W CW)	Amp. Bal. (±dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
QH11687	90°	500-6000	150	0.7	0.75	SMT	1.28 x 1.08 x 0.13
QH11443	90°	600-6000	150	0.8	0.70	SMT	1.30 x 1.30 x 0.13
QH10756	90°	700-6000	100	0.6	0.55	SMT	0.74 x 0.45 x 0.09
QH10541	90°	700-6000	150	0.6	0.50	SMT	0.86 x 0.66 x 0.09
QH10827	90°	1000-7500	100	0.7	0.65	SMT	0.86 x 0.61 x 0.09
QH10828	90°	1000-8000	100	0.7	0.90	SMT	0.65 x 0.50 x 0.07

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TABLE OF CONTENTS

Cover Feature

6 mmWave AESA Phased Arrays and MIMO Radar Trends: Aperture to Data
Mark Walker, Cobham Advanced Electronic Solutions

Perspectives

20 An R&D Investment Strategy to Maintain Aerospace & Defense Leadership
William Conley, Mercury Systems

28 Bridging Commercial and Defense Technology to Maintain EW Innovation
Benjamin McMahon, BAE Systems

Technical Feature

36 Cognitive Countermeasures Determine Mission Success
Nancy Friedrich, Keysight Technologies

Product Features

42 Simulating Real World Radar Scenarios with Vector Signal Generators
Rohde & Schwarz

46 4 & 5 kW GaN Pulsed Transmitters for C- and X-Band
RFHIC Corp.

Tech Briefs

50 Low Smoke, Zero Halogen, Twinax Cable Assemblies
MilesTek

50 High-Power Class AB Amplifier Modules
Fairview MIcrowave

Company Showcase

52 Descriptions of company literature and products

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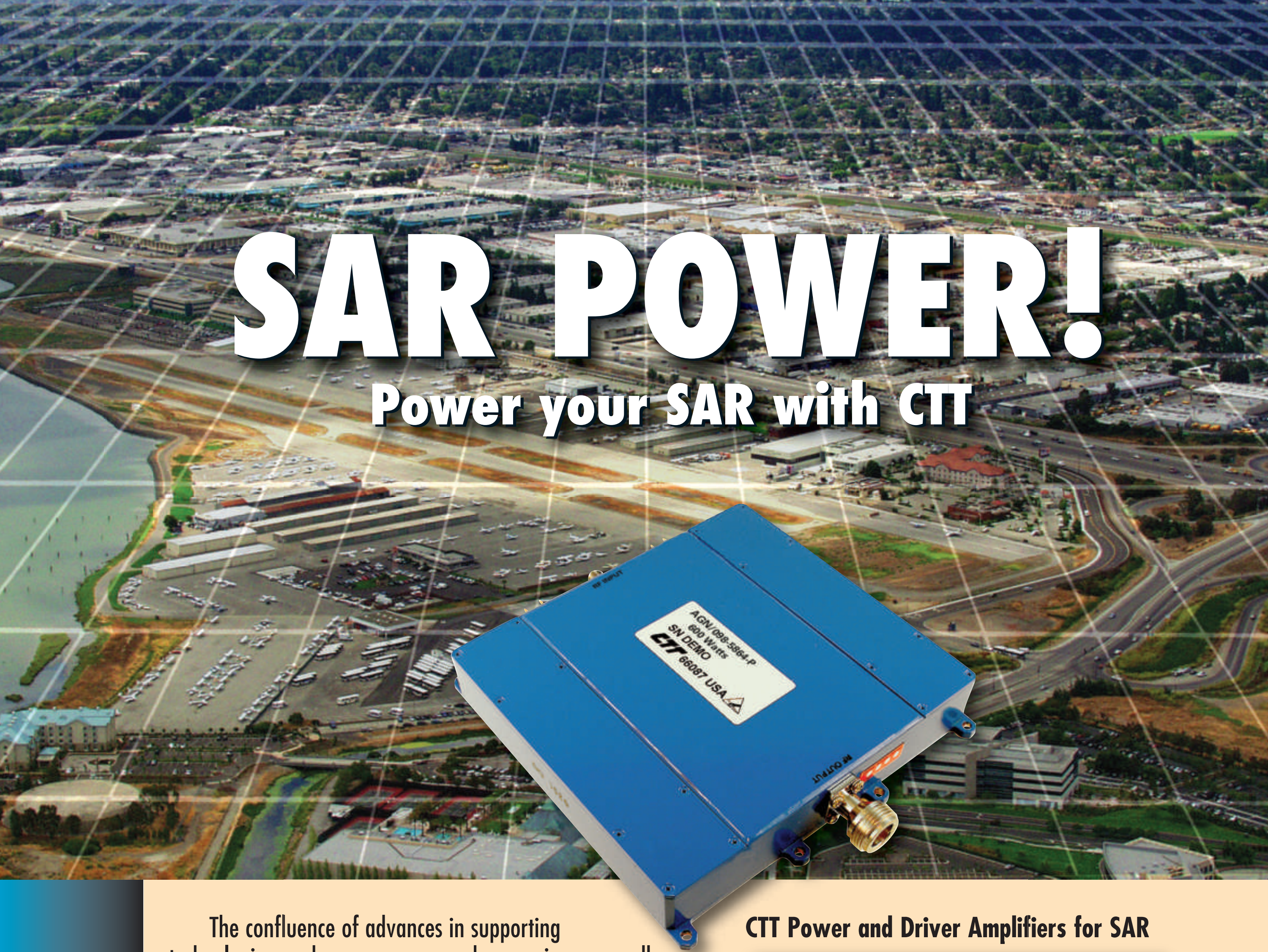

The confluence of advances in supporting technologies, such as processors and memories – as well as developments in UAVs – coupled with geopolitical demands for *increased homeland security and greater* intelligence gathering has pushed SAR (synthetic aperture radar) into the ISR (intelligence, surveillance and reconnaissance) spotlight.

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mmWave AESA Phased Arrays and MIMO Radar Trends: Aperture to Data

Mark Walker
Cobham Advanced Electronic Solutions, Arlington, Va.

Fig. 1 Evolving role of AESA arrays and radar.

Radar plays an expanding role with wide-ranging applications in the world today. Many defense contractors are developing active electronically scanned array (AESA) technologies for mission-critical systems in support of radar, EW, missile/munitions, space, communication, navigation and IFF (CNI) applications. These technologies can be found on major platforms in diverse environments: from destroyers and missile defense radar systems to space deployments in GPS, AEHF, Iridium Next, Orion, the Mars rover and the International Space Station (see ***Figure 1***). Through advanced ICs and packaging, miniature multi-mode custom arrays can offer customers a new set of capabilities with "aperture to data" to support the U.S. military in today's environment of evolving threats to enable enhanced performance at lower cost and simple implementation.

The U.S. DoD must leverage historical technology and embrace new commercial technologies against advancing security threats. Investments in phased array and multiple inputs multiple outputs (MIMO) radar technologies—along with underlying IC and packaging technology—are required to meet demanding threat detection requirements. Today's solutions must be affordable and capable of rapid deployment. Solutions for these radar products are built upon highly integrated system-on-a-chip (SoC) custom ICs and MMICs along with advanced packaging and integrated subsystem products for applications in the aerospace and defense market. Unique combinations of differentiated technology aggregated with advanced packaging and automation is making it possible to build small lightweight integrated AESA solutions.

Advanced technology integration is required to be an integrated solution provider from aperture to data. New technology roadmaps coupled with close relationships with fielded applications offer a fresh new look at the AESA technologies. It is critical to offer cutting-edge sensor technologies in partnership with system providers to deliver solutions aligned with program needs and the needs of our warfighters. Advanced packaging of SoC solutions with fully integrated subsystems widens opportunities to deliver a strategically important supply to defense primes and key subsystem providers (see ***Figure 2***).

Circuit loss and performance come at a premium when operating in the mmWave frequency range. Recent FCC news regarding the multi-billion dollar bids for mmWave frequency


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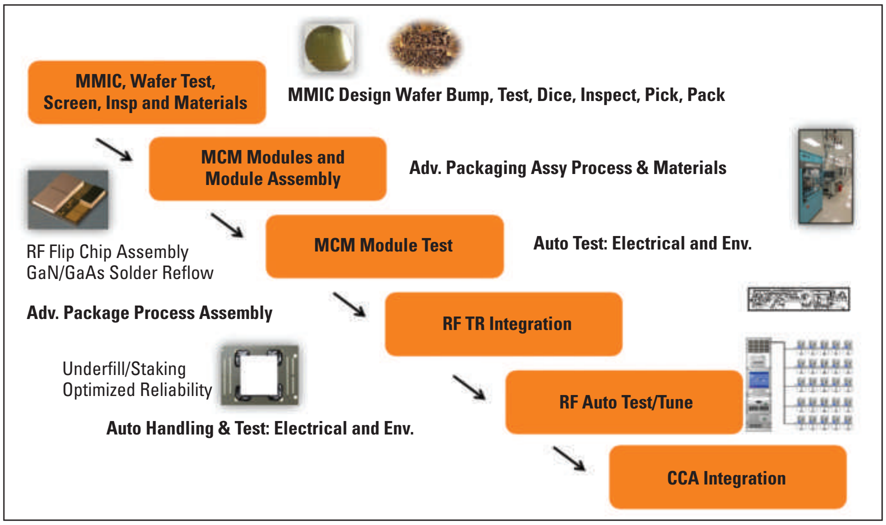
bands along with expansive 5G rollout indicate long term technology development. Connector and waveguide technologies are improving to support the growing need for and uses of mmWave frequency expansion. Leveraging longstanding RF expertise, defense contractors can now offer broad solutions and capabilities including antenna systems, transmit/receive (T/R) electronics and beam-formers, up/down converters, digitizers, interconnects and positioners. Utilizing advanced packaging technologies, digital and direct conversion technologies have become part of the signal chain. The result is a unique integration of the complete signal chain into an integrated mmWave solution with higher power, wider bandwidth and high reliability in austere environments. Integration lowers size, weight, power and cost while meeting stringent application requirements for highly sensitive solutions with optimum probability of detection.

Several years ago, development on mmWave AESA started with cooperative research with AFRL. Cobham Advanced Electronic Solutions (CAES) has enjoyed many years of successful technology development transitions into multiple DoD programs for MMICs and phased array programs. Going forward, constant independent research and development (IRaD) funding has been applied toward developing this critical new technology. When CAES acquired Aeroflex Corporation in 2014, the CAES technology portfolio expanded to include many new, reliable, advanced packaging and assembly options, including flip-chip, bumped die and packages. Among those technologies, the incumbent semiconductor business with broad and deep experience for the high reliability space and medical semiconductor industry—including LEAN Rel™—is enabling small integrated AESA arrays for DoD applications. With ongoing development, these advanced process options are constantly upgrading.

A tailored approach to building AESA systems utilizing new technology offers cost, size, reliability and performance advantages. AESA markets under consideration include—but are not limited to—air surveillance including airborne early warning radar, intercept or acquisition control, ballistic missile warning and acquisition, surveillance, mapping and missile tracking and guidance. Frequencies under consideration include Ka-Band and W-Band. These mmWave steerable systems track target range, position and velocity vectors. Target detections must be resolvable from each other even when targets are substantially contrasting in reflection cross-sections at variable range. Key performance criteria include simplifying the array control and system interfaces with higher levels of integration.

TECHNOLOGY APPLICATION

mmWave phased array dimensions with typical λ/2 element spacings are very small (approximately 5 mm at 30 GHz to 1.9 mm at 80 GHz). Therefore, placing transmit and receive elements at the aperture is feasible and is nearly ideal for T/R electronics at lower



▲ Fig. 2 Vertical integration needed for small mmWave AESA.

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	865	100 kHz to 6, 12.75, 20, 26, or 40 GHz	20 µs
Vector Signal Generator	875	10 MHz to 4, 6, 20 or 40 GHz	200 ns

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mmWave frequencies using quad-channel MMICs and Silicon ICs. Communication arrays are well suited for these form factors with transmit power at less than 0.2 W/element where silicon technologies match the application. Phased array with transmit powers greater than 0.75 W/element require more sophistication in TR electronics and often require active cooling within the array. Fortunately, exotic cooling substrate materials and techniques are not required for power densities lower than 10 W/element. The total transmit power for small arrays is primarily limited by available prime power and the dissipated power in the form of heat generated from each element's T/R amplifiers RF conversion efficiency. At mmWave frequencies, the factor limiting operation is typically heat dissipation. Power added efficiency at mmWave—established by semiconductor technology and circuit implementation—should be 5 percent or higher for a multi-stage MMIC amplifier.

There are many mechanical concerns in constructing mmWave arrays. Key concerns include—but are not limited to—supply voltage current density on voltage supply lines, location of the RF, DC and control lines. In the case of higher transmit power, active cooling may be required for long term operation.

Higher operating drain voltages of GaN MMICs help lower current density in connectors and distribution networks. GaN on SiC MMICs offer the thermal advantages of SiC to spread the heat from the transistor and passive heat sources within the MMIC. DC and RF connectors and interconnects present problems as they are a notable source of RF losses and increased product cost.

Likewise, space-consuming interconnects have a direct impact on array scalability and overall cost. It is challenging to build scalable mmWave phased arrays with λ/2 spacing while using the smallest available RF connectors, in addition to being cost-prohibitive. While there have been many advances in mmWave and RF connectors over the past few years, the best way to leverage their impact is through higher levels of integration within the array aperture. Further, the implementation of these arrays into application platforms demands as much simplification as possible to optimize size and performance, and for electrical and thermal interconnects. When building arrays within the Ka-Band frequency range, it has become increasingly obvious that higher levels of integration with customized SoC and automated assembly processes drive performance and affordability toward planar phased array architectures.

KA-BAND PHASED ARRAYS

Since 2016, core building blocks built from custom ICs and packaging technology have been specifically created for Ka-Band AESA hardware. Key pieces of the development include, 1) multi-channel Silicon-Germanium (SiGe) beam-former ICs, 2) multi-channel GaN T/R MMIC with PA, LNA, switches, et. al., 3) chip-scale flip-chip packaging (K-CSP) for both die on organic substrate, 4) integrated heat sink and 5) I/O RF, DC and control signals. The silicon die utilizes solder bump flip-chip technology, and the GaN MMIC die utilizes Cu pillar flip-chip technology. The K-CSP configuration leverages production flip-chip processes developed and qualified to QML Class-Y. These are automated processes for environmentally extreme rugged use conditions. The MMIC and mmWave SoC combination was designed a few years ago with specific features needed for phase array operations.

