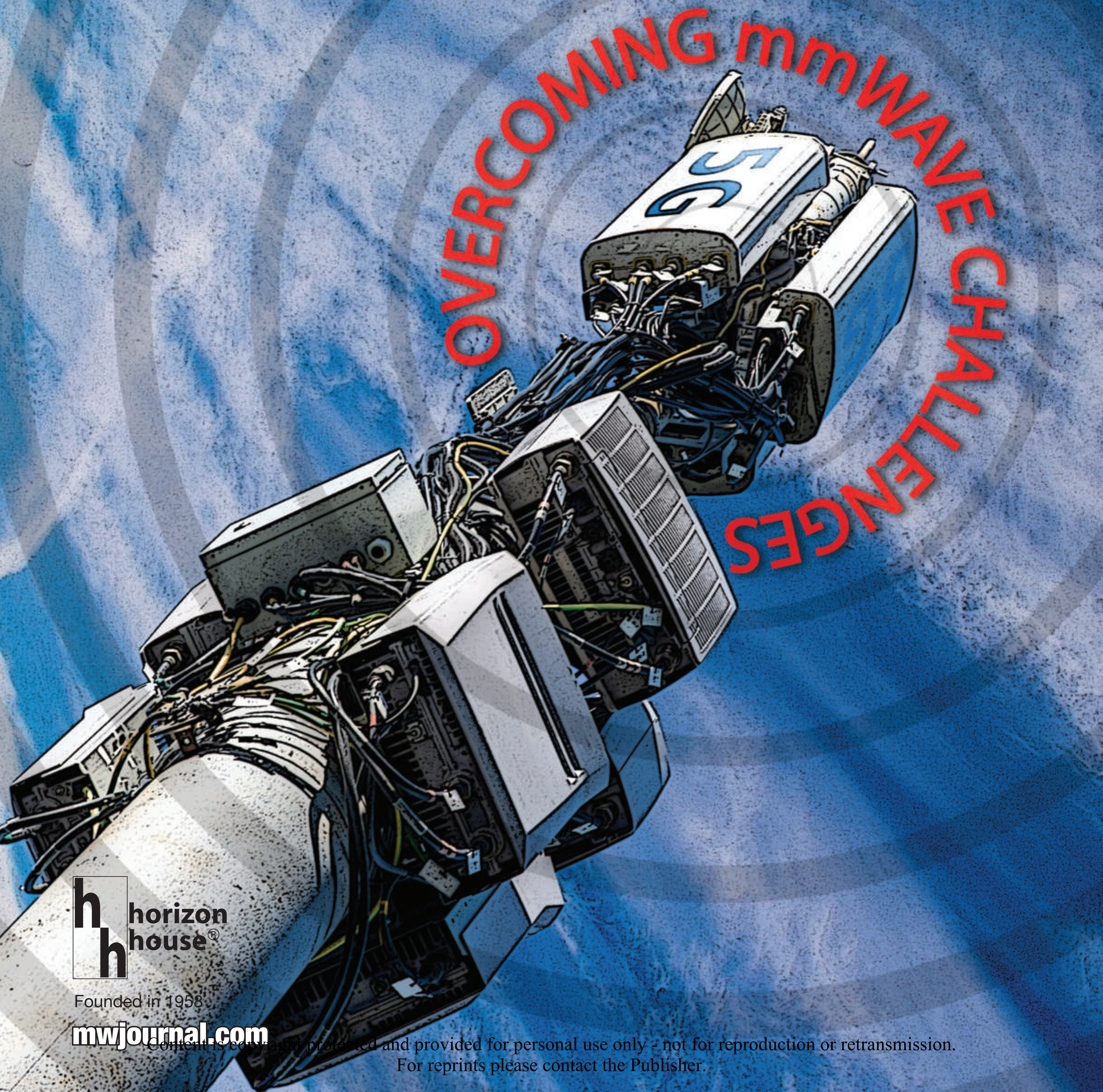
Vol. 63 • No. 4 April 2020

Microwave Journal



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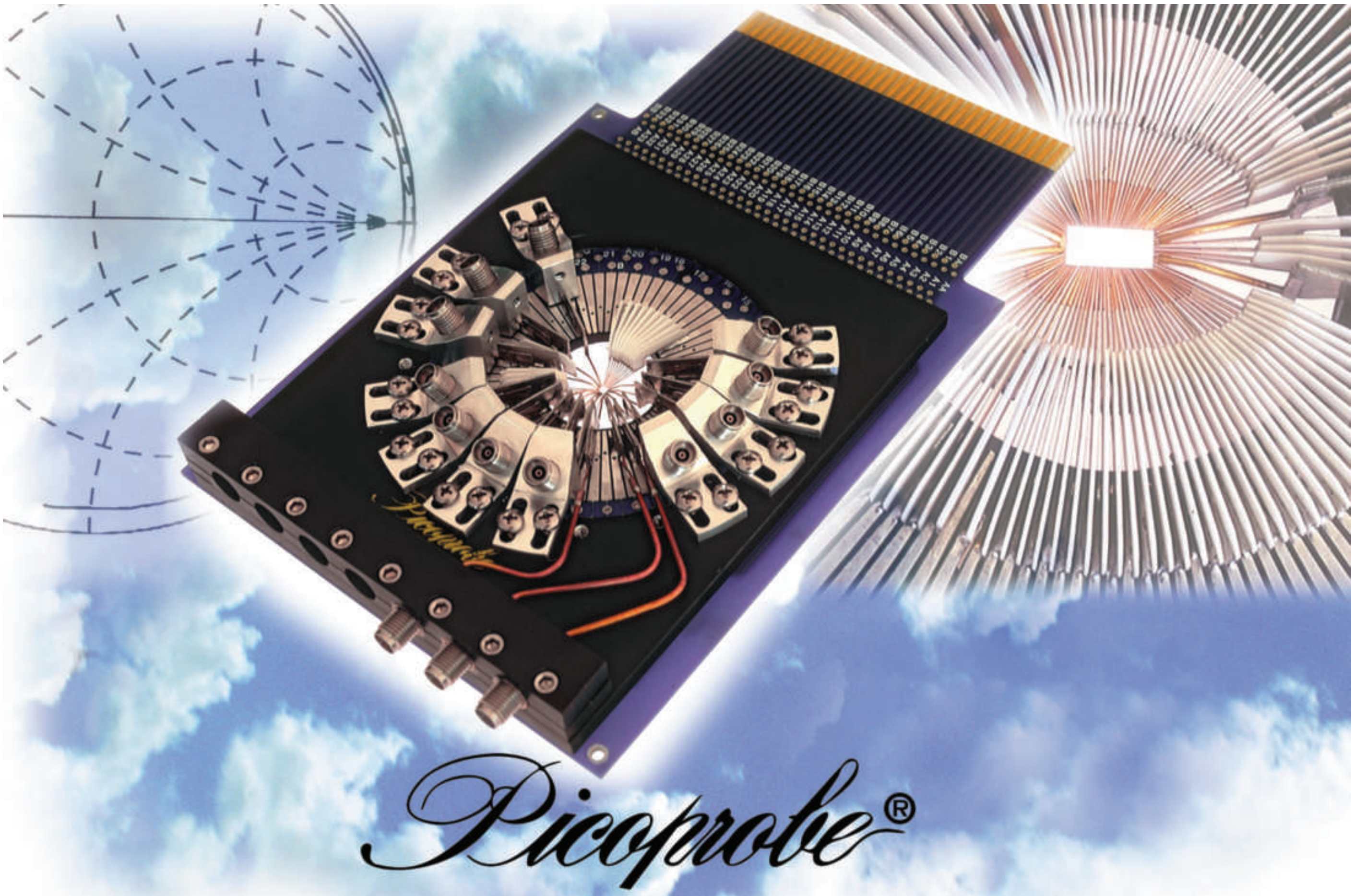

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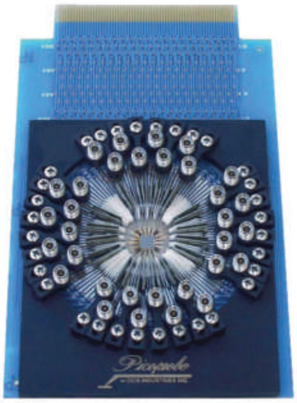

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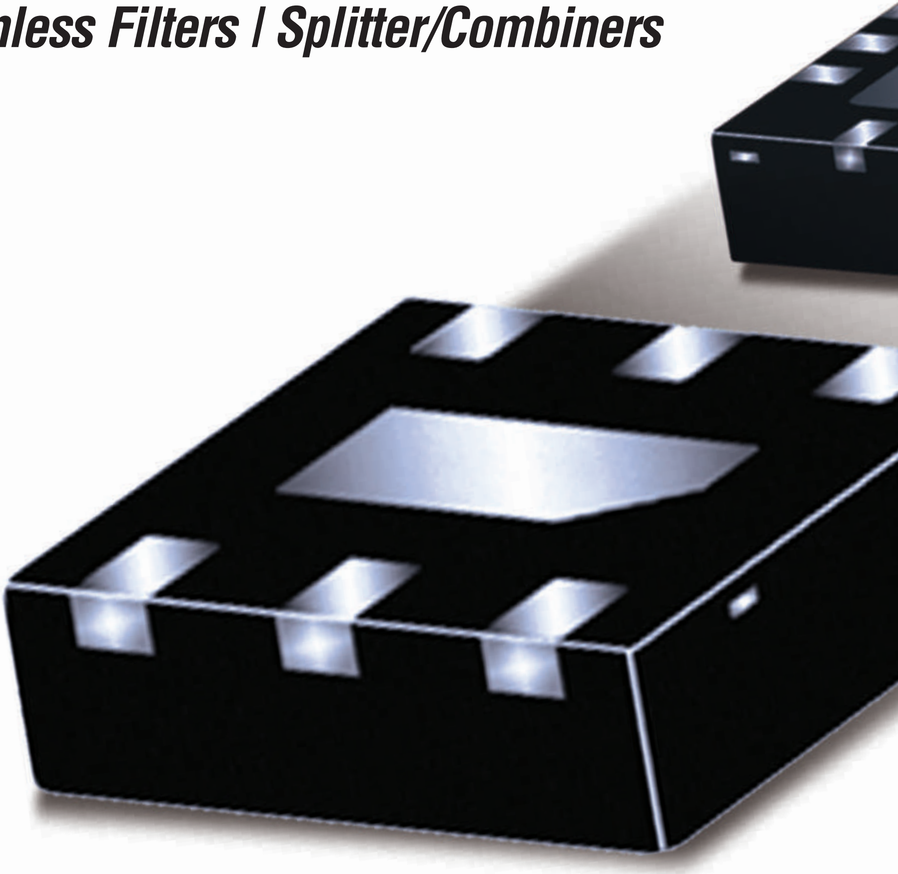