Currently, the GaN T/R MMIC is a multi-channel mmWave RFIC with approximately 15 percent bandwidth and electrical channel-to-channel symmetry. The T/R MMIC has ≥ 1 W/channel transmit output power and ≤ 5.5 dB receive noise figure as integrated with low insertion loss T/R switches. PA efficiency, LNA noise figure and T/R switch power handling and loss were optimized to near performance limits offered by short gate length GaN technology. The SiGe SoC was set up for an analog beamforming to work specifically with the GaN T/R MMIC in a 3D stack. The SiGe SoC has 30 dB amplitude control, and near six-bit phase control. The I/Q performance plane is corrected with built-in coefficients for small and simple calibration stored within on-chip register space. Calibration tables are very small and allow a single 64-bit serial beam-steering command to repoint the entire array with potentially many hundreds or thousands of elements.

Figure 3 pictures the SiGe/GaN test boards used to characterize the channel characteristics, RF and thermal performance and is the basis of the ongoing 8 × 8 phased array modules optimized for

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All the while, there are a greater number of applications that rely ever more heavily on radionavigation, communication, and sensing technologies including unmanned, naval, land mobile, and commercial/military aerospace systems. High performance resonator technology is now becoming increasingly valuable for virtually every application including bandpass filtering, notch filtering, electromagnetic compliance (EMC), passive intermodulation (PIM) filtering, and broadband duplexing/multiplexing.

The key considerations for high quality filters are the resonator technology and overall filter design and manufacturing expertise. Though clever filter design can overcome some of the limitations of low quality resonator materials, inferior resonator materials can lead to other detrimental factors, especially at microwave and mmWave frequencies. Many of the applications that employ microwave and mmWave filters also require these devices to be thermally, and otherwise, environmentally stable. High quality resonator materials and design are necessary to ensure that a filter performs as designed in all environments. Filter complexity is also significantly reduced through the use of high quality resonators, directly reducing the size and cost of a filter relative to filters designed with low quality resonators.

For these reasons, and many others, it is even more crucial for systems integrators and microwave/mmWave system manufacturers to have access to a supplier that leverages the use of both high quality dielectric resonators/substrates as well as the filter and passive component design expertise necessary to realize the benefits of such high quality materials. This is why MCV Microwave has made addressing the customer's microwave and mmWave resonator, filter, and other passive components challenges it's mission since 1995. **With truly vertically integrated filter and component manufacturing, MCV is the ideal supplier to support quick-turn high-reliability (Hi-Rel) defense/aerospace and 5G/IoT commercial wireless communication applications.**

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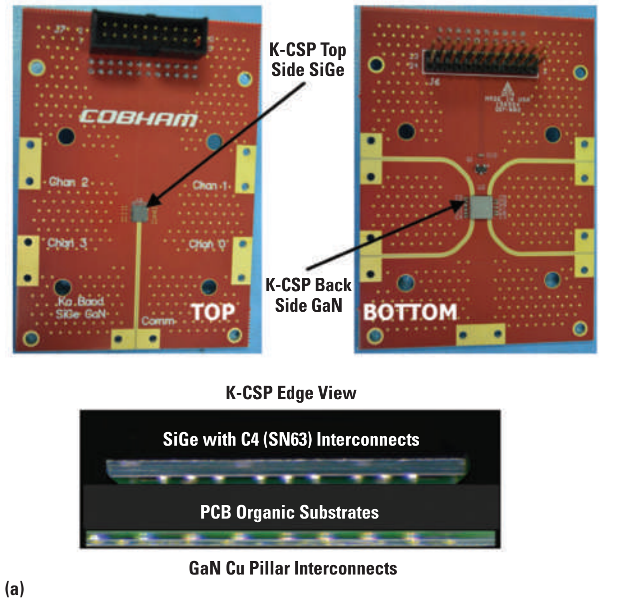

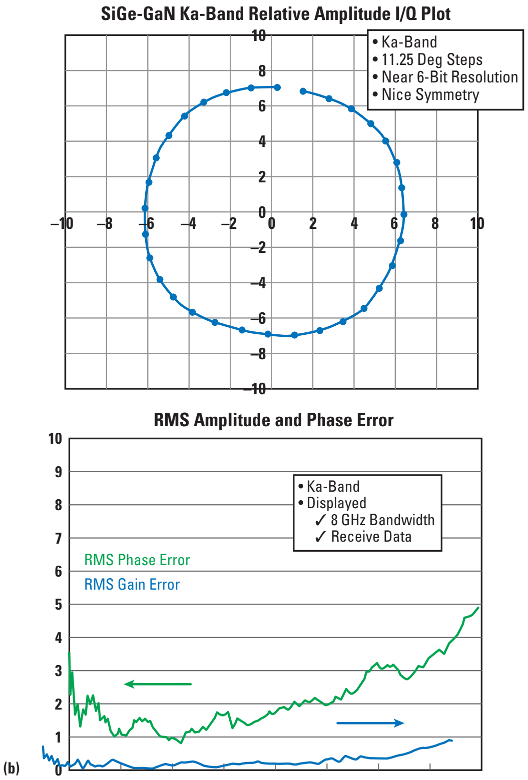

▲ Fig. 3 K-CSP test board (basis for 8 x 8 array) (a) and SiGe/GaN beam-former I/Q performance, and RMS phase and amplitude error (b).

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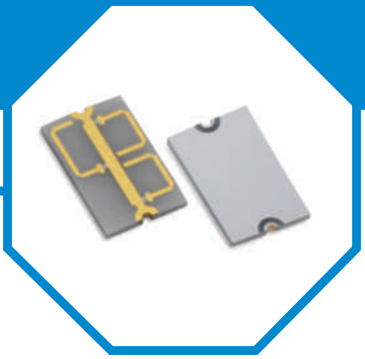

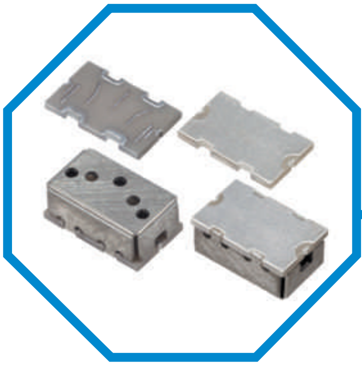

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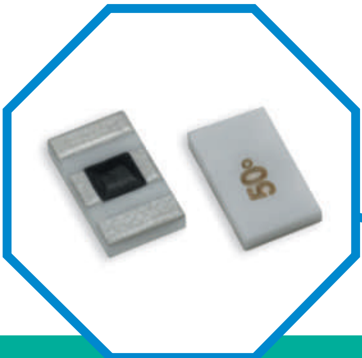

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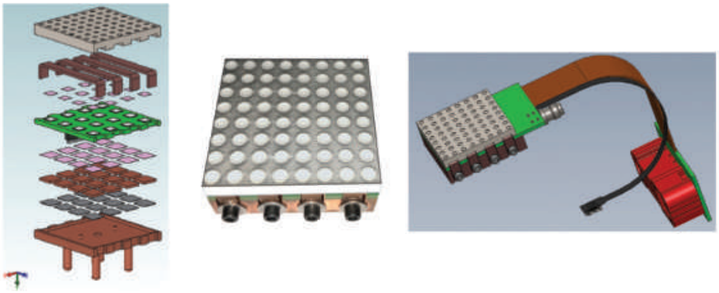
organic substrates. With nearly six bits of phase resolution channel performance, the test demonstrated RMS error of 2.4 degrees mid-band phase error and 0.36 dB of mid-band gain error.

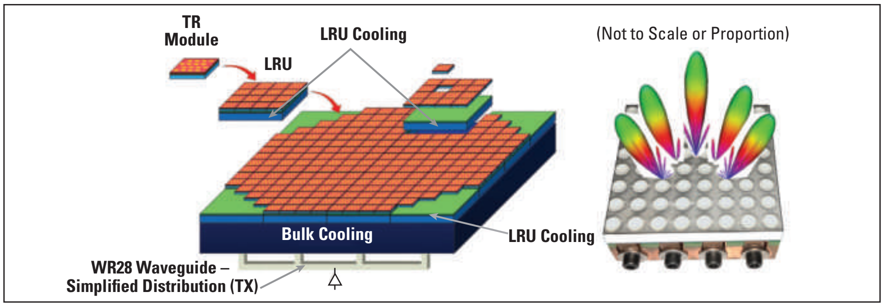
Figure 4 illustrates a 64-element sub-array and vertically integrated assembly. Extensive reliability analysis (including solder stress and mechanical stress predictions) and environmental test verification offer a path to reliable automated assembly processes for IC integration. These small integrated arrays (38.1 × 38.1 × 20.3 mm) are assembled to withstand austere environments with reliable operation both mechanically and thermally. The use of commonly available organic substrates provides the opportunity to tailor array pattern variation with custom printed circuit board shapes (i.e. round, rectangular, octagonal, etc.). The GaN MMIC has fractional-power modes and may be scaled up in output transmit power to 8 W/element or more for array architectures with a limited number of elements.

The array has a 120-degree field of view with 3 dB beam width of ± 5 degrees and less than 3 dB of scan loss at ± 60 degrees. The effective isotropic radiating power for a 256-element array is approximately 83.3 dBm (≥200 kW) with beam

Characteristics	Performance
Operating Frequency	35 GHz (20% BW)
Instantaneous Bandwidth	> 500 MHz
Scan Volume – Azimuth	+/– 60°
Scan Volume – Elevation	+/– 60°
Scan Loss (+/– 60°)	< 3 dB Estimated
Azimuth and Elevation Beam Width (3 dB)	+/– 5°
Noise Figure	5.5 dB @ 64 Elements Sub-Array
Antenna Gain	23.3 dB @ 64 Elements Sub-Array 29.2 dB @ 256 Elements (4 Sub-Arrays)
EIRP (Sub-Array/Array)	71.3 dB @ 64 Elements Sub-Array 83.3 dBm @ 256 Elements (4 Sub-Arrays)
Input Voltage	28 V DC
Cooling	Liquid Cooled
Operating Temperature	–20 to + 85° C
State Switching Speed	2.5 uS



▲ Fig. 4 64-element planar Ka-Band test sub-array and performance goals.



◀ Fig. 5 AESA topology scalable from a few elements to 1,000s of elements with LRU building blocks.

state switching speed of less than 2.5 µs. The radiating elements are circularly polarized, and the current demonstration array is half-duplex. Dual polarization configurations are also under development. The arrays are liquid cooled—with PAO or other suitable cooling liquids—to maintain a uniform temperature and low thermal gradients across the array. Integration of the Ka-Band AESA architecture is scalable into large arrays, or scalable down into arrays with fewer elements as shown in ***Figure 5***.

Fully scalable arrays require all signals to be routed through the backside of the array (including thermal) and require a blind-mate interconnect solution for both electrical (RF, control and DC) and mechanical (fluid). Each sub-array has a single RF port to be used with a sum and difference mono-pulse comparator for direction finding and tracking. This technology is manufacturable and reliable, with field-replaceable upgrades and improvements. It is also adaptable to changing requirements and technology upgrades, including polarization diversity and other advancing technologies. The applied technologies are quickly advancing manufacturing readiness levels toward production capability.

MMWAVE AESA TECHNOLOGY EVOLUTION—APERTURE TO DATA

Performance advancements in recent years in small geometry Si CMOS technology (including RF CMOS), have allowed higher levels of integration to become a reality. Work extending the multi-channel planar approach of the Ka-Band array to include other key pieces of the radar is underway with architecture studies and demonstrations. This new integration will make ultra-small advanced capability arrays with digital conversion a reality in the coming months and can be shown using mmWave radar demonstrations.

IRaD is currently underway to evolve the up/down converters, transmit signal synthesis (DAC) and receive digitization (ADC) at rates exceeding 1 GS/s and to include radar detection and digital-signal-processed datasets directly in the aperture electronics. This architecture enables multi-beam software-defined digital beamforming (or mixing of digital and analog beamforming). This capability enables digitally modulated radar sensor operation utilizing beamforming


5G

and code division multiplexed MIMO radar capabilities. The MIMO feature offers extended virtual receive channels, improved angular resolution and interference immunity associated with digitally coded channels. These extended capabilities also offer improved range resolution, better signal to noise ratio at similar frame rates and faster updates with short system cycles. The system can also switch between phase array modes and massive MIMO processing mode or a combination thereof. Advance digital processing ICs utilizing these capabilities result in 4D detection datasets with spatial position and velocity for many targets. This is the new world of aperture to data.

This architecture offers other advantages. The integration of the RF converter, ADC/DAC and radar data processor into the aperture electronics will drastically simplify interconnect solutions. Traditionally, the direct digital conversion and processing functions have been power-hungry; now these capabilities may be included more efficiently, with less prime power and lower heat generation. mmWave RF connections (coax or wave guide) are no longer needed to route signals throughout the application platform. Interconnect simplicity is achieved by way of high-speed data uplinks (10/100 Gbit/s) through Ethernet or proprietary vehicles—along with simple DC supply line distribution—making radar and sensor aperture deployment easier and faster. Further, widely used production processes for fully automated assembly processes are utilized to minimize human touches, improve reliability, eliminate tuning and ruggedize the platform for austere environments and challenging operating conditions. Improved system performance (associated with RF signal loss), simpler interconnects, faster integration, smaller size and weight and lower cost offer overall system value.