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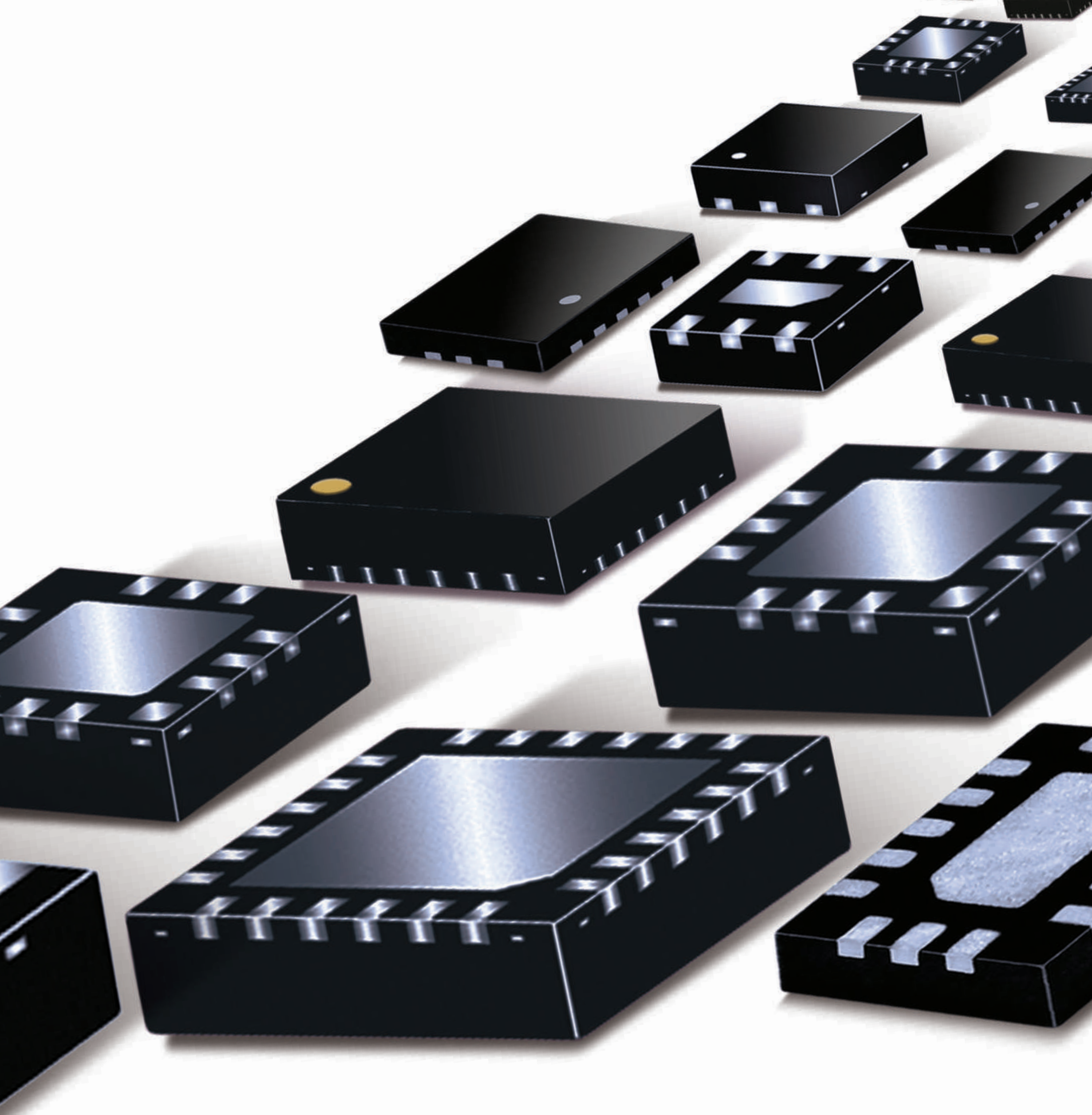

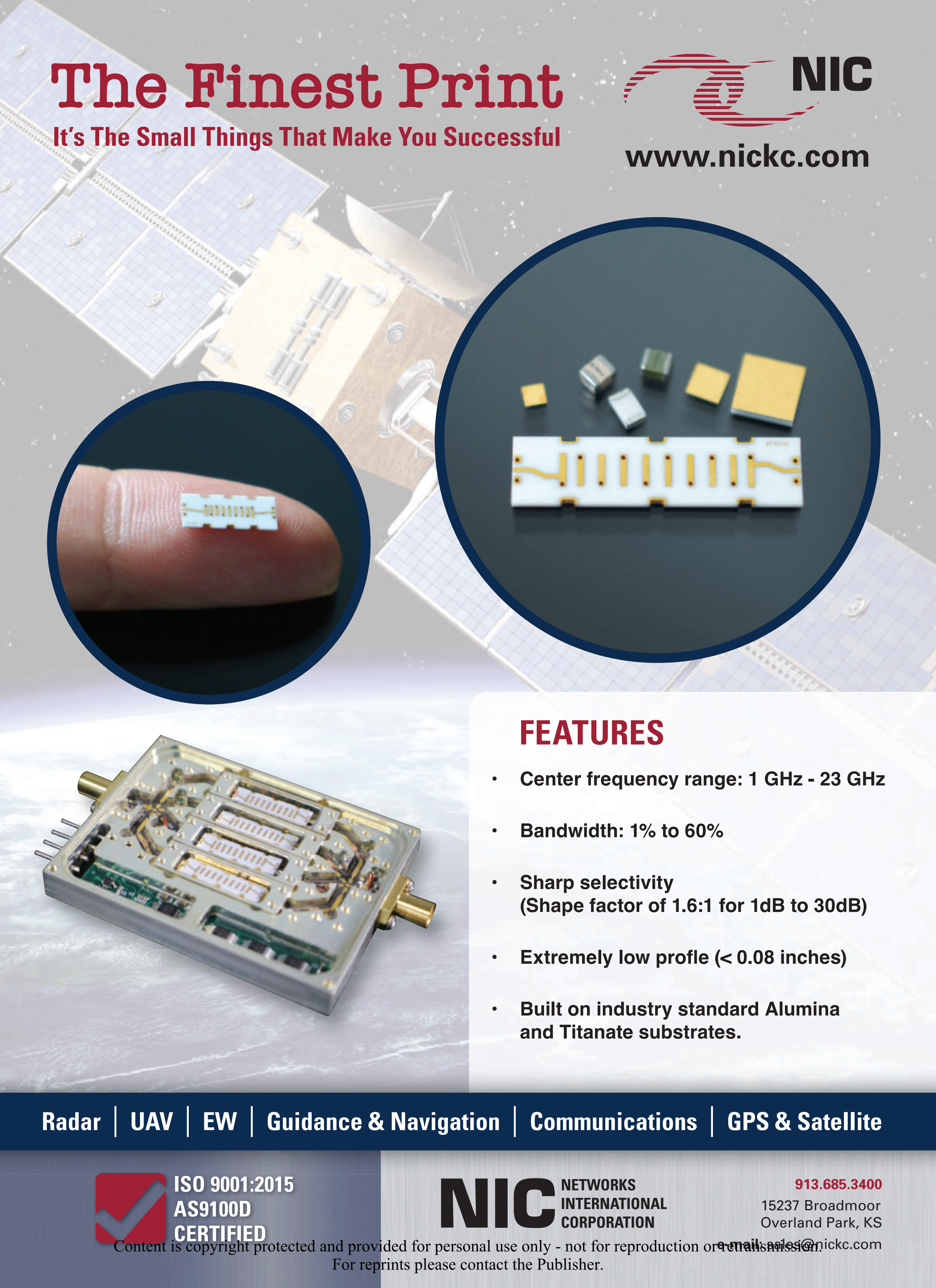
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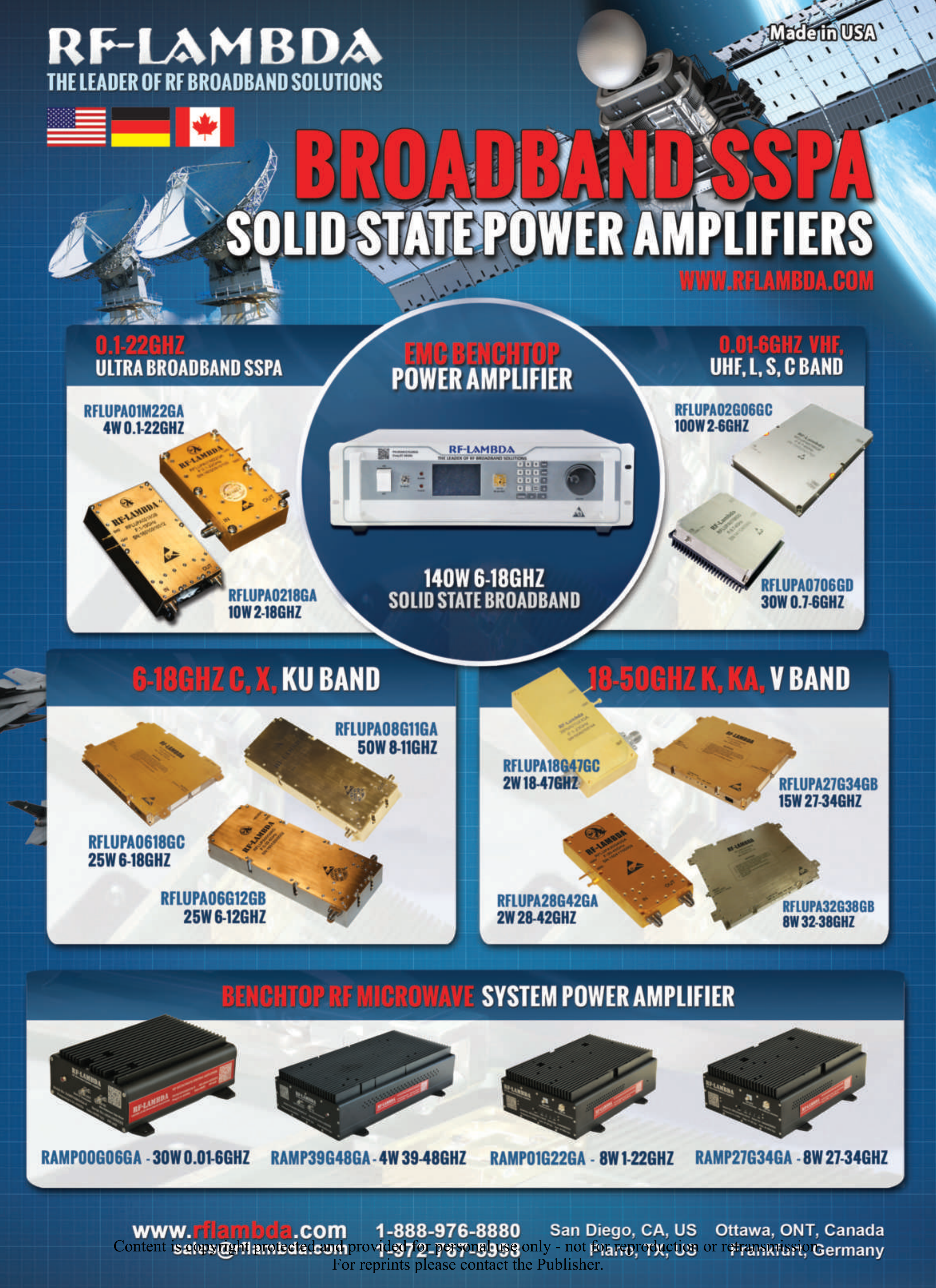
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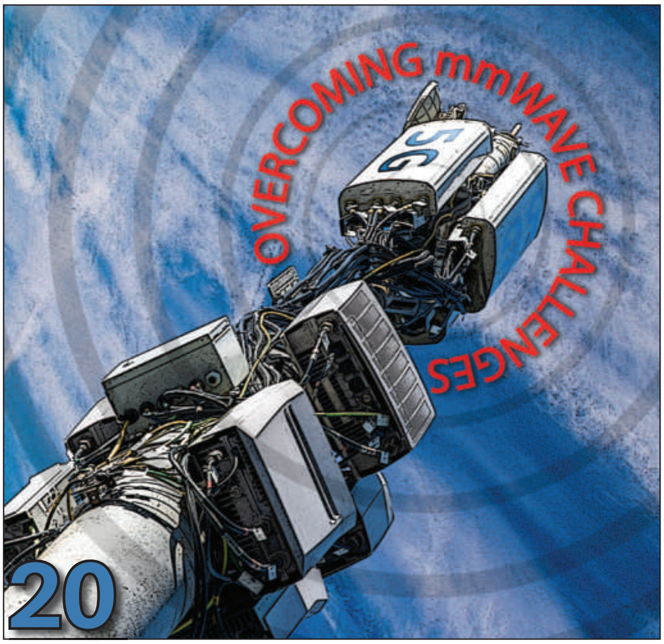