SUMMARY

The extended capabilities and value proposition associated with integrated and multi-mode mmWave array technology include:

- Advanced packaged 3D electrical and thermal integration at the aperture
- SiGe beam-formers and advanced custom CMOS ICs for advanced functionality
- Higher transmit power and rugged assemblies for integrated multichannel GaN T/R MMICs
- Multi-channel digitally coded phased array, MIMO sensor capabilities
- Mono-pulse direction finding
- Advanced angular resolution
- Improved Doppler
- Multiplicity of scans in compressed scanned times
- Fast uplink
- Simpler integration and deployment
- Smaller packages (size and weight)
- No tuning automated assembly
- Lower cost
- Scaled solutions (from a few elements to 1,000s of elements)
- Integrated "aperture to data" architecture

It is a great time to be involved in today's battlefield, which is simplified by the value proposition of advanced technology solutions for broad deployment to the warfighter. ■

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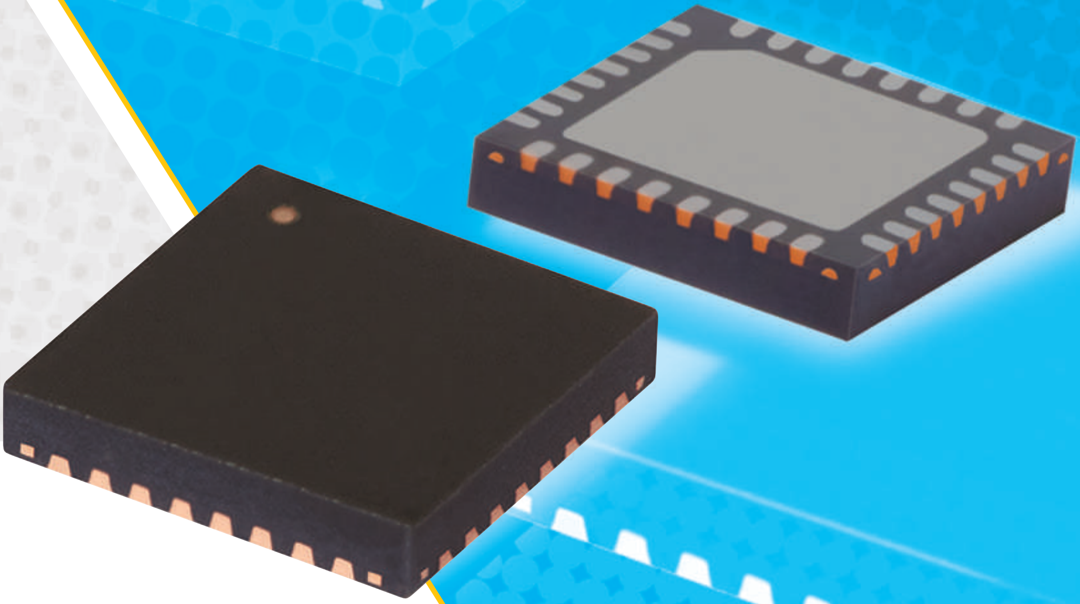

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Editor's Note: In this year's Aerospace & Defense Electronics supplement, we are fortunate to have two perspectives from senior members of the defense industry, who discuss challenges faced by the U.S. in maintaining technical superiority amidst the explosion in low-cost commercial technology.

Bill Conley, the chief technology officer at Mercury Systems and former director for electronic warfare (EW) in the Office of the Secretary of Defense, examines the imbalance between Department of Defense (DoD) and commercial R&D. To counter China's growing power, he argues the U.S. must leverage commercial technology with targeted funding for unique defense capabilities.

Ben McMahon, a technology development manager at BAE Systems' FAST Labs, describes how the adoption of mmWave spectrum by commercial systems and the underlying technology are challenging the capabilities of EW systems. He writes the future of electromagnetic spectrum operations will require multifunction systems designed for rapid upgrades, blending commercial and defense technologies.

An R&D Investment Strategy to Maintain Aerospace & Defense Leadership

William Conley
Mercury Systems, Andover, Mass.

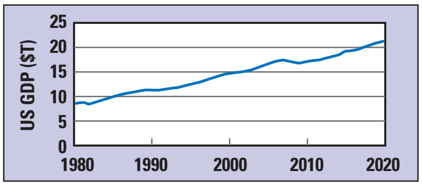
Our RF/microwave industry is unique in the larger aerospace and defense (A&D) marketplace. Fundamental technical and economic reasons drive our industry to have distinct and innovative processes to meet our national security needs. Frequently, we are the trailblazers, pushing ahead for our customers, exploring advanced new technical approaches and processes, all the while providing amazingly complex components, modules and assemblies. For that reason, it doesn't surprise me that over the past century, we have historically been early adopters of key innovations in response to evolutions in the global marketplace. This article provides context for the continuing changes in the A&D landscape and how we can lead in implementing these changes to meet our national security objectives.

NEW GLOBAL LANDSCAPE

From my experience in the Pentagon, seven different methods of international power are commonly discussed: diplomacy, information, military, economic, financial, intelligence and legal. These are commonly referred to by the acronym DIMEFIL (pronounced dime-phil). Prior to the foundation of global communications, diplomacy was paramount. Through the two world wars, military power was vital and supported through economic power. The Cold War was largely based on information and economic power, with military taking a back seat. As more financial transactions become electronic in the global marketplace, sanctions became an effective method for deploying financial power. The ratios among the methods are constantly evolving; but together, they underpin how innovation occurs and how technology is adopted by governments.

Several of these methods of international power can be directly measured with common metrics. Economic power can be approximated by a nation's gross domestic product (GDP). ***Figure 1*** shows the growth of the U.S. GDP since 1980. ***Figure 2*** shows defense spending, a proxy for military power, and R&D investment—the implications of the latter will be discussed later in this article—over that same period. All the values are in constant-year dollars to provide a fair comparison. In the second graph, both the Cold War buildup and the Global War on Terror following 9/11 are readily observable by upticks in defense spending. Unlike the peaks and troughs in military spending, R&D investment has steadily increased and is an increasingly important part of international power, as it underpins both military investments as well as economic growth. These macroscopic metrics can be compared among countries using well-established data sets. All the data uses purchase power parity (PPP) conversation rates, which is a fairer comparison, not only of the exchange rate but also the cost of goods.

Figure 3 shows the relative size of the economy, military spending and nationwide R&D of the Chinese state compared to the U.S. The direct comparisons are not exact but do show important trends. For example, this analysis assumes the published U.S. and China budgets show the full investment; in both cases, the values shown are likely lower bounds. Note that a PPP comparison shows the Chinese state with a larger economy than the U.S., largely due to the lower cost of materials and goods in China. The data also shows a much faster growth rate for China's economy, and China has prioritized increasing R&D spending faster than they have increased military spending. While the U.S. still invests more in R&D, the 60 percent mismatch with China today drives us to a very different strategy than we pursued during the Cold War. The size of the American economy supported substantially more military and R&D spending in the U.S. than the Soviet Union could match. The data presented here reveals we can-



▲ Fig. 1 U.S. GDP in constant-year dollars.

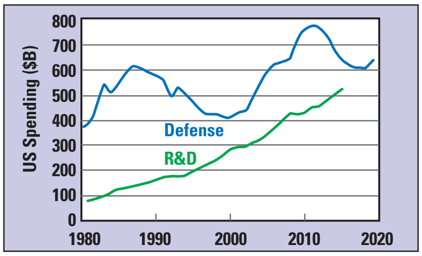
not out-innovate in today's era of Great Power competition.

SHIFTING INVESTMENT

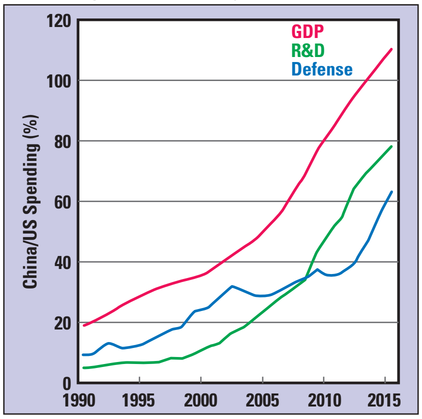
The source of innovation across the U.S. economy has shifted dramatically over the past several decades. While total R&D spending has increased continuously, ***Figure 4*** shows the relative ratio of federal to commercial R&D investment. For most of the Cold War, the federal R&D investment was approximately double commercial R&D. This began to shift around 1970, leading to parity in 1980. Over the past two decades, commercial R&D investment has been at least 2× federal investment and is rapidly approaching 3×.

While investments in hypersonic weapons are exclusively pursued with federal R&D investment, RF/microwave R&D blends commercial and federal investment, with commercial dominating. Military systems use less than one percent of all microelectronic components produced, according to estimates. The dominance of commercial investment means that the A&D market for RF/microwave components is largely built on commercial investments and, thus, commercial requirements. This generalization is not universal: some specialty components are exclusive A&D opportunities, where governments can gain sustained technical advantages. However, these opportunities are declining as multi-function, broadband, reconfigurable and software-defined RF/microwave systems are being developed to increase scale for commercial applications.

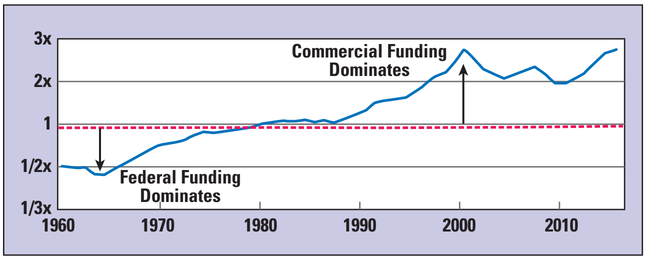
While the RF/microwave industrial base has experienced these investment mismatches for decades, emerging technologies such as artificial intelligence will accelerate the mismatch. It's estimated the training capability of neural nets is doubling every 3.4 months, which makes Moore's Law—a doubling of transistor density every 18 months—appear as a relaxed speed of adopting new technology. The military impacts from this rate of change are profound. It means that a system is only 10 percent as capable a year after fielding and only one percent as capable after two years. Many military systems operate for a decade; at the end of this typical life, they would only have a billionth the capabil-



▲ Fig. 2 U.S. defense and R&D spending in constant-year dollars.



▲ Fig. 3 China vs. U.S. GDP, R&D and defense investment (PPP comparison).



▲ Fig. 4 U.S. commercial vs. federal R&D investment.

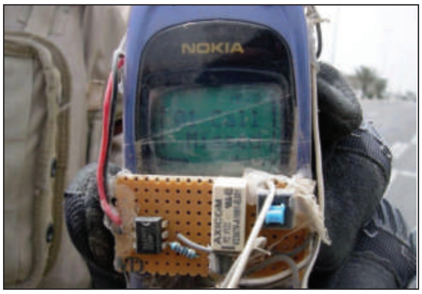
ity of a new system. As the technical advantage of a newer system will translate into an operational military advantage, we should expect to see military systems continue to drive toward open systems, composability and rapid upgradability. Military systems lacking these traits for electronics will be obsolete very quickly.

Another example of commercial investment outpacing federal investment relates to 5G. Earlier in my career, I personally reverse engineered a variety of improvised explosive device (IED) detonators using commercial devices. A commonly shared photo at the time (see ***Figure 5***) reminds us of our former threat zeitgeist. As a result of those experiences, I'm skeptical that 5G devices will be broadly adopted by militaries because of the mission vulnerabilities introduced. However, the expanded frequency range of 5G devices into Ka-Band is developing new modeling and simulation capabilities, analog components and broadband transceiver technology. All these advances will substantially impact A&D systems operating at Ka-Band. The lower price and globally democratized design capabilities mean we should expect a proliferation of Ka-Band systems in the next few years, due to commercial investment being transferred back into military systems.

CULTURAL INFLUENCES

I've focused so far on the technical aspects of investments, which are underpinned by company cultures. Most A&D companies are valued largely on the return on invested capital. Technology companies are valued on growth. The need to sustain growth will drive technology companies to adopt new innovative approaches, even faster in the future. However, A&D companies may view capital investments as being prohibitively high when measured by the return. The impedance mismatch between the nation's industrial base and the self-identified defense industrial base (DIB) will continue to grow.

This is not the first time that the DIB and national industrial base have been intertwined, however. The stories during World War II (WWII) of auto manufactures responding to defense needs is well known. Perhaps less well known, the original investment in Sili-



▲ Fig. 5 Cellular phone used to trigger an IED.

con Valley largely came from the needs for electronic warfare systems during WWII. Steve Blank's "Secret History of Silicon Valley" does an excellent job telling the full story of how investments during the 1940s shaped the culture of responding quickly and developing amazingly complicated technical solutions. Even during WWII, a typical electronic countermeasure was only useful for about four months, when it was countered by the adversary. The operations analysis book "U-Boats in the Bay of Biscay" discusses this in detail.

As we've seen again this year, the entire country's industrial base is capable of mobilizing to meet our security needs, evident in the global response to the coronavirus. Manufacturers from defense to fashion to consumer goods to automotive have pivoted to make personal protective equipment and medical devices. The pivot occurred within a month to respond to a rapidly emerging threat to our health and livelihoods.

MODEL FOR FUTURE SUCCESS

The examples cited demonstrate how the entire industrial base can be pivoted to solve our national security needs. I am hopeful the nation's industrial base considers itself part of the national security community. While the traditional members of the DIB can meet the nation's needs during times of relative peace, we must all be prepared to surge if a major conflict occurs.

Quoting the late Deputy Assistant Secretary of Defense for Tactical Warfare Systems, Jimmy MacStravic, "We move at the speed of trust." Returning to the development of open systems, fully sharing interface documentation is critical. Most standards need to be formed in collaboration among purely commercial companies and those serving the A&D market. As we've seen, commercial investments will drive many important advances in the future; however, physics is application agnostic. I am hopeful the design tools and fundamental understanding will be fully and quickly used in both commercial pursuits and A&D applications. Critical capital investments will be required to align these ecosystems.

Many of today's defense challenges involve the integration of advanced technologies onto platforms. Similar challenges drove the automotive and aerospace markets during past decades. As we look to an IoT future, I am hopeful that more of the commercial composability will be applicable to managing the complexity of future military systems. It's obviously quixotic to assume that all the challenges of multi-domain operations will be addressed by commercial advancements, but best practices need to be broadly shared to realize—and afford—the future operating concepts of the DoD.

In summary, it's an exciting time to work in a business on the technological seam between commercial and defense applications. We'll see this continue to be critically important: The strategies from the Cold War are based upon substantially different assumptions, so new processes, new policies and adopting new solutions faster will be increasingly important. I fully expect the rate of change will continue to accelerate in the RF/microwave portion of the A&D ecosystem. As a community, we are well positioned to lead the nation's defense into the future.■

Bridging Commercial and Defense Technology to Maintain EW Innovation

Benjamin McMahon
BAE Systems, Nashua, N.H.

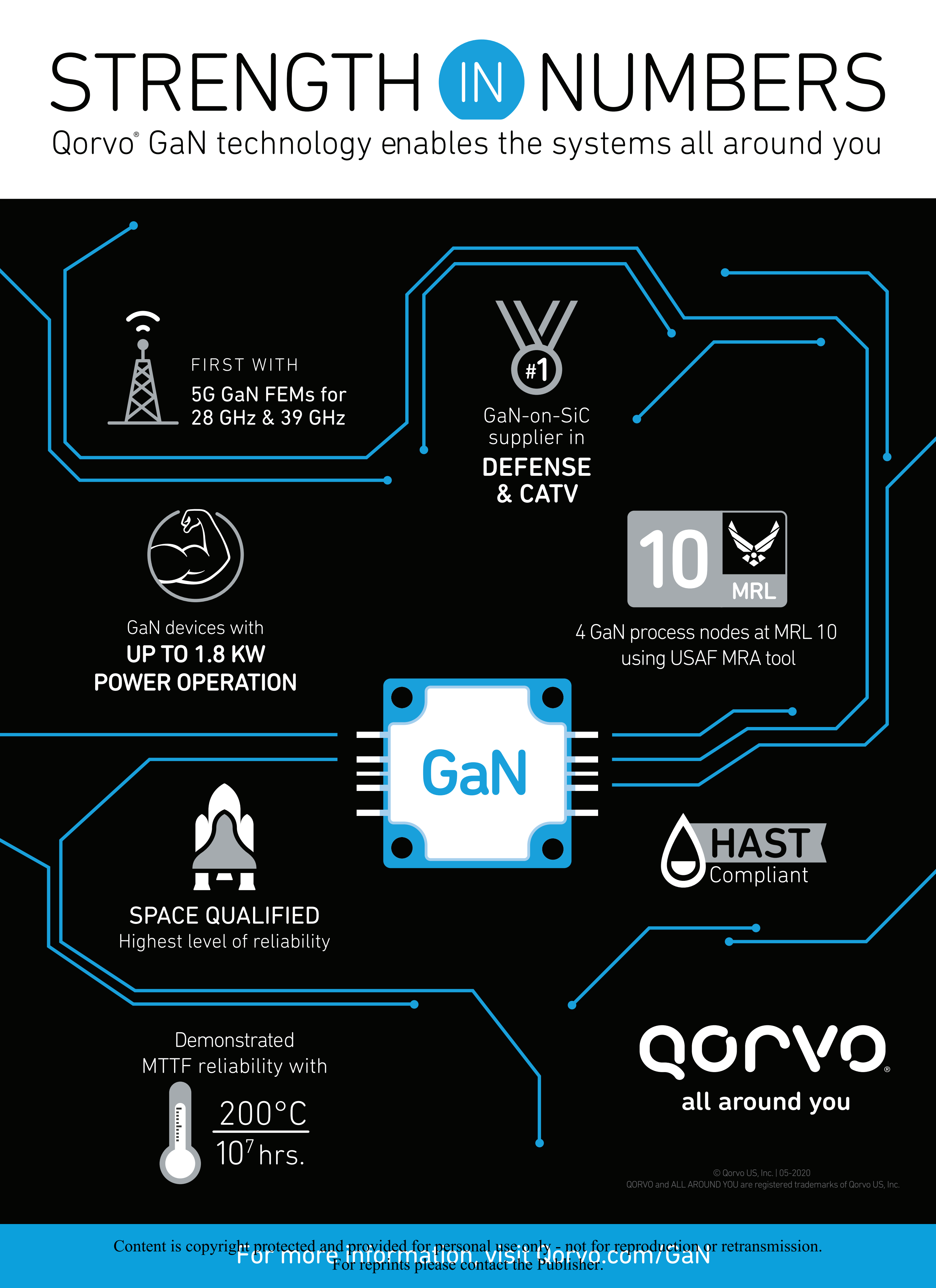
From an electronic warfare (EW) perspective, offensive or defensive, in most engagements we do not control the pace or band of the electromagnetic spectrum operations. Rather, our systems react to the emitters or target systems' capabilities, operations and locations. We must address as many of the emitters as possible to maximize the benefit to the warfighter, both effectiveness and lifecycle cost. Emitters of interest for our EW systems span communications, radars and unintended radiation sources; a subset are passive sensors, with no intended radiation at all. In many cases, radar and communications systems have moved higher in frequency over the decades, while legacy systems maintain persistence in the lower frequency bands. Our EW systems must detect, identify, locate, intercept, report and sometimes engage these sources of intended and unintended emissions, regardless of frequency.

The limiting factor for our adversaries is the efficiency and cost of the electronics. This, ultimately, controls the growth of emitters to higher frequencies. This growth necessitates a wideband EW system, or series of systems, that must address threats from VHF through mmWave, sometimes in the same mission. The proliferation of 5G high-band communication systems and automotive radar drives the efficiency and cost of high frequency electronics at a commercial scale. This creates a dilemma for EW systems: the volume driving this commercial scale generates tremendous increases in radar and communications network performance at mmWave frequencies on an almost annual basis. EW systems must operate in extreme environmental conditions, where automotive radar and 5G communications operate in comparably moderate conditions. Further, our adversaries have access to the same commercial electronics we do, with the ability to leverage the commercial scale to build and deploy high performance systems that threaten our warfighters' ability to dominate the electromagnetic spectrum.

Higher band radars have better performance because they provide better range and Doppler resolution and require tightly integrated electronics. Radar systems will operate in higher bands when possible, where less congestion and noise impact the ambient noise floor. For a "threat radar," these parameters translate to more accurate "weapons quality" tracks on aircraft, projectiles and UAVs. Radars with advanced high frequency electronics and apertures are becoming land mobile, meaning they can be moved rapidly and do not require hardened installations. The uncertainty of the location of these threat radars at any given time necessitates the effectiveness of EW systems to protect our assets from engagement.

From an electronic support measures (ESM and often referred to as ISR) perspective, we see the density of higher frequency emitters growing. Our adversaries can now develop radar and communications systems using commercial scale electronics to proliferate emitter density to the point where every platform must be equipped with a high performing EW system to maintain persistent awareness of the emitters on the battlefield. This awareness maximizes opportunities for electronic attack (EA) engagements or self-protection. Without addressing the higher frequency bands in this environment, our ability to maintain spectrum dominance erodes. This uncertain future necessitates investment in DoD-quality, high frequency electronics.

Since the end of World War II, the United States has maintained technological advantage over our adversaries as a deterrence and to provide technological overmatch when conflict arises. That technological advantage has waned in recent decades, partly because of the massive influx of commercial investment in electronics, manufactured mostly outside the United States, and the relative decline of investments in DoD electronics. High performance electronics designed and fabricated at scale offshore further intensifies the dilemma for EW systems. In 2019, Intel's R&D investments alone were nearly 40x DARPA's investment in the Electronics Technology program element of the DoD Budget Estimates, which makes pivotal investments in breakthrough technologies for national security. Today, our adversaries have open and commercial access to these technologies. Among the top 10 found-


STRENGTH IN NUMBERS
Qorvo® GaN technology enables the systems all around you
FIRST WITH
5G GaN FEMs for 28 GHz & 39 GHz
#1
GaN-on-SiC supplier in
DEFENSE & CATV
10
MRL
4 GaN process nodes at MRL 10 using USAF MRA tool
GaN devices with
UP TO 1.8 KW POWER OPERATION
GaN
HAST
Compliant
SPACE QUALIFIED
Highest level of reliability
Demonstrated MTTF reliability with
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ries by revenue in the world, a small percentage can produce International Traffic in Arms (ITAR) regulated parts for use in DoD systems. Recent efforts, such as DARPA's Electronics Resurgence and OSD's MINSEC initiatives, are addressing part of the dilemma.

DIVERGENT MILITARY AND COMMERCIAL REQUIREMENTS

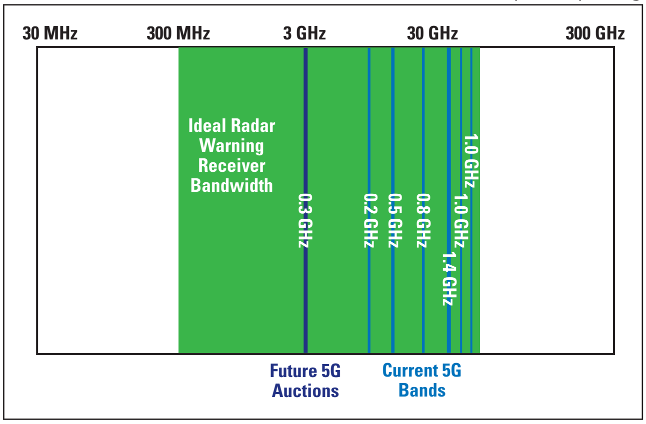
There will always be divergence between DoD and commercial electronics requirements. In some cases, DoD electronics will require non-commercial sources, while continuing to use commercial off-the-shelf (COTS) electronics where possible. Certainly, the DoD will not be able to drive its unique requirements into commercial nodes and foundries at the volumes of commercial production. The primary differences between the two sets of requirements are:

Operating thermal environment—Broadly known temperature grades for active electronics are 0°C to 45°C for commercial, -20°C to 85°C for industrial and -55°C to 125°C for military. Some DoD applications exceed the military operational range, making commercial parts far out of reach for most DoD environments, with the exception of very few high grade automotive components. Due to the economies of scale in commercial electronics, the relatively small quantities of DoD systems prevent commercial investment and continued attention.

Bandwidth—International regulatory agencies control the spectrum used by 5G and automotive radar, for good reason. Next-generation EW systems ideally operate over all these bands to counter as many emitters as possible with a single system. The alternative of employing multiple banded systems, each intended for a different band or emitter type, applies pressure on the size, weight and power consumed by the solution. ***Figure 1*** illustrates the challenge, showing current and planned frequency allocations for 5G, including the recent FCC auctions allocating spectrum at mmWave (i.e., auctions 101, 102 and 103). A future ideal radar warning receiver must cover low frequency radars through 5G frequencies. All components, from the front-end electronics to the transceiver and digital processing, contribute to the identification of signals, either instantaneously over a wide band or by tuning across a wide band. Current 5G and automotive applications are standardized by the spectral regulatory framework and are optimized for narrower bandwidths, preventing these electronic components from being used in broadband EW systems.

Assured supply chain—GlobalFoundries' recent decision to stop development of a 7 nm CMOS production process sent shivers through the DoD supply chain. One of the few capable on-shore, advanced node CMOS foundries made a cost-driven decision to discontinue development, leaving DoD with no on-shore trusted source. This event blunted hopes of a small geometry CMOS, on-shore capability with the potential for trusted production. While relying on non-trusted and off-shore foundries for high frequency DoD electronics will reduce cost, it leaves our ability to maintain critical supply chains to foreign corporate profit and loss decisions, political circumstances and, in case of a military or "trade war" conflict, the possibility of a complete embargo or shutdown in supply.

Secure supply chain and counterfeit parts—ITAR and Export Administration Regulations, while preventing the export of DoD technology, also help prevent malicious actors from participating



▲ Fig. 1 A future ideal radar warning receiver will cover all radar bands, to include the new 5G mmWave bands.

in the fabrication of hardware going into DoD systems. In 2015, Bloomberg reported malicious hardware was found on Supermicro motherboards in DoD data centers, CIA drones and Navy warships. The chips were allegedly inserted at factories in China, though the story has not reached any conclusion. This scenario highlights the risk of not only board-level malicious hardware trojans, but also chip-level trojans even more difficult, if not impossible, to discover.

Obsolescence—The upgrade cycle of high volume commercial products, such as mobile smartphones and personal computers, is high. DoD systems will use the same component for decades beyond the day the manufacturer discontinues it, forcing "lifetime buys" and costly redesigns to prevent obsolescence, even when a redesign cycle is not necessary for any other reason. A commercial foundry will not continue manufacturing electronics nodes only used in decades old, low volume systems.

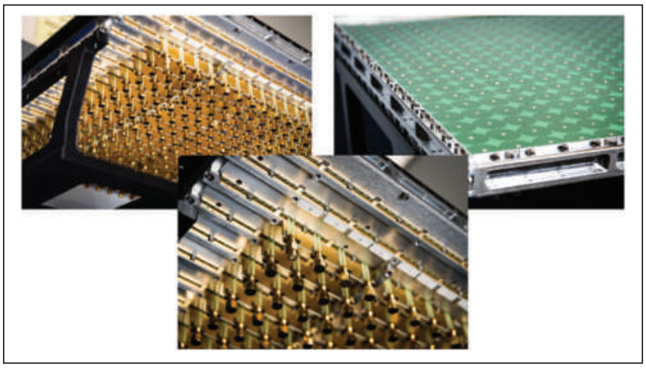
▲ Fig. 2 The F-22 Raptor development began in 1986 and is expected to fly for another decade or more. Source: BAE Systems.

As an example of the obsolescence challenge, the F-22 Raptor's development began in 1986, and the AN/ALR-94 EW suite, one of the most technologically advanced systems on the F-22, was first delivered in 1999 (see ***Figure 2***).[1] Now, 21 years later, with 183 F-22s in service, the Air Force continuously faces the need for modernization to keep pace with adversary capabilities. As part of its mid-life upgrade, F-22 sensor modernization is due in the middle part of this decade. The F-22 is expected to be superseded by a sixth-generation tactical fighter sometime within the next two decades, underscoring that the fighter's electronics are required to operate between two and four decades.

ASSURING MISSION SUCCESS

How do we solve the EW system dilemma? There is no single answer. To start, there are areas of common technical ground where development will benefit both DoD and COTS systems.