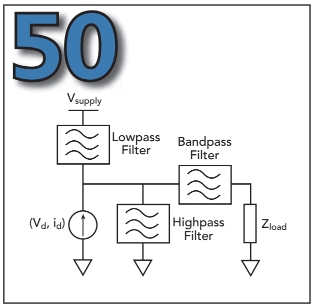

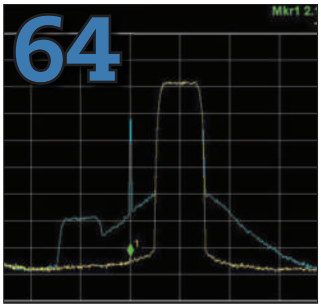

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POSTMASTER: Send address corrections to Microwave Journal, PO Box 1028, Lowell, MA 01853 or e-mail mwj@e-circ.net.com. Subscription information: (978) 671-0446. This journal is issued without charge upon written request to qualified persons working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

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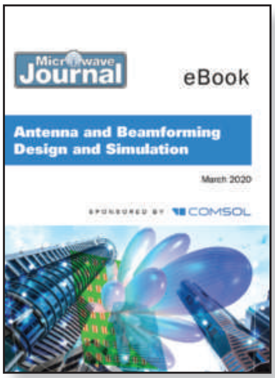

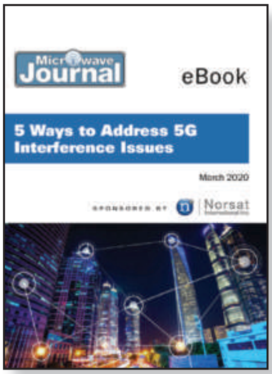

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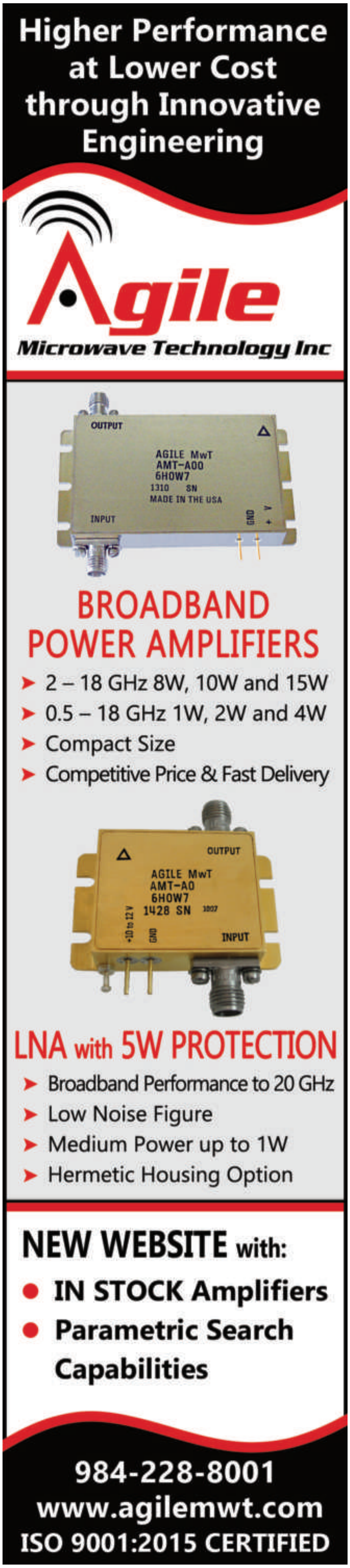

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RF SOI can Save $Billions in 5G mmWave Network Costs with Efficient PAs

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mmWave 5G networks are a high priority for operators, as the rapid growth of consumer data demand will soon outstrip the capacity of sub-6 GHz networks forcing American operators to rely on the more difficult mmWave bands.[1] In fact, operators driven by high urban data density deployed more than 85,000 mmWave radio units in 2019. There is no better way to add truckloads of capacity.

However, 5G mmWave deployment has been a bumpy road so far. Operators have discovered that signals above 20 GHz do not behave well. The systems work as expected for line of sight conditions, but non-line of sight links are not as stable. In field deployment so far, the uplink is the clear limitation. This has always been the case, in 2G, 3G and 4G systems, as the link budget is usually 2-3 dB weaker for the uplink than the downlink. This time, however, mmWave field trials have shown more than 15 dB difference between the two link budgets. 5G networks need a closed loop for channel estimation, so both uplink and downlink are necessary. The result has been unstable performance in the field.

Another major challenge in mmWave comes from high attenuation along the propagation path. Obstacles, foliage, rainfall or even hands holding the device can add 30 dB of attenuation or more. Phased arrays partially overcome this limitation via spatial power combining, focusing the signal into narrow steered beams, as well as spreading the antenna array over a wider area. The benefits of phased arrays have made them the foundation for 5G mmWave deployments, but the lesson here is that the system needs margin, because any small change in the channel can quickly add 10 dB of path loss.

Today's 5G mmWave networks are limited by RF power and heat dissipation. The uplink Effective Isotropic Radiated Power (EIRP) from early user equipment and customer

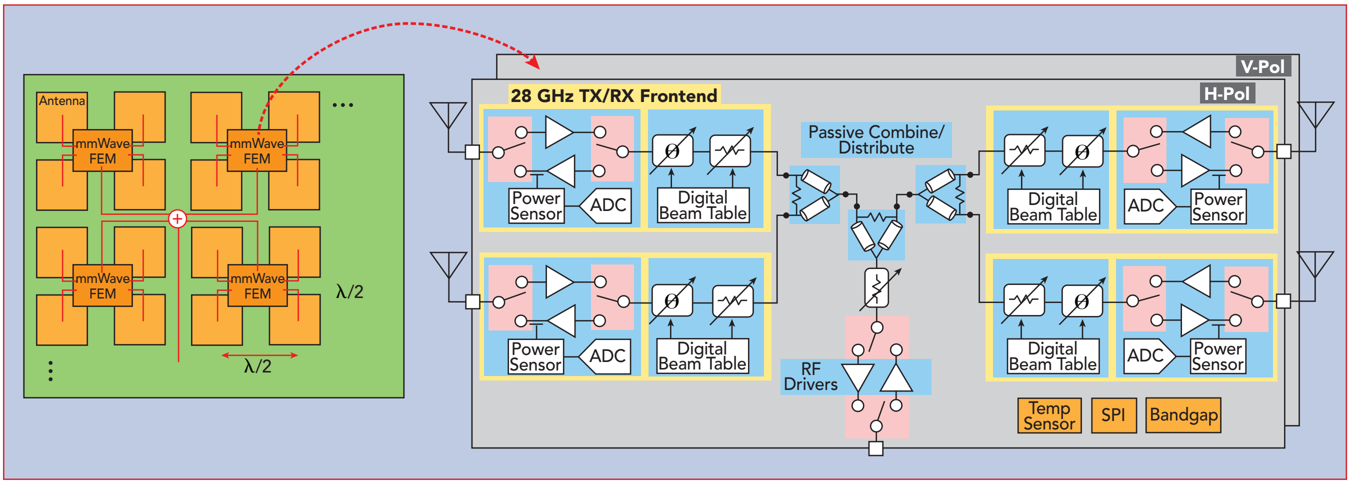

Fig. 1 Large-scale mmWave phased array constructed using tiled 2x2 dual-pol. beamforming front-end modules (FEM).