Modern mixed-signal nodes, such as 7 to 14 nm CMOS, 90 nm SiGe and the DARPA T-MUSIC 45 nm SiGe on-shore foundry, are driving higher frequency performance and higher computing capability for less size and power. However, having higher power densities, these nodes in the extreme temperature environment of DoD systems require exquisite cooling approaches, further increasing overall power consumption. We need continued advancement of high operating temperature electronics requiring less cooling, such as mixed-signal SiC that can operate at very high junction temperatures, reducing the need for active cooling. Future military operating temperatures may exceed 225°C, for which there are currently no mature solutions. If your organization has technology to offer, the DoD wants to see it.



▲ Fig. 3 A mid-frequency phased array using connectorized electronics becomes intractable as arrays move to mmWave and higher frequencies.

The rapid growth of multichannel phased arrays and extension into mmWave bands drives the integration of electronics into smaller packages. Heterogeneous packaging enables interconnects between ICs of different nodes, with each node optimized for its function, eliminating transmission lines on the carrier circuit board. As we push to higher frequency bands, the loss between die within the package becomes more critical. DoD systems require higher yield, lower loss heterogeneous packages to minimize the footprint of high frequency transceivers. As phased arrays move to mmWave and higher bands, circuit board and cable connections between the antenna elements and front-end electronics will be a non-starter to achieve the required electrical performance and size (see ***Figure 3***).

The tighter integration of electronics enables the realization of high channel count, element-level digital phased arrays, adding low probability of intercept communications, massive MIMO, directional EA and multiband ESM to the radar functions. High input/output, reconfigurable logic devices, such as the Xilinx VU13P, may aggregate hundreds of channels to form beams; however, they have grossly oversized logic and IP cores that go unused, unnecessarily increasing size, weight and power (SWaP). Reconfigurable beamforming ASICs are needed to reduce the SWaP of multifunction digital phased arrays.

ASICs are driving down the cost, size and power consumption of commercial systems. The rapid upgrade cycle of commercial electronics will require modification of these ASICs over time and occasional redesign into new nodes when the benefit outweighs the cost. Similarly, on DoD systems, incremental upgrades are costly but less frequent. A standing capability to rapidly upgrade and modify ASICs for incremental improvements is favorable for both DoD and commercial markets.

Attention to these areas of common ground among commercial and DoD markets will benefit both. With careful attention to detail and prudent design decisions, the innovators of DoD electronics will be able to leverage some, although not all, of the technologies being developed at commercial scale. ■

Reference

1. Military Periscope, "AN/ALR-94 Electronic Warfare Suite," www.militaryperiscope.com/weapons/sensorselectronics/electronic-support-measureselectronic-warfare/analr-94-electronic.

Cognitive Countermeasures Determine Mission Success

Nancy Friedrich
Keysight Technologies, Santa Rosa, Calif.

As electromagnetic spectrum operations dominate the modern electronic warfare (EW) environment, countermeasure approaches increasingly leverage software and machine learning to win.

The global fight for EW dominance often plays out in smaller incidents. If one fighter jet faces off against a rival, they may do small maneuvers to see which can outperform the other. While such exhibits used to rely on the pilot's prowess, today's scenarios reveal much more about a country's technology. Forces want to know if other militaries can detect, identify and locate their assets—as well as what they can do to counter those capabilities. Beyond the physical presence of warfighters, a larger conflict rages for dominance of the electromagnetic (EM) spectrum. With the rise of adaptive threats and countermeasures, the winner's system is the one that outwits its opponent. As threats grow more sophisticated, countermeasures must evolve at or beyond that pace. With radar, for example, every evolution brings more complexity. Yet countermeasures must achieve the same complexity and, potentially, move beyond it. Techniques continue to evolve, often relying on some standard jamming approaches.

JAMMING TECHNIQUES

A simple way to undermine a radar is by jamming it with broadband noise. The radar sends out a pulse, which reflects off objects in the environment and returns to the radar receiver. If a pulse is sent where an F-35 is flying, for example, the RF energy bounces off the aircraft and returns. At the exact time when the skin or echo return hits the receiver, a noise jammer sends broadband RF noise into the receiver, obscuring the skin return because the receiver can only see the huge amount of noise energy.

Jamming techniques like range gate and velocity gate pull-off advance this approach by sending a pulse that looks like the skin return—yet slightly altered. As a result, the target appears to be moving in a different direction, so the radar loses track. With this approach, the aircraft seems like it is flying in a different direction than its true course.

Another well-known jamming method, digital radio frequency memory, receives a radar's RF signal, digitizes it and creates new RF signals


Superior Hybrid Rotary Joints and Slip Rings
Slim Sized Rotary Joint
Dual Channel WG Coax
Fiber Optic Rotary Joint and Slip Ring
Hybrid Rotary Joint

based on the received pulse. Because this approach has very fast processing, it can create many pulses or false targets, tricking the radar into "thinking" there are a thousand aircraft instead of just one.

Stealth has been the leading edge in countermeasures for years. Like the other jamming approaches, it confuses the radar about the target: creating uncertainty about whether a target is present or, if it is detected, misconstruing its location or the number of targets. The radar sends out a pulse but cannot get a good skin return. Stealth relies on the design of the fighter's surfaces and the materials comprising it—which do not reflect RF energy well—so the radar return is very low. However, the stealth code has been somewhat cracked in recent years, and stealth has lost its lead position, unless new countermeasures can be employed to combat successful detection.

THE NEW STATE-OF-THE-ART

While adaptive threats and countermeasures are not new to EW, cognitive EW integrates advanced technologies such as artificial intelligence (AI), and the resulting countermeasures gain speed and efficiency to boost the identification and tracking of threats. Because cognitive EW implements more of an AI or machine learning approach, it surpasses adaptive countermeasures. When a threat wins against a cognitive countermeasure, the countermeasure learns from the experience and becomes more effective.

With AI, machines can perform smarter tasks using capabilities like signals recognition. Machine learning takes AI one step further, allowing machines to continuously learn from new data and adapt. As these computers learn rapidly, threats using machine learning will learn from every conflict, determining ways to be more effective to prevail against future countermeasures. In the cat and mouse game of EW, countermeasures must leverage machine learning to stay ahead of the threats.

This evolution in capability does not need human interaction because the computer decides how to alter its behaviors. When tested or engaged, cognitive systems learn from the experience and modify future behavior—the computer decides the next steps. As these systems advance, they will adapt and alter their courses of action increasingly rapidly. For example, if a radar is trying to track a jet, the adversary's countermeasures may first stop it from succeeding; with machine learning, the radar would repeatedly try new approaches to successfully track future targets.

Modern machine learning techniques to increase cognitive ability include target recognition, intelligent decision making and autonomous learning. Complex and congested signal environments make it challenging to locate, identify, jam and confuse enemy communications systems, especially if they are adaptive. Adaptive radars make it challenging for countermeasures to isolate pulses from threatening radars, understand threats from hostile radars and provide adequate responses.

Military technology is increasingly turning to machine learning to create cognitive EW countermeasures to successfully operate in these complex electromagnetic environments. These systems use software-defined capabilities to gain operational flexibility in congested and contested environments, quicker upgrades and greater affordability (see ***Figure 1***). Software-defined systems can alter parameters such as waveforms, frequencies, techniques and timing. This rapid pace of change will be faster than most system development lifecycles.

Combining cognitive approaches, increased capabilities and lower cost leads to threats evolving more quickly than the responding countermeasures can be built. The issue of congestion

▲ Fig. 1 EW systems increasingly use software-defined capabilities to alter parameters such as waveform, frequency, technique and timing. *Source*: Getty Images

further complicates the effectiveness of countermeasures, as the crowded EM spectrum often yields an overwhelming noise floor, so some signals of interest get lost in the noise. With the trend of more affordable and sophisticated technologies, some adversaries can create systems that hide within the noise—the challenge is like finding the proverbial needle in a haystack. Even if the system does pick out the right signal and identifies it, the signal can change in a moment. Nonetheless, the system must separate the relevant from the irrelevant data to yield actual intelligence, so the signals of interest are detected and located.

▲ Fig. 2 Signal generator output with two chirped radar emitters, 1.5 GHz wide and 7 GHz apart.

ELECTRONIC COUNTERMEASURES ANALYSIS

A hindrance to success is that EW systems traditionally work off legacy, fixed information about the EM environment. Such systems identify radars by characteristics such as appearance and emitted RF energy and usually employ these steps:

- The threat becomes known.
- Identifying parameters are added to a database, such as the radar type, frequency band where the threat operates, bandwidth and country of origin.
- If the system sees this threat again, it will respond with the appropriate countermeasures.

With the rapid evolution of cognitive EW threats, this database approach becomes unwieldy, especially when interacting with unknown threats from unknown origins demanding a quick response. If a threat radiates on one frequency, then changes frequency moments later, it poses a problem for militaries using such databases. If the data is constantly changing, the database will not be current or useful.

As a result, militaries are moving away from legacy systems and adopting approaches that respond to new threats with machine learning. Rather than rely on a fixed database, newer systems learn and adjust as the threats do. They can better detect and analyze advanced threats, adjusting and keeping pace as those threats change, based on observed behaviors (see ***Figure 2***). Advances in countermeasure analysis also test and stress the system's response to a dense threat environment, as real world scenarios have large numbers of simultaneous threats.

▲ Fig. 3 Responding to technology advancements in the threat environment, EW systems must be flexible, scalable and meet program and test requirements.

In contrast, newer systems emulate real world threats, generating and sending signals (see ***Figure 3***). They help the military detect and analyze these signals more quickly, providing the knowledge and opportunity to respond with the optimal countermeasures. As threats augment their capabilities, electronic countermeasures must also boost capability. Even with these newer methodologies, challenges arise analyzing modern electronic countermeasures. Ironically, countermeasure analysis will prevail by leveraging much of the same advancements used by the threats: cognitive capabilities, software-defined radios and highly increased processing power.■

Simulating Real World Radar Scenarios with Vector Signal Generators

Rohde & Schwarz
Munich, Germany

Testing radar warning equipment in realistic scenarios is crucial to reliable performance in the field. Traditionally, dedicated instruments or test systems have been used for this. Now, commercial vector signal generators (VSG), such as the R&S®SMW200A from Rohde & Schwarz, offer an attractive alternative because of their increased bandwidth and processing power.

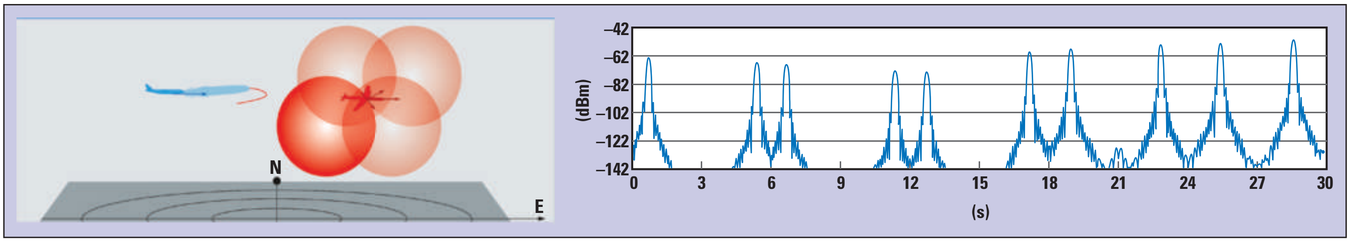
REALISTIC SCENARIOS

Modern VSGs can generate a realistic, dense RF environment, with the capability to play back a nearly unlimited range of signals from simple unmodulated pulses to radar signals with modulation on pulse (MOP). The high modulation bandwidth of these VSGs enables modern frequency-agile radars to be simulated. The signal source can be shared among different applications, from simple VSG to high-end radar simulation—all benefiting from outstanding RF performance. Using a single source for many applications reduces test and measurement costs and provides users with flexibility.

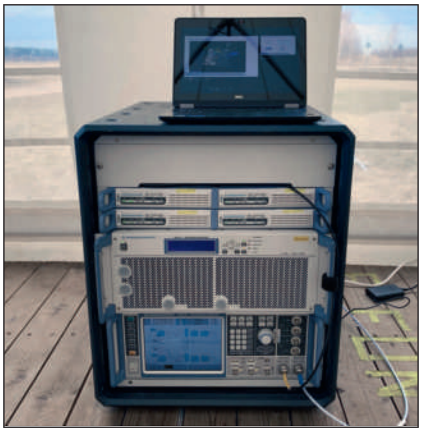
▲ Fig. 1 The R&S SMW200A VSG with R&S Pulse Sequencer PC software provides a compact, powerful radar simulator for the lab.

With the SMW200A VSG, Rohde & Schwarz offers a solution for testing radar warning equipment with realistic scenarios. Combining the generator with the PC-based R&S Pulse Sequencer software creates a powerful simulator with everything needed for testing (see ***Figure 1***). The simulator can generate current and future radar signals, creating scenarios with multiple complex, high-resolution signals, and it can be used for all phases in the equipment lifecycle, from early design in the lab, integrated system testing in production, testing in the field and maintenance. The heart of the solution is the VSG, which supports all typical radar bands to 44 GHz. The flexibility of the digital hardware with 2 GHz internal I/Q bandwidth enables simulation of pulse-on-pulse scenarios with up to six overlapping pulses in an instrument with one RF port and a maximum pulse density of 6× 3.3 million pulses per second.

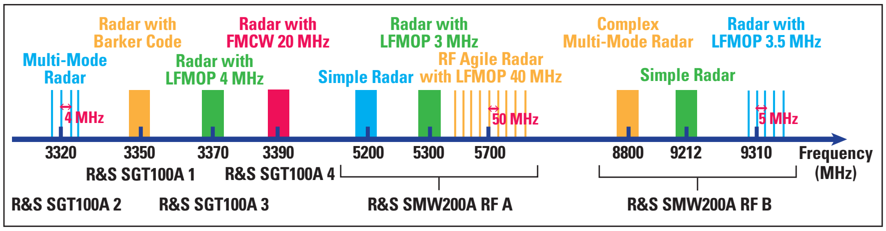
Radar warning receivers use input signals from multiple antennas to determine the direction of arrival of the signal from an emitter. This functionality can also be tested in the lab with coupled instruments that provide multiple synchronous signals.



▲ Fig. 2 3D flight scenario with the emitter and receiver moving.



▲ Fig. 3 At an OTA demonstration at Tartu Airport in Estonia, the signal generators and amplifier were mounted in a small rack, with the R&S Pulse Sequencer software running on a commercial laptop.