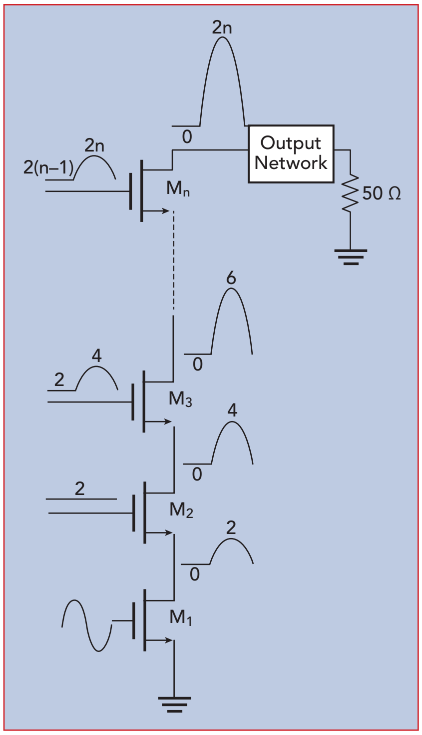

Fig. 2 RF-SOI stacked-FET PA concept.

premise equipment (CPE) has been too weak to provide the necessary link budget margin. At the same time, some devices have shut down during testing due to overheating.[2]

The success of mmWave clearly depends on solutions to a few key challenges: 1) Cost associated with limited range, 2) thermal and electrical power budget and 3) module cost. This article highlights these challenges and demonstrates how RF SOI based mmWave phased array systems can enable the optimum solution for future mmWave 5G infrastructure compared to other semiconductor technologies.

BASIC ARCHITECTURE OF THE PHASED ARRAY AND KEY METRICS

Phased arrays consist of multiple antenna elements with phase shifting at each element to steer the beam (see ***Figure 1***). Phase shifting can occur in either the RF, as depicted in Figure 1, or digital domain. For optimal beam shape, the spacing of antenna elements in the phased array (lattice spacing) is typically a half wavelength. On-chip and PCB routing loss are very high at mmWave, so minimizing loss in routing from chip to antenna is important. As a result, mmWave front-end components (LNA, PA, switch) need to be physically close to each antenna element. At 28 GHz, λ/2 is 5.4 mm and at 39 GHz, it is 3.9 mm. The lattice spacing constraints and need for IC/antenna element co-location creates a thermal challenge. This is exacerbated by the low PA efficiency of first generation solutions. The high peak to average power ration of 5G NR modulation results in a large back-off from peak power operation, where the PA is inherently inefficient. With transmit efficiencies as low as 5 percent to 10 percent, the great majority of front-end power dissipation goes to heat generation concentrated within the lattice spacing as opposed to RF signal power. Improving transmit path linear efficiency is thus of paramount importance for next generation designs.

The array gain of a phased array is proportional to the number of array elements (N). On the Tx side, the combination of array gain and additional power per element results in an N^2 increase in output power as compared to a single element. This fundamental property of the phased array enables a trade-off between semiconductor performance and the size of array needed to meet system requirements. In particular, the N^2 reduction in output power per element to achieve the same system EIRP targets makes silicon technologies an attractive choice for all but the highest power applications.

The minimum requirement is adequate transistor performance (f_T and f_{max}). Designers need a minimum of 5x and preferably 10x ratio between transistor cutoff frequencies and operation frequency for acceptable gain and circuit margin at the mmWave carrier frequency. This means that at the 39 GHz 5G band, a 200 GHz f_T/f_{max} is the minimum acceptable and 400 GHz is preferred. Due to the high losses at mmWave, parasitics of active and passive elements are critical. Minimizing loss in the metal/dielectric stack is important since transistors must drive transmission lines at the top metal levels and for efficiency in power combining networks. Thick metal and dielectric stacks are important in minimizing this loss. Substrate losses are also important; quality factor of matching networks and transmission line insertion loss improves with higher resistivity substrates. On the Rx side, transistor NF_{min} is important for low noise circuits; on the Tx side, breakdown voltage and safe operating area are paramount for efficient power generation in the PA and for power handling in the antenna switch.

SEMICONDUCTOR TECHNOLOGIES — RF SOI VS CMOS VS GaN

In RF SOI technology, CMOS transistors are built on a top layer of silicon isolated by a buried oxide (BOX) layer from the silicon substrate. The oxide isolation reduces FET junction capacitance to substrate and improves FET performance. As a result, transistor f_T and f_{max} in an SOI technology are higher than in a comparable node planar CMOS technology.

For example, GlobalFoundries (GF) has a 45 nm RF SOI in production that has been optimized for mmWave performance. NFET and PFET f_T/f_{max} are 290/330 GHz and 245/300 GHz, respectively. Metal/

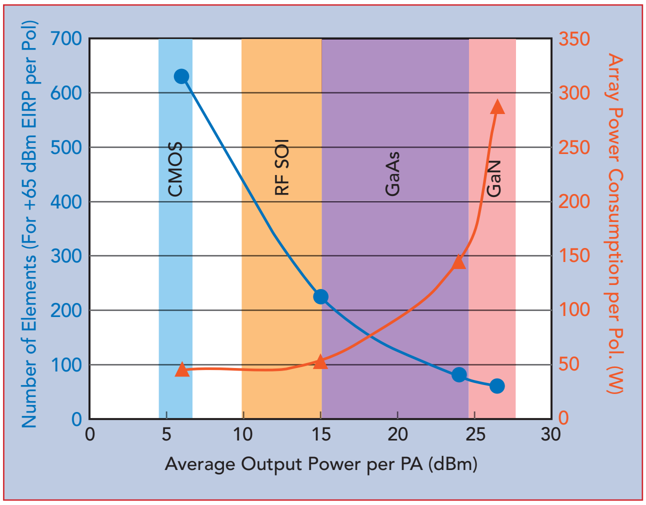

Fig. 3 Comparison of semiconductor technologies for 5G 28 GHz infrastructure phased-array Tx applications.

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dielectric stacks are optimized for mmWave performance and offer single and dual ultra-thick Cu levels for low loss transmission lines and combining networks and high Q passives. With the superior front-end performance and 45 nm logic density, the typical integration level for solutions based on RF SOI encompasses the PA, LNA, phase-shifter, and combiner front ends for 4-element and 8-element beamformers, and may also include mmWave up/down conversion and RF transceivers. 45 nm logic density enables the integration of high-speed SPI interfaces with large beam tables containing 1000s of entries, allowing for agile beamforming for high mobility applications.

A unique advantage of RF SOI technology is the capability to engineer the substrate for improved RF performance. High resistivity (>1K ohm-cm) substrates reduce signal loss to the substrate and improve transmission line loss and Q of matching networks. Higher Q input matching networks result in lower LNA NF. In addition, engineered substrates with trap rich layers under the BOX reduce parasitic conduction mechanisms that otherwise will degrade switch harmonics and linearity.

RF SOI transistors are fully isolated from each other by the surrounding oxide. Since the FETs are electrically isolated and there is no common substrate node as in bulk CMOS, FET's can be connected in series ("stacked") and biased such that the voltage is distributed equally across the stack (see ***Figure 2***). Stacking overcomes the low breakdown voltage limitations of advanced node CMOS since the breakdown voltage of the stack is the sum of the BV_{ds} of the individual transistors in the stack. This is a significant benefit to front-end circuit performance, resulting in higher PA output power and efficiency and improved antenna switch insertion loss and power handling. 45 nm RF SOI PAs can deliver peak output power of 20-23 dBm at 28 GHz with high efficiency (>40 percent PAE). This is in contrast to solutions in advanced CMOS, where the low breakdown voltage of advanced node FETs results in lower Pout and PAE. The higher efficiency of RF SOI PAs is important in reducing thermal dissipation and addressing one of the key technology challenges of 5G arrays.

With 5G NR modulation, the PA will experience peak RF voltages that are 2x the supply voltage. Accurate evaluation of transistor degradation under complex 5G waveforms is important to assure the high reliability and lifetime requirements of 5G infrastructure are met. This is best done with PDK tools that seamlessly integrate reliability models with circuit design and simulation.

5G mmWave base stations are targeting EIRPs of 60 to 65 dBm. ***Figure 3*** compares the number of elements required in the Tx phased array to achieve 65 dBm EIRP, as a function of the average modulated output power per PA element, and the associated overall Tx array power dissipation. This figure has been compiled using publicly available information on output power and

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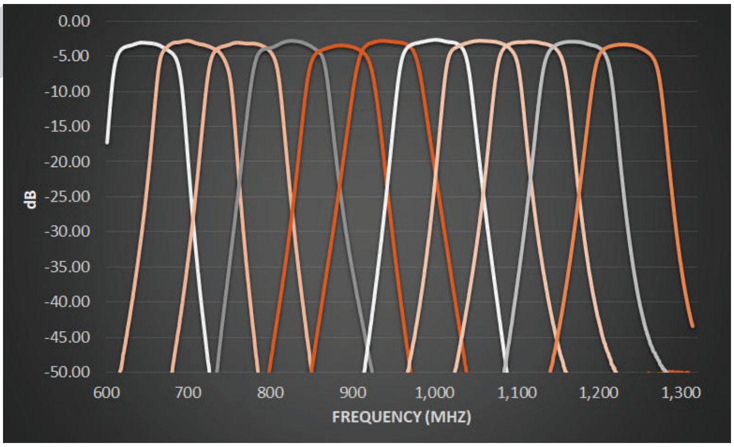

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efficiency of PAs implemented in different technologies, and factors in the power consumption in the "plumbing" of the array, namely PA drivers, beamforming circuitry etc. It can be seen that at the lower end of per PA output power (corresponding to CMOS solutions), the number of array elements becomes very large, exceeding 500 elements and increasing implementation complexity and cost. On the other hand, at the higher end of per PA output power (corresponding to GaN), the number of array elements required becomes quite small (as low as 32 elements). This drives up the overall array power consumption, since the N^2 array gain is small, implying that the EIRP is being achieved through raw output power generation. RF SOI CMOS sits in the "sweet spot" of complexity versus DC power, as the per PA output power achievable results in manageable array sizes of 256 elements and low overall Tx array power consumption.

So, there are three general areas where each technology has its strength. CMOS is best for very large arrays, because it achieves low cost when the power per amplifier is low. RF SOI occupies the "middle ground" where cost, power efficiency and output power are balanced, such as CPEs and urban mobile infrastructure. GaN comes into its own where the link is not uplink limited like point-to-point backhaul and at higher frequency bands (≥60 GHz) where high power per GaN amplifier can be leveraged for smaller array but still maintaining large point-to-point distance. Because mmWave networks will need to cover a wide variety of terrain and capacity requirements, it is clear that all three of these solutions will have a place: CMOS phased arrays are well suited for down link with large number of access points like in a stadium with large numbers of beams and no need to penetrate building walls or windows. GaN is well suited to long-distance transport network with wider beams and less steering requirements. RF SOI appears to be best for fixed-wireless CPEs and mobile infrastructure in urban environments.

DESIGN CHALLENGES FOR RF SOI mmWAVE FRONT-END MODULES

While RF SOI allows for superior Tx and Rx performance, as well as digital integration capability, there is significant opportunity for innovation in the circuit design as well as the system architecture, both of which are being actively pursued by companies such as MixComm (in partnership with GF in this case). On the Tx side, circuit approaches that extract best output power and efficiency from stacked SOI CMOS PAs while maintaining long-term reliability are critical. Even more important than peak efficiency is the average efficiency under modulation, with 5G NR waveforms typically dictating ~8 dB of back-off from the 1 dB compression point to achieve the required 3 percent EVM on the Tx side. In addition to the PA circuit design, the overall front-end module (FEM) architecture can also have a significant impact on the average

system efficiency, and careful system architecture design and planning is critical.

Digital pre-distortion (DPD) may be employed to extract even better performance from the PAs, but is complicated by the fact that there will be both systematic and random variations between the PAs of a large-scale array due to process and temperature variations, as well as amplitude tapering in the beamforming. Therefore, new array DPD algorithms and PA architectures that are friendly to DPD will enable improved Tx performance.

The use of DPD is possible for massive MIMO arrays, but it must be a "light" DPD algorithm that consumes less DC power than is saved in the PA. For very large arrays with low power per PA path, DPD may not be worthwhile, but for small arrays, at higher RF power levels, DPD may become an important element. One strong possibility here is to have a DPD algorithm and adaptation engine that is shared among multiple RF paths, essentially updating the DPD algorithm periodically instead of continuously to save on cost and power devoted to a single PA path. This approach sacrifices the level of linearization but improves efficiency which is more important.

Large-scale phased arrays are subject to amplitude and phase mismatches arising from process, temperature and package interface variations across the channels of a single FEM chip, as well as across chips. Built-in self-test and calibration approaches that can compensate for these mismatches are important for the realization of robust and accurate large-scale arrays. Implementation of these techniques allows for a self-aligning array, which adapts to field conditions and manufacturing variation to optimize performance in the critical RF front-end.

HOW RF SOI CAN ADDRESS CARRIERS' CHALLENGES

Transmitter output power is perhaps the most fundamental metric of a radio, and higher output power can be used to improve virtually every dimension of a mmWave link. Higher output power increases range, which translates to large cell radius, and consequently fewer base stations can be deployed, reducing operator CAPEX. Alternatively, for the same cell radius, it enables higher rates at the cell edge, improving quality of service. Higher per PA output power can be used by beamforming algorithms to enable "broad beams," as opposed to the conventional narrow "pencil beams," thus improving robustness in highly mobile scenarios. Higher per PA output power can also be used to reduce BOM cost, as a smaller array is needed to achieve the same EIRP. A smaller array also comes with natural beam broadening and associated robustness. ***Figure 4*** compares the median CPE uplink throughput rate of a baseline bulk CMOS-based CPE array with a DPD 45 nm RF SOI-based CPE array with equal number of antennas. It can be seen that the higher output power per PA enables significantly


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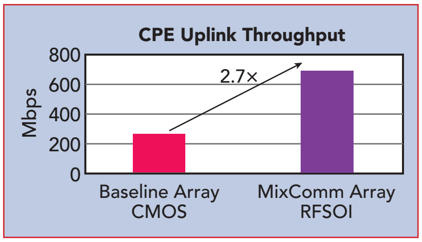
925.0 MHz
960.0 MHz
-135.9 dBm

superior link budgets, allowing a 2.7x increase in throughput rate.

WHAT'S THE IMPACT OF AN IMPROVEMENT IN THE mmWAVE AMPLIFIER?

Three challenges will dictate the success of mmWave for mobility: network cost, thermal/power budget and BOM cost. Our detailed review of semiconductor fundamentals illustrates that RF SOI brings advantages in all of these areas.

- Higher transmitter power has a huge impact on the financial case for the operators. Adding 3 dB higher EIRP to a CPE can save 20 percent of the cost of network deployment, by allowing base stations to be deployed farther apart, and also providing higher spectral efficiency. That's billions of dollars of savings at the network level, plus a bonus of higher capacity.



▲ Fig. 4 Comparison of median CPE uplink throughput rates for a baseline bulk CMOS-based CPE array and a MixComm GF 45 nm RF-SOI-based CPE array.

- Almost all radios in the market today are limited by their thermal profile. Improvements to the PA efficiency have a direct impact on the real-world EIRP that is achieved. RF SOI sits in a "sweet spot" for thermal performance compared with other technologies, allowing for tradeoffs of power, linearity and efficiency that far outperform the bulk CMOS used in many CPEs today.
- RF SOI-based radios can achieve high transmitter power without using hundreds of array elements. The RF SOI process allows for integration of the PA, LNA, and up/downconverter, keeping the BOM cost low and the supply chain simple.

Overall, it's clear that weak power in the uplink presents the biggest problem to 5G operators today. Simply upgrading CPEs to use RF SOI amplifiers can boost uplink EIRP by 3 dB or more, improving both coverage and capacity of the network. Other products such as gNodeB arrays and handsets can also benefit in similar ways. CMOS phased arrays are best suited for down link with large number of access points like in a stadium with large numbers of beams and no need to penetrate building wall or windows and GaN is well suited to long-distance transport network with wider beams and less steering requirements.■

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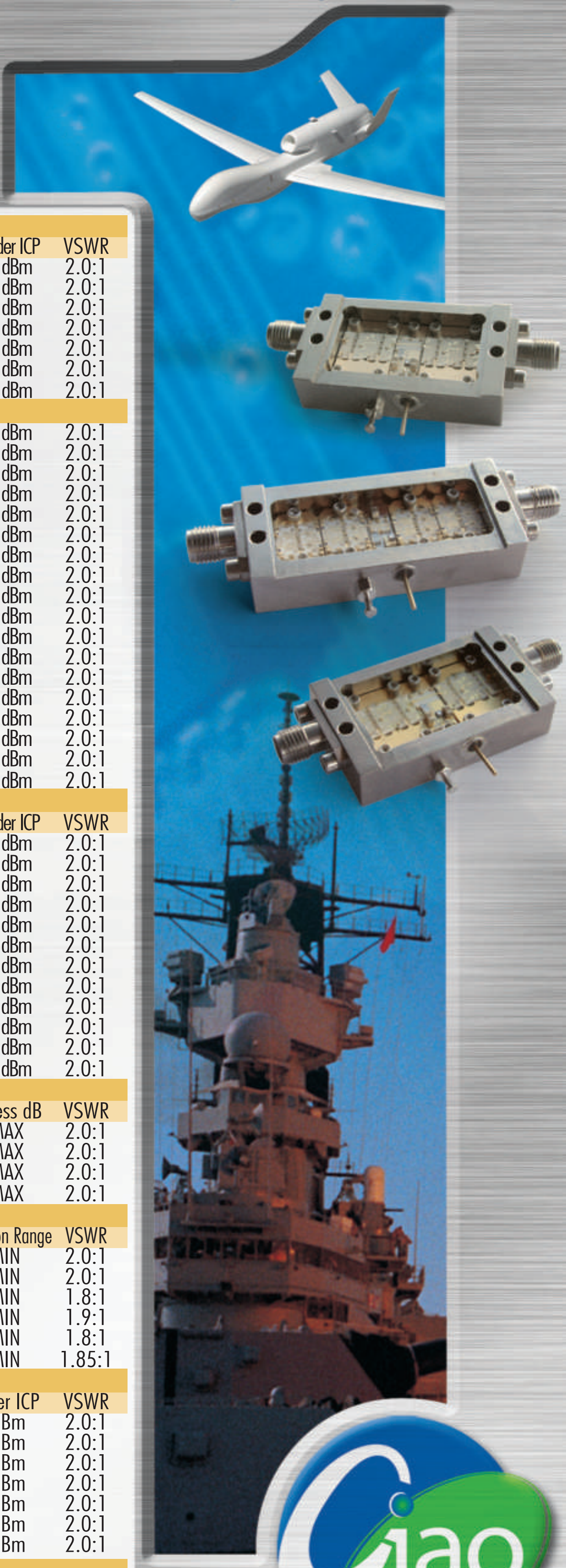

OCTAVE BAND LOW NOISE AMPLIFIERS

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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Four Nations to Be Protected with Next-Generation Radar

Through partnerships with the U.S. Government, Spain, Japan and Canada, Lockheed Martin's solid-state radar (SSR) technology will provide front-line defense to nations around the world with cutting-edge air and missile defense capabilities. These nations are part of a growing SSR family of 24 platforms, ushering in the next generation of maritime and ground-based advanced radar technology. The basis of SSR technology is the Long Range Discrimination Radar (LRDR), which the Missile Defense Agency (MDA) selected Lockheed Martin to develop in 2015 with an on-track delivery set for 2020. In 2019, Lockheed Martin's SSR for Aegis Ashore Japan was designated by the United States Government as AN/SPY-7(V)1.

SPY-7's core technology is derived from the LRDR program, which has been declared Technical Readiness Level 7 by the U.S. Government. The technology consists of a scalable and modular gallium nitride (GaN) based "subarray" radar building block, providing advanced performance and increased efficiency and reliability to pace ever-evolving threats. As part of its investment into the advancement of SSR, Lockheed Martin built a solid-state radar integration site to conduct detailed testing to prove the maturity of the system and reduce fielding risk. Scaled versions of the LRDR site will be utilized for future radar programs including Aegis Ashore Japan, Canadian Surface Combatant and MDA's Homeland Defense Radar in Hawaii.

Solid-state offers powerful capabilities to detect, track and engage sophisticated air and missile threats, including the very complicated task of discriminating–or picking out–and countering lethal objects present in enemy ballistic missiles. The Lockheed Martin SSR uses state-of-the art hardware and an innovative software-defined radar architecture to meet current requirements while providing extensibility features to pace evolving threats for decades to come. Its unique maintain-while-operate capability provides very high operational availability and enables continuous 24/7 operation.

LRDR (Source: Lockheed Martin)

SSR is a multi-mission system providing a wide range of capabilities, from passive situational awareness to integrated air and missile defense solutions. Its combined capability and mission flexibility has gained the attention of new and current users of the Aegis Weapon System, the world's premier air and missile defense combat suite.

While LRDR is the first program to use Lockheed Martin's new SSR building blocks, over the past three years Lockheed Martin has been selected in open competitions to equip an additional 24 platforms in four nations. SPY-7 provides several times the performance of traditional SPY-1 radars and the ability to engage multiple targets simultaneously with the latest proven interceptors.