▲ Fig. 4 Example signal plan used at the Tartu Airport demonstration. One dual-path R&S SMW200A and four R&S SGT100A VSGs generated 10 simultaneous radar emitters between 3 and 9.5 GHz.

SCENARIO EDITOR

In all stages of development, from initial functional testing to final operational simulation testing, engineers want realistic test cases reflecting what the radar warning receiver will see in operation. To support realistic simulation, the R&S Pulse Sequencer software can define a wide range of radar scenarios, from simple pulses to dense multi-emitter environments. As a standard feature, the software has smart pulse interleaving algorithms with an optimized, user-defined priority scheme. This feature enables lowest drop rates.

Alternatively, users can simulate actual pulse-on-pulse situations as they occur, without any pulse dropping. The user can configure all typical radar types: CW, frequency modulated continuous wave (FMCW) or pulsed, including wide bandwidth, frequency-agile radars with complex inter-pulse modulation (IPM) or MOP. For maximum realism, emitters and the receiver can "move" along predefined or imported trajectories with six degrees of freedom, making the simulation as realistic as possible. As usability is a core requirement for the software, the R&S Pulse Sequencer software has 3D previews and graphical live visualization of configured scenarios to quickly familiarize users with the software (see ***Figure 2***). Calculation of complex multi-emitter scenarios is fast, minimizing the waiting time for results and enabling users to conveniently optimize test cases.

HIGH SPEED PDW STREAMING

Ultra-long scenario playtime and real-time changes to the simulation can be achieved by streaming Pulse Descriptor Words (PDW) using a network connection to the VSG, which serves the role of an agile RF signal source. It supports classical unmodulated radar pulses, Barker coded pulses, FMCW signals and any I/Q modulation on the pulse, enabling the most modern, low probability of intercept radars to be simulated. The R&S SMW200A supports PDW rates up to 12 million PDWs per second.

FIELD DEMONSTRATION

During a live demonstration at the 2019 EW Live event in Tartu, Estonia, a radar simulator from Rohde & Schwarz was operated over-the-air (OTA) with a free-space distance of 1.3 km to the ELINT and radar warning receivers. An R&S SMW200A VSG with two, 20 GHz RF paths controlled by the R&S Pulse Sequencer software served as the signal source (see ***Figure 3***). The SMW200A VSG's large internal modulation bandwidth of 2 GHz enabled generating radar signals from multiple emitters in a single RF path. Four compact R&S SGT100A RF sources were also integrated into the system to simulate additional radars operating below 6 GHz. This setup supported OTA test scenarios with 10 simultaneous radar emitters between 3 and 9.5 GHz.

Figure 4 shows a signal plan for one simulation. In this scenario, the R&S SMW200A generated six radar signals simultaneously, three in RF path A and three in path B. Splitting radar signal generation between two paths makes it possible to create very realistic scenarios, including those with colliding pulses and highest dynamic range. In RF path A, signals from radar systems with operating frequencies between 5 and 6 GHz were simulated, while path B had signals in the 9 GHz range. Each R&S SGT100A generated one additional radar. The signal plan defined different radar signals, from simple, unmodulated pulses to complex I/Q modulated pulses (e.g., AMOP, FMOP, PMOP, chirps and Barker code pulses). Diverse IPM profiles, such as pulse repetition interval staggering and frequency hopping, were used. A complex, multi-mode radar featuring frequency and time agile operation, as well as diverse antenna patterns and scans, was included.

For the EW Live demonstration, the flexibility and powerful performance of the R&S SMW200A and R&S SGT100A VSGs created a full-featured radar simulator. The VSGs demonstrated high performance field testing for relatively low cost and effort using standard components. Added benefits were quick installation of the setup at a remote location and verification of the performance of the systems to be tested.

VENDORVIEW

Rohde & Schwarz
Munich, Germany
www.rohde-schwarz.com

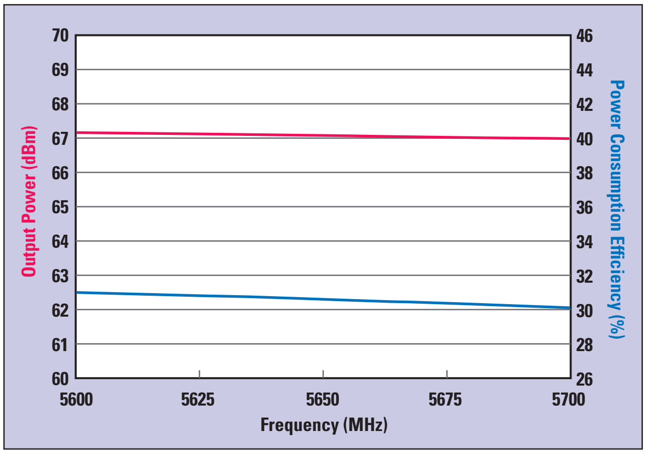
4 & 5 kW GaN Pulsed Transmitters for C- and X-Band

RFHIC Corp.
Anyang, South Korea

RFHIC Corporation has developed solid-state pulsed transmitters for C- and X-Band radar, providing 4 kW output power at C-Band and 5 kW at X-Band. The transmitters use RFHIC's own GaN power devices in a redundant power amplifier (PA) architecture, which provides long lifetimes with "soft" failure. The systems are cooled using forced air.

C-BAND TRANSMITTER

The C-Band transmitter, model RRT54594K0-66, was designed for maritime, surveillance and weather radar applications between 5.4 and 5.9 GHz. The transmitter delivers a minimum of 4 kW peak pulsed power with 31 percent power consumption efficiency (see ***Figure 1***). It handles pulse widths of 1 to 100 µs and up to 10 percent duty cycle, with typical pulse drop of 0.5 dB or less and rise and fall times less than 100 ns. The transmitter has excellent pulse fidelity, with pulse stability of 55 dB and spurious signals no greater than 40 dBc in the operating band. An input power of at least 15 dBm is sufficient to drive the transmitter to rated power.



▲ Fig. 1 Output power and power consumption efficiency of the C-Band transmitter.

The RRT54594K0-66 integrates four, 1.2 kW pulsed modules (RRP54591K2-42), which use RFHIC's 240 W GaN on SiC transistors (IR56240NN). The GaN modules provide high power with high efficiency and an MTBF of approximately 80,000 to 100,000 hours. The transmitter is designed with an expandable hardware architecture, enabling users to add modules to achieve higher power without manually phase matching the modules.

The C-Band transmitter has embedded monitoring capabilities to detect abnormal system conditions, such as low power, excessive temperature, high voltage standing wave ratio (VSWR) or DC failure. An RS232 interface provides warning alarms or automatic shutdown to safeguard the system.

The RRT54594K0-66's RF input connector is SMA, and the output is WR-159 waveguide, which has an insertion loss no greater than 0.2 dB and VSWR below 1.5:1. Weighing 88 lbs., the transmitter is packaged in a compact 47.4 cm x 42.1 cm x 25.1 cm "box," which supports easy and stable installation on an antenna mast. The housing can be modified to fit in a standard 19 in. rack, an option if required by the application.

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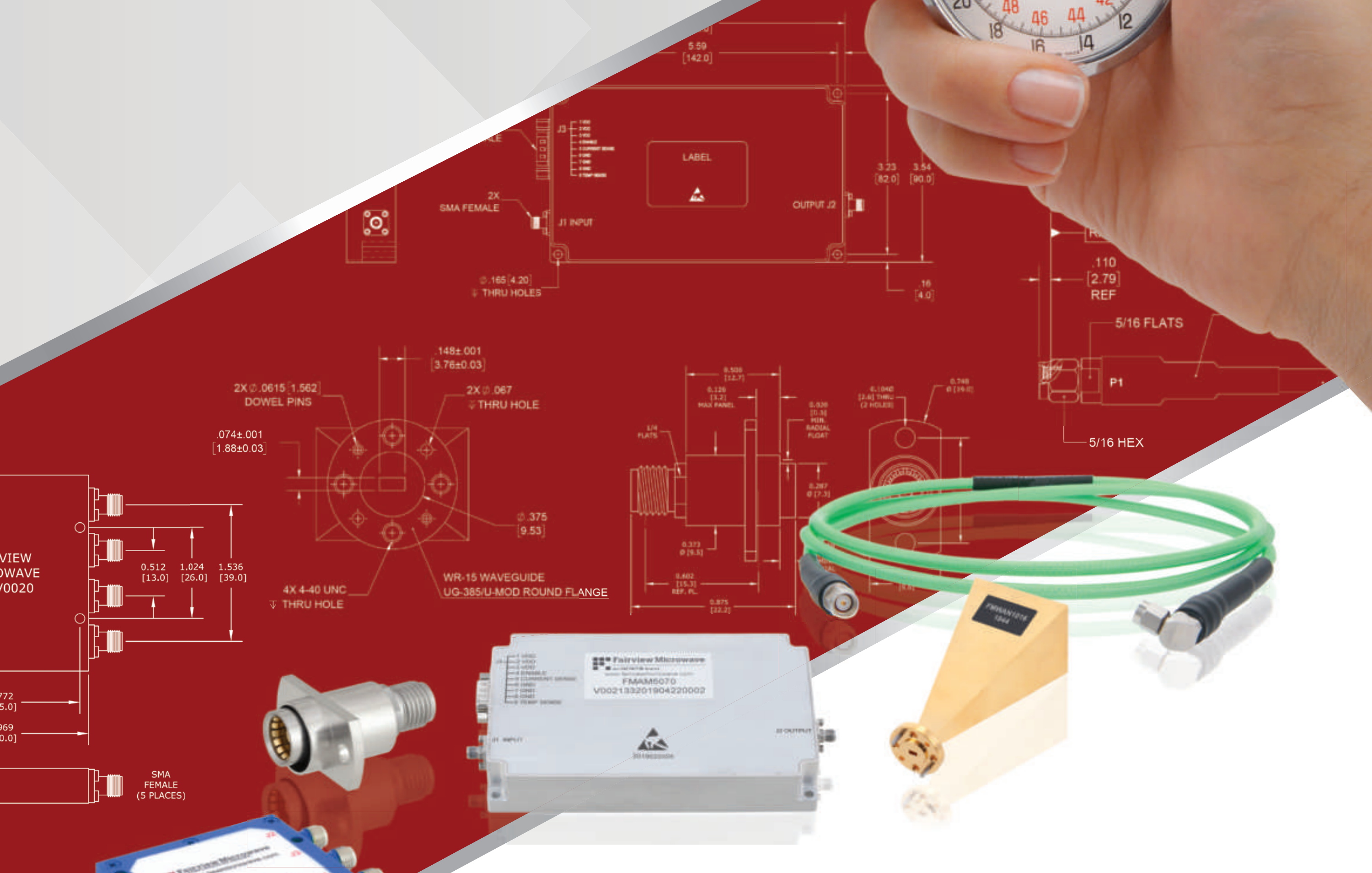

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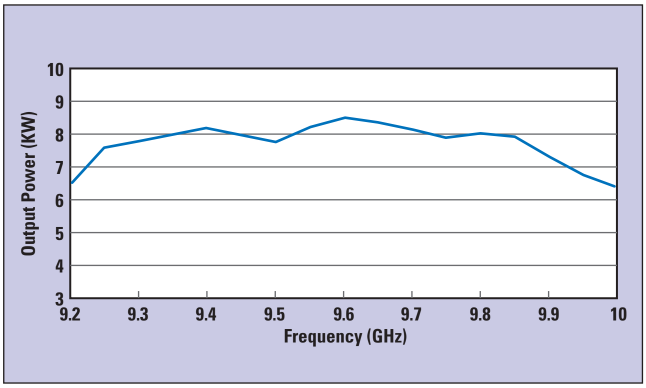
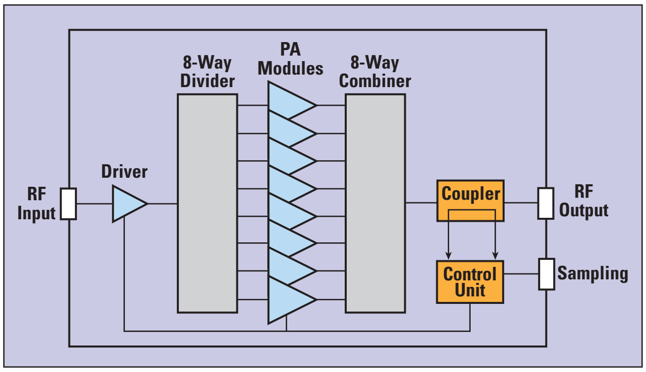


▲ Fig. 2 Output power vs. frequency of the X-Band transmitter with a 50 µs pulse at 10 percent duty cycle.



▲ Fig. 3 Redundant architecture of the X-Band transmitter. A similar approach is used with the C-Band transmitter, which integrates four PA modules.

X-BAND TRANSMITTER

The X-Band pulsed transmitter, model RRT901005K0-57, was designed for radar applications operating between 9 and 10 GHz with an instantaneous bandwidth up to 500 MHz. The transmitter delivers at least 5 kW peak pulsed power (see ***Figure 2***), with pulse widths to 100 µs and 10 percent duty cycle. Pulse droop is no greater than 1.0 dB, and pulse rise and fall times are less than 100 ns. Spurious signals are no greater than 60 dBc from 9 to 10 GHz. With 6 kW output power and 10 percent duty cycle, the power consumption is 4 kW maximum.

The transmitter combines eight, 800 W GaN PAs using RFHIC's GaN on SiC transistors and achieves approximately 80,000 hour MTBF (see ***Figure 3***). As with the C-Band transmitter, the RRT901005K0-57 is expandable. Users can add power modules to increase the output power without manually matching the phase of the new modules.

The transmitter has an RS-422 control interface to provide warning alarms and automatic shutdown to safeguard the system from damage. Should a PA module fail, the RRT901005K0-57's control system will automatically identify and report it to the user through the upper management system. A liquid crystal display monitor on the front of the system shows the real-time status of operation, such as output power—with an accuracy of ±0.5 dB.

The RF input connector is SMA and the output has a WR-90 waveguide. The unit has a small form factor: 6 U x 19 in. for rack mounting, enabling straightforward system integration, and it weighs 117 lbs.