Spain's Ministry of Defense stated its preference for Lockheed Martin's technology for its five F-110 class frigates in 2017 and awarded the ship construction order to Navantia in 2019. These ships will host the first-ever S-Band variants of the SPY-7 radar for the Spanish Navy. Production will be a collaboration between Lockheed Martin and Spanish company, Indra. When the frigates deploy in 2026 the SPY-7 variant will be integrated as part of the Aegis Weapon System. The frigates will also incorporate the International Aegis Fire Control Loop (IAFCL) integrated with SCOMBA, the national combat system developed by Navantia.

Canada's Department of National Defence also selected Lockheed Martin as the naval radar provider for its 15 Canadian Surface Combatant (CSC) ships. Lockheed Martin's IAFCL is integrated with Canada's combat management system, CMS 330, developed by Lockheed Martin Canada for the Royal Canadian Navy's HALIFAX Class ships. The program will make Canada the owner of the world's second largest Aegis fleet, and the SPY-7 radar variant will enable CSC to conduct highly advanced maritime missions for decades to come.

Including LRDR, the 24 Lockheed Martin SSR platforms selected to date represent a total of 91 antennas of varying sizes, collectively composed of over 15,000 subarrays. On LRDR alone, Lockheed Martin has produced an equivalent of eight Aegis shipsets to date. The U.S. Government's LRDR has a planned service life for decades to come and will be supported and maintained throughout that period. This ensures the U.S. and its allies will have a large and stable base of cost-effective logistics and support for many years in the future.

Advanced Space Radio Monitoring System Assures Satellite Spectrum

Kratos Defense & Security Solutions, Inc. recently announced that it was awarded an $11.5 million contract to build an advanced space radio monitoring system for a government customer. The system will incorporate Kratos technologies and integrated products to help the U.S. regulate and protect the satellite spectrum. As part of the multi-million dollar project, Kratos is responsible for the turnkey

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design, installation and integration of the advanced space radio monitoring system including the core satellite technology and associated hardware and software. The system includes a fixed site and mobile unit to monitor satellite downlinks. The scope of work includes Kratos antennas, a satellite monitoring and geolocation solution and an unmanned aerial vehicle spectrum analysis solution.

Kratos will deploy GeoMon, a specific application for frequency regulators to implement ITU missions, as well as the Monics® carrier monitoring, satID® geolocation, Compass® network Monitor & Control and Skyminer ground system data analytics products integrated with the Kratos-designed antennas/RF system to provide an end-to-end management solution. Skyminer will enable the operators to collect performance data across ground systems and use business intelligence to analyze satellite measurements from both regulatory and technical perspectives.

First Lower Tier Air & Missile Defense Sensor Radar Antenna

Raytheon Company finished building the first radar antenna array for the U.S. Army's Lower Tier Air and Missile Defense Sensor (LTAMDS).

LTAMDS (Source: Raytheon Company)

Raytheon completed the work less than 120 days after the U.S. Army selected Raytheon to build LTAMDS, a next-generation radar that will defeat advanced threats like hypersonic weapons. The sensor is a simultaneous 360-degree, active electronically scanned array radar powered by the company's gallium nitride circuits.

The newly built primary array, similar in size to the Patriot™ radar array, will provide more than twice its performance. Following extensive testing, the radar array will be mounted on a precision-machined enclosure for integration and further evaluation. The enclosure uses advanced design and manufacturing techniques for accelerated manufacture to support the U.S. Army's Urgent Materiel Release program.

Raytheon is working closely with hundreds of suppliers across 42 states, including a core team playing a strategic role in building the LTAMDS solution. The core team includes Crane Aerospace & Electronics, Cummings Aerospace, IERUS Technologies, Kord Technologies, Mercury Systems and nLogic.

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Cliff Drubin, Associate Technical Editor

5G Available in 378 Cities Globally

Viavi Solutions Inc. recently revealed new industry data demonstrating a rapid surge in the spread of 5G technology. As of January 2020, commercial 5G networks have been deployed in 378 cities across 34 countries, according to the new VIAVI report "The State of 5G Deployments," now in its fourth year.

The country with the most cities with 5G availability is South Korea with 85 cities, followed by China with 57, the United States at 50 and the U.K. with 31. In terms of regional coverage, Europe, the Middle East and Africa lead the way with 168 cities where 5G networks have been deployed. Asia is second with 156 cities followed by 5G across the Americas with 54 cities covered. Deployments include both mobile and fixed wireless 5G networks.

As the battle for 5G supremacy heats up, VIAVI findings indicate that several operators are blanketing the largest population centers, with as many as five communications service providers deploying 5G in cities such as Los Angeles and New York.

"For 5G operators there is a heady mixture of optimism and fear," said VIAVI's Chief Technology Officer Sameh Yamany. "The optimism is related to a plethora of new commercial applications that could change operator economics for the better, even though they may not feel the commercial impact for some time. The immediate fear is that they will get left behind in the short-term marketing battle by rival operators if they're not fast enough in their landgrab."

Yamany continued, "Nonetheless, very quickly, the overarching driver will change from simply having 5G network availability to having the best 5G networks. Even as operators continue their 5G build-out, they must simultaneously shift gears from network validation and verification to advanced analytics and automated network troubleshooting. The race for the best 5G network has only just begun."

The data was compiled from publicly available sources for information purposes only, as part of the VIAVI practice of tracking trends. The "State of 5G Deployments" serves as a companion document to the "VIAVI Gigabit Monitor," a visual database of gigabit internet deployments worldwide.

LTE Drives Short-Term Opportunity for Cooperative Mobility

Cooperative mobility is set to be propelled by the mass adoption of Long-Term Evolution (LTE) vehicle connections and investment in roadside infrastructure connectivity. Shipments of vehicles that can communicate with LTE networks and road traffic agents will reach 62 million by the end of 2020 and over 97 million in 2024, according to a new market data report from ABI Research. Most of these shipments, 98 percent in 2020, will be led by vehicles that can share and receive messages about the vehicle status and the existence of dangerous situations via a traditional cellular network connection (V2N).

V2N LTE communication is widely available and well suited to non-mission-critical applications. Here, use cases such as Green Light Optimal Speed Advisory (GLOSA) and Intersection Collision Warning can add value to safety and traffic efficiency, reducing the number of road incidents. "V2N offers the greatest opportunity in the next four years, with 60.8 million shipments in 2020 rising to 76.6 million in 2024. This represents an immediate monetization opportunity for players, yet not many OEMs offer V2N services to drivers," said Research Analyst at ABI Research, Maite Bezerra.

The main obstacle to V2N implementation is the uncertainty surrounding the business model. Coupled with a scarcity of infrastructure, OEMs lack experience in software development.

Although, a notable use case comes from Audi. Audi has implemented network-based GLOSA at nearly 5,000 connected intersections in the U.S. since 2017, and the service is now available in Ingolstadt and Düsseldorf, the latter committing to connect 75 percent of its traffic lights by September 2020. According to preliminary studies, the application can reduce fuel consumption by 15 percent.

Due to a lack of experience and skills in developing applications, OEMs offer expensive and unintuitive V2N services with a slow time-to-market. Drivers will not subscribe to expensive services that do not add value, especially while apps such as Waze offer map updates and hazardous location notifications for free.

Vehicles able to communicate to other vehicles and traffic agents directly (V2X), will see minor deployment in 2020, but will then gather pace in 2021, reaching nearly 4 million shipments. V2X communication will allow nearby traffic agents to directly exchange messages about detected objects, so vehicles are made aware of objects outside their line-of-sight. V2X enables a range of advanced safety applications. Where vehicles communicate with one another, for example, the National Highway Traffic Safety Administration estimates that traffic accidents can be reduced by 13 percent. However, predominantly as a short-range technology, V2X requires high market adoption to reach full potential, which will take several years.

Vehicle communication using 5G will allow the introduction of autonomous vehicles (level 3 and 4) and services including cooperative perception and sensor data sharing. However, these use cases will only be feasible

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in the long term, requiring considerable infrastructure development. Vehicles able to communicate to cellular networks and directly to other devices via 5G will not emerge as a force until 2027, when shipments will hit 16.3 million.

Microwave Electron Tube Market Once Again at Over US$1 Billion

While microwave and mmWave high-power vacuum electron devices (VEDs) main "below the radar" of many industry observers, the total available market for this segment is once again over U.S.$1 billion, as it has been for the last several years, according to a new market data report from ABI Research.

"Despite its size, and although these tubes remain essential elements in specialized military, scientific/medical and space communications applications, this market is generally under-reported by the electronics industry at large and poorly understood by those not directly involved in it," explained Research Director Lance Wilson at ABI Research.

Essentially, this continues as a stable industry after several rounds of consolidation in the past decade. There is some potential for further consolidation; but there are no signs that more is yet to come. "However, one new RF semiconductor technology, gallium nitride, will soon change the competitive landscape. While it is not yet near monopolizing the microwave RF power industry, GaN is advancing steadily and is a technology that should be closely watched, as it will be a threat to some aspects of the lower-power microwave and mmWave VED marketplace," Wilson stated.

> No other way to generate high levels of RF Power.

The size of this historic market continues to surprise everyone and its longevity and firm resistance to RF power semiconductor encroachment is equally surprising. However, that will be changing to some degree as GaN devices move up in frequency and power. Despite all this, microwave and mmWave VEDs are showing some growth, in part being driven by larger and more stable defense spending in the U.S.


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Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

IN MEMORIAM

▲ *Roberto Sorrentino*

It is with great sadness that we report that **Professor Roberto Sorrentino** died on Tuesday, March 3, 2020. Roberto Sorrentino was an electronics engineer who had a distinguished career in the field on microwave and mmWave circuits and antennas. He received in recent years the IEEE Microwave Career Award, the EuMA Distinguished Service Award and the Order of Merit of the Italian Republic. In 2007 he founded RF Microtech srl, a successful spin-off company from the University of Perugia specializing in microwave and RF technologies. This Umbrian company became a leader in the field of antenna design and satellite communication systems, employing 25 people. He was the author of more than 150 technical papers in international journals and 200 refereed conference papers and he wrote and edited several books for John Wiley and McGraw-Hill.

MERGERS & ACQUISITIONS

Qorvo® announced that it has completed its acquisition of **Custom MMIC**, a supplier of high-performance GaAs and GaN MMICs for defense, aerospace and commercial applications. As part of Qorvo's Infrastructure and Defense Products (IDP) business, the Custom MMIC team will continue to expand its mmWave capabilities for products used in defense phased array and AESA radars, electronic warfare, satellite communications, wireless backhaul and microwave test equipment. Chelmsford, Mass.-based Custom MMIC was founded in 2006 and has extensive experience developing MMICs at frequencies up to 70 GHz.