MODULAR DESIGN

With both the C- and X-Band transmitter designs, if one of the PAs fails, the output power drops by the power of the failed module. Unlike TWTAs or other tube amplifiers, the transmitters do not require full redundancy; even with multiple PA failures, the system gracefully degrades. Due to its scalable architecture, it allows the user to build higher power systems when needed.

RFHIC has an extensive PA portfolio to support customized design for unique customer requirements, from output power to frequency bands. RFHIC is the first and only commercial company whose portfolio spans GaN devices to systems. This high quality capability offers customers both off-the-shelf products and custom solutions, which help reduce capital expenses and shorten project development time.

RFHIC Corp.
Anyang, South Korea
www.rfhic.com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At Integra, we've spent decades building a vast RF power library with breakthrough products for radar delivering up to 85% efficiency with best in class power and efficiency. We know the challenges you are facing and we're here to help. Integra can rapidly optimize a cost-effective semicustom or custom RF pallet solution for your exact system needs.
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INTEGRA

Low Smoke, Zero Halogen, Twinax Cable Assemblies

MilesTek now stocks a complete line of high temperature, low smoke, zero halogen (LSZH) cable assemblies for military and aerospace applications. With an operating temperature range from -30°C to +80°C, the MSA005 series cables have LSZH jackets, using a compound that reduces the amount of toxic and corrosive gases emitted during combustion. This makes the cable assemblies well suited for enclosed areas where PVC's toxic properties are restricted, such as military vehicles, aircraft, ships, control centers or other enclosed buildings.

These MIL-STD-1553 cables satisfy the multiple requirements of many military installations, including use of LSZH jackets, lead-free solder, high temperature rating and RoHS and REACH compliance.

Connector options include two- and three-slot TRB and TRS plugs and jacks, bulkhead jacks, insulated and non-insulated connectors and versions with blunt cut ends. Some models have a metal spring bend relief to reduce the stress on the cable where it exits from the connector. Off-the-shelf lengths range from 0.03 to 6 m, depending on the model, and each cable assembly is constructed with 0.155 in. outside diameter, 78 Ω, LSZH twinaxial cable.

Unlike suppliers with six to eight week lead times for these assemblies, MilesTek stocks all versions of the MSA005 series in multiple lengths, available for same-day shipping. MilesTek also offers the option for custom orders with special labeling and different connector types and lengths.

VENDORVIEW

MilesTek
Lewisville, Texas
www.milestek.com

High-Power Class AB Amplifier Modules

Fairview Microwave has released a new series of 18, broadband, class AB power amplifier modules covering various frequency bands from 1.5 MHz to 18 GHz with 10 to 200 W saturated output power, power-added efficiency to 40 percent and power gain to 53 dB. Designed for 50 Ω systems and unconditional stability, the amplifiers use GaN, LDMOS or VDMOS transistors to obtain optimum performance; the lower frequency amplifiers use VDMOS or LDMOS, while the higher frequency designs use GaN.

To minimize baseplate temperature and ensure the best performance, the amplifiers can be mated to an optional heatsink with DC-controlled cooling fans. Designed to be rugged, the high-power amplifier modules operate over a temperature range from -20°C to +60°C and withstand relative humidity to 95 percent.

The compact coaxial packages have Type N or SMA connectors and D-subminiature connectors for DC bias, TTL control and temperature and current sense.

This new power amplifier family offers many options for designers seeking high efficiency, linearity and dynamic range in a small form factor. All of the products in the series are in stock and available for immediate shipment with no minimum order quantity.

Since 1992, Fairview Microwave has been providing high-quality RF/microwave components, including adapters, connectors, attenuators, coaxial cables and terminations. Specializing in immediate product needs, Fairview offers same-day shipping on thousands of in stock items with no minimum purchase required. Fairview has over 5,000 RF/microwave products, most of which are in stock and ready to ship.

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Lewisville, Texas
www.fairviewmicrowave.com

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ADI Power by Linear

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With Analog Devices Power by Linear™ products, available from Richardson RFPD, you can depend on consistent quality, proven reliability, high performance, long life cycles and customer and factory support. Analog Devices' power management offering includes Silent Switcher® DC/DC converters and uModule regulators. ADI's portfolio of compact, ultra low emission, high speed synchronous monolithic stepdown Silent Switcher® regulators are perfect for noise sensitive and space critical applications. These regulators minimize EMI/EMC emissions while delivering highly efficient operation even at high switching frequencies.

Analog Devices Inc.
https://apps.richardsonrfpd.com/mktg/Analog-Devices-Power-by-linear.html

RF and Microwave Semiconductors

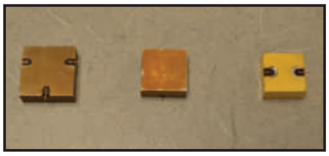
Founded in 2003, BeRex is a fabless semiconductor company that markets, designs and supports innovative RF and microwave semiconductors worldwide. BeRex Corporation specializes in the development, marketing and support of semiconductors in support of the current and next generation wireless communications and cellular infrastructure applications worldwide. Product segments served include 5G, IoT, military/satellite and wireless infrastructure.

BeRex Corporation
www.berex.com

Ultra-Agile Signal Source

The APUASYN20 is a very compact and agile signal source up to 20 GHz. It combines fast switching speeds with good phase noise and signal quality. The single-channel unit is available as mountable module or in a compact enclosure with display and front panel control. The multi-channel version APUASYN20-X is available in one to four channel configurations in a standard 1U 19" rack-mountable enclosure. For high phase coherence, RF channels are locked to a single reference source.

AnaPico Ltd.
www.anapico.com



SMT Isolators and Circulators

VENDORVIEW

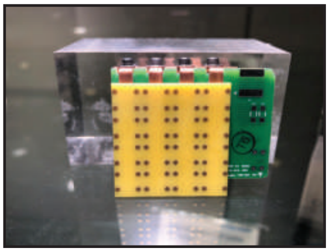
Cernexwave's CSC and CSI series SMT isolators and circulators are offered to cover the frequency range of UHF to 40 GHz. These isolators and circulators are designed and manufactured to provide low insertion loss and high isolation for SMT component and module integrations. The 50Ω input and output SMT line configuration is immediately ready for circuit insertion. While the isolator is an important device where port isolation or VSWR is concerned, the circulator offers duplexing functions in many radar and communication systems.

Cernex
www.cernex.com

Low Phase Noise Amplifiers for Surveillance Radars

Phase noise is a critical characteristic in high performance radar and communication systems, affecting the ability of the surveillance system to lock on its intended target. Degrading residual phase noise is one of the most difficult signal-processing challenges to overcome, but it can be addressed by using low phase noise amplifiers which improve the signal-to-noise ratio. APITech guarantees high quality, ultra low phase noise performance across its amplifier product line.

APITech
www.apitech.com/products/rf-solutions/amplifiers/



Introducing New Ka-Band AESA Technology

VENDORVIEW

Leveraging decades of aerospace and defense system design expertise, Cobham Advanced Electronic Solutions' new 256-Element Tx/Rx Ka-Band array features small form factor, high power, aperture to data capability for mmWave arrays, flexible and low cost systems, built for rugged defense environments, very fast beam steering and control and the ability to broadcast a single steering vector for the entire array.

Cobham Advanced Electronic Solutions
www.cobhamaes.com/KaBandArray

4 to 18 GHz Ultra-Wideband High Power Solid-State GaN RF Amplifier Module

Comtech introduces the Model BME49189-50, the latest in GaN-based 4 to 18 GHz RF amplifiers. The small amplifier module delivers greater than 50 W of power over the full frequency range of 4 to 18 GHz. The BME49189-50 amplifier operates from +28 VDC and meets all specifications over -40° to +55°C. This highly integrated design is ideal for communication, electronic warfare and radar transmitter systems where space, cooling and power are limited. This unit is ideal for UAV/airborne, ground mobile, surface and shipboard applications.

Comtech Power Systems Technology
www.comtechpst.com

Custom MMIC Is Now qorvo

Custom MMIC is Now Qorvo

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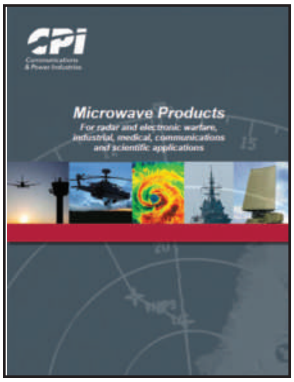
Qorvo and Custom MMIC have joined forces to deliver the industry's most innovative high performance GaN and GaAs MMICs in the industry. By merging these two best-in-class RF and mmWave product portfolios, we can now provide our valued customers with the industry's most innovative products—from a single discrete component to a fully integrated module solution. Qorvo's industry-leading portfolio includes high performance GaN and GaAs power amplifiers, LNAs, mixers, switches and other products to tackle the toughest design challenges and to push the limits of technology.

Custom MMIC
https://www.custommmic.com



Communications and Power Industries

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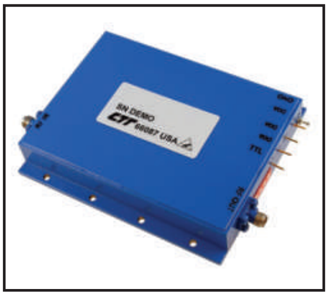
CPI is the world's largest manufacturer of receiver protectors. CPI designs and manufactures a broad range of RF and microwave products for radar, communications, electronic warfare, medical and scientific applications. They also manufacture a broad range of pressure windows and pressure bypass windows. Their products are found in numerous radar systems operated by the U.S. military and militaries around the world. Contact CPI at www.CPII.com or ElectronDevices@CPII.com for high power microwave components.

CPI
https://www.cpii.com/

RF Receivers and Sources for Radar Simulation

dB Control introduced a line of radar simulation systems to test the field-worthiness of EW systems. This new line of RF sources and receivers includes frequency locked oscillators, instantaneous frequency measurement units, digital control units, antenna control units and integrated digital control units. These products can be customized even for the most rigid SWaP requirements and can remain effective across a range of temperature extremes.

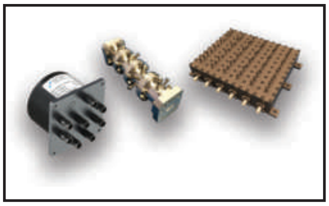
dB Control
www.dBControl.com



2 to 18 GHz, 8 W GaN Power Amplifier

SWaP solutions for many applications including EW, radar, missile guidance and SATCOM. CTT's new solid-state GaN-based power amplifier, Model NGX/0218-3946, covers 2 to 18 GHz with 8 W (+39 dBm) of CW power output. The compact size of 4.25 in. (L) x 3.25 in. (W) x 0.88 in. (H) offers RF/microwave designers an excellent choice for SWaP solutions in many S- through Ku-Band applications, including EW, radar and SATCOM.

CTT Inc.
www.cttinc.com



High Performance Passive Components

VENDORVIEW

Exceed Microwave provides custom high performance passive microwave component designs up to 67 GHz for defense, space and commercial applications. Exceed Microwave is AS9100 certified and ITAR registered, providing high quality, high performance passive components. The company provides various types of designs, each with its own unique values and are designed and made in U.S. Many of its designs offer extremely high Q factor, allowing very low insertion loss and high power handling.

Exceed Microwave
www.exceedmicrowave.com

RF and Microwave Class AB High Power Amplifiers with Available Heatsinks

VENDORVIEW

Fairview Microwave, a leading provider of RF, microwave and mmWave components available for same day shipping, now offers a comprehensive line of class AB broadband high power amplifiers spanning 20 MHz to 18 GHz frequencies. These designs are unconditionally stable and operate in a 50 Ohm environment, providing power gain up to 53 dB and saturated output power from 10 to 200 W. The line offers optional heatsink modules with DC controlled cooling fans to ensure optimal baseplate temperature.

Fairview Microwave
fairviewmicrowave.com

SENCITY Occhio Distributed Antenna System

The HUBER+SUHNER SENCITY Occhio DAS (distributed antenna system) or small cell antenna for indoor use, offers the operator 5G coverage, a simple, time-saving installation process and an attractive industry preferred design with a small form factor. Thanks to its multiband capability between 1.7 to 6 GHz and 2 x 2/4 x 4 MIMO configurations it supports today's and future wireless applications. Watch how the awarded antenna has been designed and get in touch if you are interested.

HUBER+SUHNER
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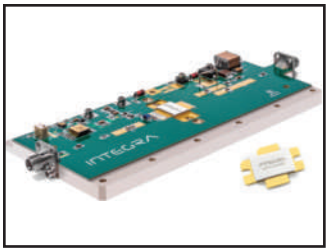
Serving the military and aerospace industries since 1961, Greenray Industries provides high performance oscillators that offer low phase noise, tight stability and low g-sensitivity and function as high precision reference sources for smart munitions, missile guidance, mobile receivers, radar systems and much more. The company's products include TCXOs, OCXOs, VCXOs and clock oscillators. For more information, visit online or call 717.766.0223 and talk to a frequency control expert today.

Greenray Industries, Inc.
www.greenrayindustries.com



Pallet Solutions

Integra Technologies Inc., a provider of RF and microwave power semiconductor and pallet solutions for state-of-the-art radar, EW and advanced communications systems, announced a new family of L-Band pallet and transistor products based on Integra's patented Thermally Enhanced GaN/SiC for multi-mode radar applications. Integra's IGN1214CW425 provides best-in-class performance delivering 425 W of CW power with an efficiency of 70 percent. Integra offers a full selection of RF power solutions ranging from UHF through X-Band.

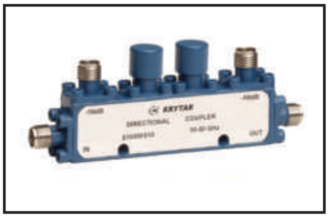
Integra Technologies Inc.
www.integratech.com

HSM Series RF Synthesizer Modules

VENDORVIEW

The HSM Series RF Synthesizer Modules are high performance, non-PLL based CW sources that exhibit exceptional frequency/phase stability. The intentional lack of a PLL supports frequency switching speeds of as fast as <10 µs (fully settled) while offering phenomenal pulse generation waveforms. These compact, broadband signal sources have a field proven MTBF of >200k hours and are available in seven models covering 10 MHz to 1 GHz, 2 GHz, 3 GHz, 4 GHz, 6.7 GHz, 12.5 GHz and 20 GHz.

HOLZWORTH
www.holzworth.com



10-50 GHz Dual-Directional Coupler for Military and Commercial Applications

VENDORVIEW

KRYTAR's Model 510050010 dual-directional coupler lends itself to designs and test and measurement applications in mmWave and 5G markets. Within a broadband frequency range of 10 to 50 GHz performance ratings include nominal coupling of 10 dB, ±1.8 dB, frequency sensitivity is ±1 dB, insertion loss less than 3 dB, Directivity greater than 10 dB, maximum VSWR is 1.8. The coupler comes with 2.4 mm female connectors and measures just 2.24 in. (L) x 0.40 in. (W) x 0.62 in. (H).

KRYTAR
https://krytar.com/products/couplers/dual-directional-couplers/dual-directional-coupler-510050010/

COMPANY SHOWCASE

Latest Microwave Technology Folder by Kuhne

The heart of Kuhne electronic beats in its own, experienced and constantly growing development department for microwave technology from 100 MHz to 50 GHz. In the company's new folder they introduce its latest developed products like microwave generators, S-Band power amplifiers and broadband preamplifiers. All key specifications and features of its new products are listed in 16 pages. Kuhne also gives a short forecast from its development pipeline in 2020/2021.

Kuhne electronic
www.kuhne-electronic.com

Newly Designed MUOS/UHF Products

For 50 years, Metropole Products has consistently introduced new solutions to markets that enable military, government and commercial clients to achieve success. Metropole Products expert engineers offer decades of proven experience in design, development, manufacturing and testing of microwave and RF components. The company's state-of-the-art technologies are critical components to the satellite, radar, communications and electronic warfare systems of our military. Contact Metropole Products today to discuss its newly designed MUOS/UHF products.

Metropole Products
www.metropoleproducts.com

RF Power Meters

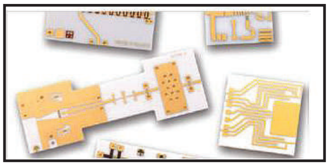
LadyBug Technologies has added four new power sensor models to its diverse portfolio of sensors. The new line includes the LB5944A 1 MHz to 44 GHz True-RMS USB RF Power Sensor. The sensor features optional capability to 50 GHz. The composite USB device utilizes both USB TMC and USB HID, allowing flexible programmatic access. Several advanced options are available including, calibrated Analog Recorder Out that can be used autonomously, unattended autonomous measurements and storage, SPI and I2C interfaces that allow direct connection to a microprocessor, FPGA or other small form factor system.

LadyBug Technologies
www.LadyBug-Tech.com

26 to 50 GHz Down-Converter

Norden Millimeter is a leading developer of microwave and mmWave products, creating standard and custom RF amplifiers, frequency multipliers, frequency converters, transceivers and custom assemblies for airborne military, commercial and test applications. Through state-of-the art prototyping and engineering, Norden's skilled team develops and manufactures products across frequencies of 500 MHz to 110 GHz, with both standard and custom designs available. Pictured is its 26 to 50 GHz down-converter which provides an IF of 3 to 18 GHz.

Norden Millimeter
www.NordenGroup.com



Now Offering mmWave Ceramic Filters 30 to 70 GHz

MCV Microwave, a provider in high quality/low loss dielectric resonator, ceramic substrate and filters is now offering mmWave filters to 5G communications, satellite internet/network services, space, aerospace defense and military industries. These miniature surface mount bandpass filters exhibit excellent passband insertion loss and rejection. A typical 29 GHz filter has less than 2 dB insertion loss over 15 percent bandwidth with 20 to 30 dB near band rejection. Contact MCV Engineering and sales for materials, design and processing quote.

MCV Microwave
www.mcv-microwave.com

MMIC Fixed Equalizers Flatten DC to 45 GHz

Mini-Circuits has expanded its popular EQY-family of MMIC fixed equalizers with new models covering the entire DC to 45 GHz frequency range. The EQY-xx-453+ series of equalizers features attenuation slope values of 3, 4, 5, 6, 7, 8, 9 and 10 dB. All models feature excellent VSWR (1.17:1 – 1.29:1) with good RF power handling (+27 to +30 dBm). These equalizers are ideal for flattening negative gain slope in test instrumentation and other ultra-wideband systems. They come enclosed in 2 x 2 mm QFN packaging and are available in bare die format on request.

Mini-Circuits
https://www.minicircuits.com

AEROSPACE & DEFENSE

COMPANY SHOWCASE

Mini-Circuits New Product Guide–Q2 2020

VENDORVIEW

Mini-Circuits is keeping up the momentum to support your needs with more products, wider bandwidths and higher frequencies. Stay up to date with the hundreds of new products in Mini-Circuits' catalog this quarter from wideband amplifiers up to 43.5 GHz to connectorized passives up to 65 GHz, new MMIC designs, designer's kits and more!

Mini-Circuits
https://www.minicircuits.com

2020 RF Product Guide

VENDORVIEW

Pasternack, a leading global supplier of in-stock, ready-to-ship RF, microwave and mmWave components, assemblies and devices offers over 40,000 popular and hard-to-find items across 107 categories of interconnect, passives, actives and antennas. Pasternack's 99.4 percent in-stock availability allows them to ship your products the same day they are ordered, with no minimum order size required. Its product engineers and experts are also on-hand to assist with technical issues and deliver creative solutions for your specific project.

Pasternack
pasternack.com

Pole/Zero Introduces its New Integrated Microwave Filters (IMF)

Digitally tunable bandpass and notch filters with accelerated tuning speeds packed in a very small, lightweight size, cleansing the EMS environment for maximum sensitivity and improved system performance. Designed for the military radar market, specifically active electronically steered array and phased array radars. IMF frequency hopping filters are available in multiple bands for 4 to 24 GHz coverage, with tune times <100 ns. Contact Pole/Zero for more information or email support@polezero.com.

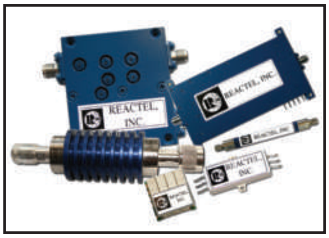
Pole/Zero
www.dovermpg.com/polezero

Microsemi
a Microchip company

Aerospace and Defense Semiconductor Solutions

Microchip has the largest portfolio of aerospace and defense semiconductor solutions in the market. These products include FPGAs and SoCs, high reliability power discretes, analog mixed-signal ASICs and ASSPs, EEPROMs, high performance oscillators, RF SAW filters, MMICs, diodes and transistors. SemiDice is franchised to deliver these solutions in wafer and bare die form. The company also offers wafer dicing, wafer probe, up screen and testing, visual inspection and long term storage. Please visit www.semidice.com for more information and its line card.

SemiDice
www.semidice.com



Filters, Multiplexers and Multifunction Assemblies

VENDORVIEW

Reactel manufactures a line of filters, multiplexers and multifunction assemblies covering up to 50 GHz. From small, lightweight units suitable for flight or portable systems to high power units capable of handling up to 25 kW, connectorized or surface mount—Reactel's talented engineers can design a unit specifically for your application. Visit Reactel online at www.reactel.com.

Reactel
www.reactel.com

20 GHz SM200C Spectrum Analyzer

Signal Hound's new spectrum analyzer, the SM200C, maintains the dynamic range, phase noise, 1 THz/s sweep speed and 100 kHz to 20 GHz tuning range that made the SM200B so popular, but now includes a full 160 MHz IBW available for calibrated I/Q data streaming, plus device control via 10 GbE SFP+ connection. No longer limited by the length of a cable, the SM200C is perfect for secure environments where USB is prohibited.

Signal Hound
www.signalhound.com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AD INDEX

Analog Devices .... COV 4
AnaPico AG 9
API Technologies 33
BeRex, Inc. 25
Cernex, Inc. 38
Cobham Advanced Electronic Solutions .... COV 2
Coilcraft CPS 21
Comtech PST Corp. 18, 26
Comtech PST Corp. (Control Components Division) 18, 26
CPI Beverly Microwave Division 43
CTT Inc. 5
Cuming Microwave Corporation 15
dB Control Corp. 24
EDI CON ONLINE 2020 .... COV 3
Exceed Microwave 30
Fairview Microwave 47
Greenray Industries, Inc. 40
Holzworth Instrumentation 14
Huber + Suhner AG 23
IEEE MTT-S International Microwave Symposium 2021 57
Integra Technologies, Inc. 49
Intelliconnect Ltd. 34
KRYTAR 16
LadyBug Technologies LLC 10
MCV Microwave 11
Metropole Products, Inc. 48
Micro Lambda, LLC 8
Microwave Journal 51
Mini-Circuits 19, 27, 35
Mini-Systems, Inc. 45
Norden Millimeter Inc. 22
Pasternack 17
Pole/Zero Corporation 39
Qorvo 3, 29
Reactel, Incorporated 7
Richardson RFPD 41
Rohde & Schwarz GmbH 12
SemiDice, Inc. 32
Signal Hound 31
Smiths Interconnect 13
Spinner GmbH 37

SALES REPRESENTATIVES

Eastern and Central Time Zones
Carl Sheffres
Publisher
(New England, New York, Eastern Canada)
Tel: (781) 619-1949
csheffres@mwjournal.com

Michael Hallman
Associate Publisher
(NJ, Mid-Atlantic, Southeast, Midwest, TX)
Tel: (301) 371-8830
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)
Tel: (831) 426-4143
blandy@mwjournal.com

International Sales
Richard Vaughan
International Sales Manager
Tel: +44 207 596 8742
rvaughan@horizonhouse.co.uk

Germany, Austria, and Switzerland (German-speaking)
WMS.Werbe- und Media Service
Brigitte Beranek
Tel: +49 7125 407 31 18
bberanek@horizonhouse.com

France
Gaston Traboulsi
Tel: 44 207 596 8742
gtraboulsi@horizonhouse.com

Israel
Dan Aronovic
Tel: 972 50 799 1121
aronovic@actcom.co.il

Korea
Young-Seoh Chinn
JES Media International
Tel: +82 2 481-3411
yschinn@horizonhouse.com

China
Shenzhen
Michael Tsui
ACT International
Tel: 86-755-25988571
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.
Nishiiko, Adachi-Ku
Tokyo 121-0824, Japan
Tel: +81 3 5691 3335
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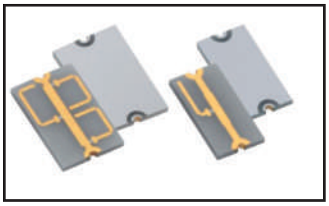

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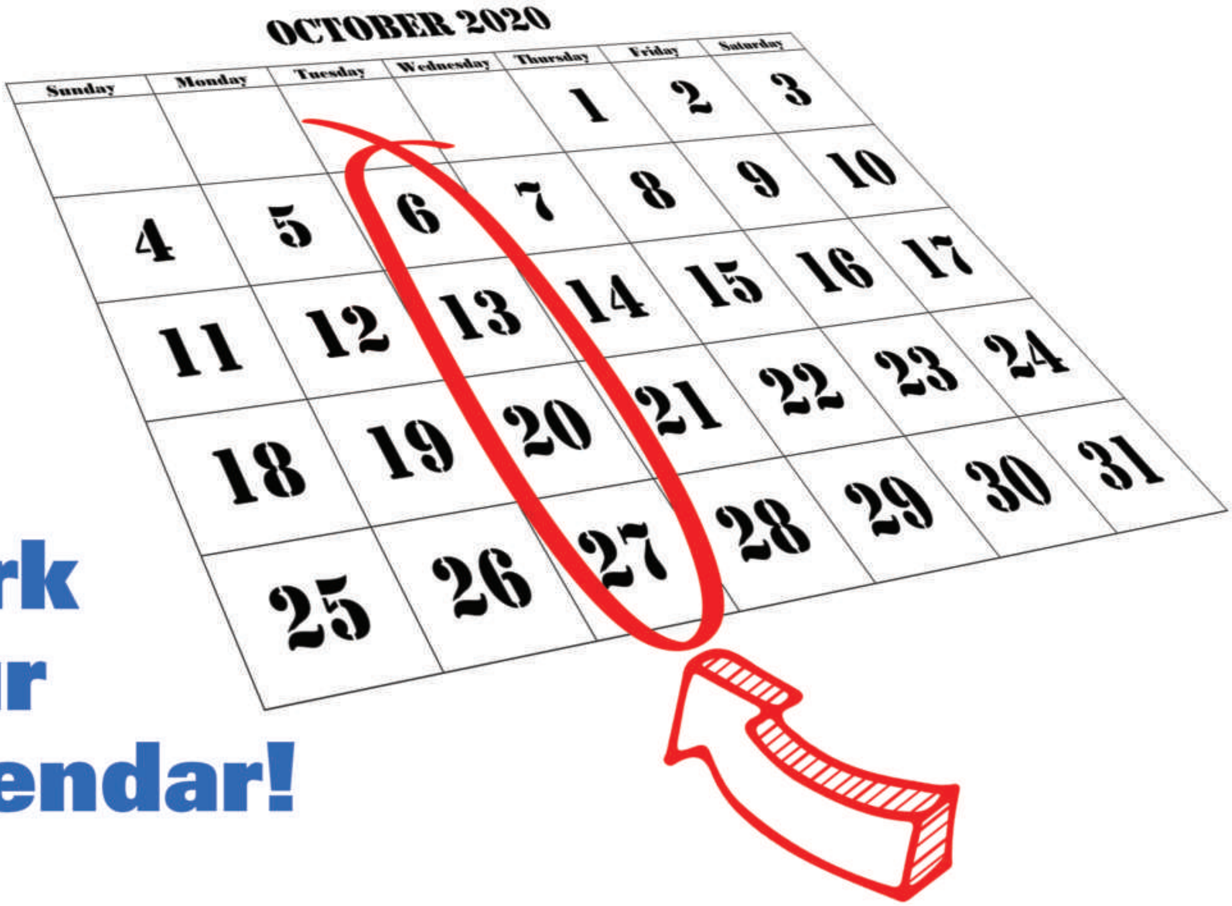

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