Strand Marketing announced that they recently completed a merger agreement with fellow Boston area digital marketing agency, **Nowspeed**. The merger brings their expert creative and web design and development skills to Nowspeed clients, and stronger SEO, digital advertising and social media marketing capabilities to Strand clients. The combined agency will keep the Nowspeed name and operate from Nowspeed's Westborough, Mass. headquarters. Strand CEO/Brand Director, David Strand joined the Nowspeed leadership team as Brand Director and will be delivering brand strategy and advanced creative solutions to all Nowspeed clients. Joining him is Creative Director David Bush, Web Developer Brad Emerson and Director of Client Services Lori Fairbrother.

Mega Industries and **Ferrite Microwave Technologies** (FMT) announced the closing of the merger of the two companies, now operating under a new holding company called **Microwave Techniques**. Deal terms were not announced. The new company includes the Micro Communications (MCI) and FXR Microwave dummy load product lines previously acquired by Mega Industries. The combination of Mega, FMT, MCI and the FXR Microwave dummy load product lines creates a global leader in high-power microwave systems and components, according to the companies, offering customers a single source to support demanding high-power microwave needs.

STMicroelectronics (ST) announced it has signed an agreement to acquire a majority stake in French GaN innovator **Exagan**. Exagan's expertise in epitaxy, product development and application know-how will broaden and accelerate ST's power GaN roadmap and business for automotive, industrial and consumer applications. Exagan will continue to execute its product roadmap and will be supported by ST in the deployment of its products.

COLLABORATIONS

Keysight Technologies Inc., with **Riscure**, a recognized vendor of security tools, services and training for connected devices, announced a collaboration to advance the development of secure and resilient 5G networks, devices and services. An integrated ecosystem will progressively rely on sophisticated security test solutions to safeguard operational activities and protect data shared between businesses, government organizations and consumers.

Rohde & Schwarz and **Gemalto**, a Thales company, are working on significantly reducing expensive and time-consuming drive tests. IoT protocol stack features have been specified by 3GPP, but IoT devices have to interact with different network configurations worldwide. This makes it important to ensure that these features are working well in all sorts of configurations, configured by different network operators. Thanks to the current cooperation, manufacturers of IoT solutions can use virtual drive tests during the development phase of CAT M1 and NB IoT modules to find and fix problems at an earlier stage. This also enables seamless cellular coverage and reliable connectivity before the integration process continues and further field tests are performed.

As part of a strategic investment program, **TMD Technologies Ltd. (TMD)**, West London-based manufacturer of advanced equipment for the microwave industry, has taken a share in **Diamond Microwave Ltd. (DML)**, a specialist in high-power solid-state microwave amplifier products utilizing GaN and GaAs technology. Diamond Microwave has been a pioneer in the development and manufacture of advanced compact GaN-based microwave high-power solid-state power amplifiers (SSPA) for the radar, electronic warfare (EW), communications and aerospace sectors. DML's chip and wire GaN technol-

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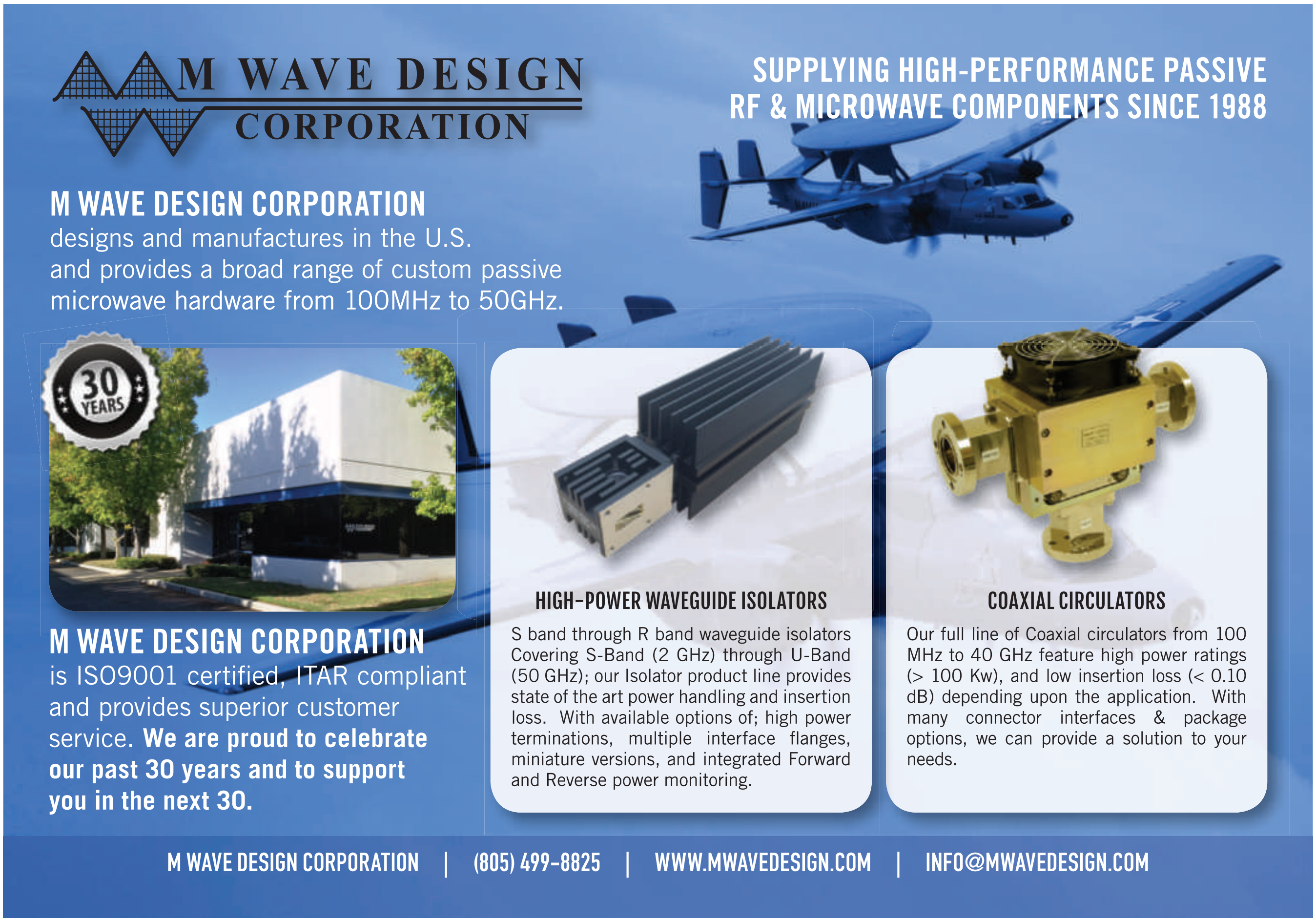
ogy is particularly suited to these demanding applications, where their power-to-volume performance is a leading-edge capability differentiator.

Modelithics welcomes **Vishay Intertechnology**, one of the world's largest manufacturers of discrete semiconductors and passive electronic components, into the Modelithics Vendor Partner (MVP) Program at the Sponsoring level. As a Sponsoring MVP, Vishay is supporting RF and microwave designers by sponsoring free extended 90-day trials (with approval) of all Modelithics models available for Vishay components, as well as collaborating with Modelithics to develop new design data and models for selected components. In addition to becoming a Sponsoring MVP, Vishay and Modelithics are collaborating to develop three new Microwave Global Models™ for Vishay's CH02016F, CH0402F and CH0603F resistors.

Nokia and **Marvell** announced that they are working together to develop leading 5G multi-radio access technology silicon innovations, including multiple generations of custom silicon and infrastructure processors to further expand the range of Nokia ReefShark chipsets available for 5G solutions.

Rakuten and **Vodafone** are now the leading investors in a venture to extend mobile coverage to more people and devices around the planet, using the first satellite-based mobile broadband network. **SpaceMobile**, a low Earth orbit (LEO) satellite network from AST & Science, will be the first to connect directly to standard smartphones. The SpaceMobile network will enable seamless roaming to and from terrestrial cellular networks at comparable data rates without specialized satellite hardware. The LEO constellation will provide a low latency link between the satellite and phone. AST & Science successfully tested its SpaceMobile technology aboard the BlueWalker 1 satellite, which was launched in April 2019, and has been validating the technology following that initial flight. The company has an extensive patent and IP portfolio for its ground and space technologies.

Marvell and **Analog Devices Inc (ADI)** have announced a technology collaboration leveraging Marvell's 5G digital platform and ADI's wideband RF transceiver technologies to deliver optimized solutions for 5G base stations. The companies will offer fully-integrated 5G digital front-end (DFE) ASICs with tightly-coupled RF transceivers and will collaborate on next-generation radio solutions, including baseband and RF technology optimized for a diverse set of functional splits and architectures. The increased complexity of 5G radios is driven by massive MIMO and mmWave operation challenges, RF and radio network designs. Optimized partitioning of the RF and mixed signal circuit functions, with both digital ASIC and baseband silicon, is necessary to achieve the low power, small size and low cost requirements of 5G.

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Around the **Circuit**

Gapwaves announced a collaboration with **Uhnder** to develop a high resolution radar for a last mile autonomous delivery vehicle. Gapwaves has developed a novel waveguide antenna technology for mmWave applications such as automotive radar and 5G telecom. Its gap waveguide technology achieves the low loss of waveguide and is compatible with high volume, cost-effective manufacturing. For automotive radar applications, its antenna provides a wide field of view and high isolation.

NEW STARTS

TowerJazz, the global specialty foundry leader, announced the launch of a new brand identity to reflect the company's global presence and strength, and highlight its focus to provide the highest value analog semiconductor solutions. The company brand name will be Tower Semiconductor and will include all of the company's worldwide subsidiaries. The new website address will be www.towersemi.com.

ACHIEVEMENTS

Triad RF Systems, a designer and manufacturer of integrated radio systems and high-performance RF/microwave amplifiers, announced that they recently received their certificate of Aerospace Standard 9100D registration from **Dekra Certification, Inc.** for its manufacturing facilities located in East Brunswick, N.J.

CONTRACTS

Leonardo DRS Inc. announced that it has been awarded a contract worth up to $808 million to provide a suite of electronic products to link C5ISR equipment to combat vehicles across the armed services and to satisfy interconnection requirements for federal agencies. Under the indefinite delivery/indefinite quantity Interconnection Equipment Contract from the Defense Logistics Agency Land, Aberdeen Proving Ground, MD, Leonardo DRS would deliver wiring harnesses, installation kits, cable assemblies, cabling, connectors and services. The products will be delivered to the Department of Defense and other federal agencies in the U.S. government.

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 more than $8.8 million for Ka-Band solid state amplifiers to be used in an In-Flight Connectivity SATCOM application.

PEOPLE

Anritsu Co. announced the appointment of **Robert Johnson** as vice president and general manager for Anritsu Americas Sales Company (AASC). In his new position, Johnson will oversee all AASC operations and position the company as the preeminent test and measurement innovator serving the 5G ecosystem, as well as IoT, cellular, military/aerospace and public safety. Prior to

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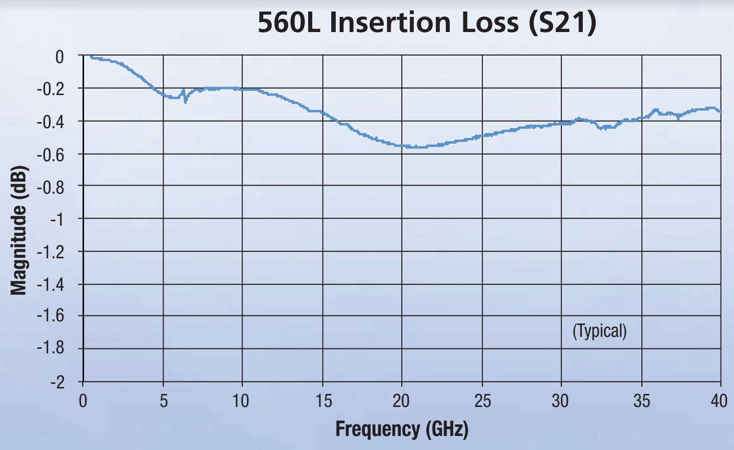

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▲ Robert Johnson

being named vice president and general manager, Johnson served as assistant general manager for AASC. He will use his 25+ years of experience in mobile technology, operations, sales management and marketing to lead Anritsu into a new era in which emerging communication technologies will be integrated into a variety of industries.

▲ David Geiling

Kymeta announced the appointment of **David Geiling** as vice president of sales, Asia Pacific, a move that will increase the availability of Kymeta solutions across multiple markets in the region. In this role, Mr. Geiling will be responsible for all direct sales and reseller management for Asia Pacific, including India. He will also be tasked with growing strategic customer accounts and partner relationships for Asia that enhance Kymeta's core business objectives. Geiling joins a team of seasoned sales professionals at Kymeta.

Raytheon Co.'s Mark Russell, vice president of Engineering, Technology and Mission Assurance, has been elected to the National Academy of Engineering (NAE).

▲ Mark Russell

NAE members honor those who have made outstanding contributions to engineering research, practice or education, including "the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education." Russell was selected for his leadership in developing radar systems that enhanced national security and safety.

▲ Thomas L. Marzetta

Thomas L. Marzetta, director of **NYU WIRELESS** and a distinguished industry professor of electrical and computer engineering at the NYU Tandon School of Engineering was elected to the NAE. The Academy specifically cited Marzetta's contributions to MIMO antenna arrays in wireless communications.

▲ Dr. Jaume Anguera

Dr. Jaume Anguera was named **IEEE Fellow** for his contributions to small and multi-band antennas for wireless telecommunication devices. The most salient contribution of Anguera, recently named FRACTUS ANTENNAS' CTO, is Virtual Antenna™ technology where he is the lead inventor together with his peer colleagues Dr.

Around the **Circuit**

Aurora Andújar and Dr. Carles Puente at NN. The range of mXTEND™ products based on the Virtual Antenna™ technology, created by Jaume Anguera and his colleagues, enables full functional multi-band wireless connectivity to smartphones and IoT devices through miniature and off-the-shelf antenna boosters that replace traditional customized antennas.

REP APPOINTMENTS

Milliwave Silicon Solutions Inc. announced that it entered a representation agreement with **Beacon Technical Sales** for its MilliBox product line in the Eastern half of the U.S. MilliBox is the first affordable, compact and modular OTA radiation pattern test tool designed by and for mmWave engineers.

Mini-Circuits announced a new distribution agreement with **Mouser Electronics Inc.**, a semiconductor and electronic component distributor. The agreement makes Mouser the first authorized distributor of the Mini-Circuits product line in the U.S. Mouser now stocks over 1,000 Mini-Circuits RF products. The company's LFCG series LTCC low-pass filters are available with passband frequencies spanning DC to 6100 MHz and rejection up to 50 dB. The tiny 0805 filters feature rugged, ceramic construction, making them well-suited for tough environments such as high humidity and temperature extremes.

Richardson RFPD, an Arrow Electronics company, announced that it has entered into a global franchise agreement with **SDP Telecom/Molex**. SDP Telecom/Molex designs and manufacturers RF and microwave solutions for the wireless communications industry. SDP Telecom was founded 1995 and acquired by Molex in 2015. SDP Telecom/Molex is headquartered in Montreal, Canada, and also has manufacturing facilities in Suzhou, China. The global agreement between Richardson RFPD and SDP Telecom/Molex includes the complete standard product portfolio of circulators and isolators for wireless infrastructure applications from 600 MHz to over 6 GHz, including a 28 GHz circulator that is currently available for sampling. Customization is also available.

PLACES

Anokiwave Inc. announced the expansion of its San Diego operations to a new facility that will triple its floor space and lab capabilities to meet its growing needs. The location will increase the capabilities of its design center by providing state-of-the-art mmWave laboratory for all mmWave active antenna and IC design and test, and room to double its local workforce. The move to Sorrento Towers South, in San Diego's tech hub Sorrento Mesa, was completed in early February 2020. This expansion is driven by Anokiwave's rapid growth in recent years, during which the company has emerged as an innovative leader in technologies critical to 5G and other advanced wireless communications markets.


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INVITED PAPER

The Maximally Efficient Amplifier

Gareth Lloyd
Rohde & Schwarz, Munich, Germany

The energy efficiency of an RF front-end (RFFE) is a vital characteristic, whether a radio is battery or mains powered. For battery powered, reducing the maximum current drawn from the battery increases the time between charges. For mains powered, important properties such as size, weight and power are dictated by the RFFE efficiency. Consequently, many amplifier architectures and inventions have been developed to minimize wasted energy in the transmitter. Although improving efficiency, some of these rely on theoretically impossible modes of operation, and some fail to fully use the device's capabilities.

This article provides some analysis of and insight into amplifier efficiency. First, the tuned amplifier concept and efficiency enhancing mechanisms are explained. Then, the effects of each mechanism on amplifier efficiency are illustrated, revealing some surprises. The better known methods for improving amplifier efficiency are classified by their mechanisms—also noting the mechanisms not used—and identifying areas for improvement. Finally, the article shows that harmonic load-pull measurements on a device highlight its potential; using such measurement data with a look-up table, for example, amplifier performance in a variety of schemes can be predicted.

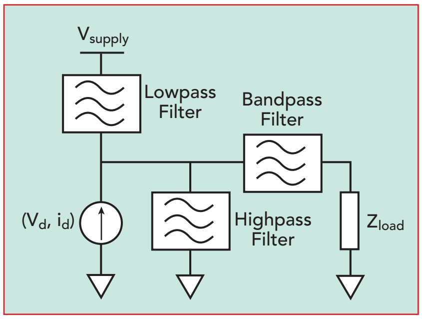

Fig. 1 **Simplified schematic of a tuned amplifier, class A to C.**

THE TUNED AMPLIFIER

A tuned amplifier circuit can be used to describe the continuum of amplifier class characteristics from A to C, via AB and B, based on sinusoidal voltage waveforms and quasi-linear operation. A more detailed explanation is provided in Chapter 3 of Cripps' book.[1] A simplified model of the power amplifier built around a controlled current source is shown in ***Figure 1***. The model can be simplified into three frequency domains:

- DC current flows through the lowpass filter and the controlled current source (i.e., the device). Its progress elsewhere in the circuit is blocked by the bandpass and highpass filters.


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- At the fundamental frequency, the signal current through the device passes solely to the intended load impedance (Z_{load}), creating a voltage across the device and load.
- Harmonic currents flowing through the device are short circuited through the highpass filter, as any harmonic currents flowing in the device "see" zero impedance and do not create any voltage.

The voltage across the device comprises only DC and fundamental components and is sinusoidal. Power is dissipated by the device when a current (i_d) flows through it with a voltage (v_d) across it and where the current and voltage overlap during the waveform cycle. For a class A amplifier, the simplest case, ***Figure 2*** shows the power dissipation versus time at three power levels. As the output power reduces, the power dissipated waveform tends to a constant value. At higher output power, the dissipated power reduces. The power consumption is constant in all cases, and the power dissipated is the total area under the power dissipation curve. In the case of this class A amplifier, the amount of power dissipated (wasted) decreases as output power level increases, from (a) to (c).

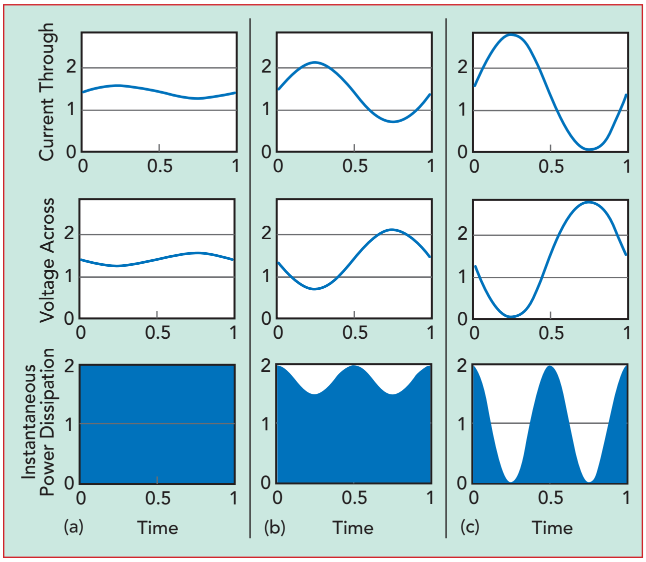

Fig. 2 **Class A amplifier waveforms at low (a), medium (b) and high (c) output power.**

EFFICIENCY ENHANCEMENT

How will efficiency enhancement mechanisms improve the energy efficiency? Consider classifying the mechanisms for reducing the wasted power in a tuned amplifier. These mechanisms relate only to the device itself, not to external modulating circuitry such as harmonic terminations or modulators. Three base mechanisms can enhance the efficiency of a single-ended amplifier: waveform engineering, supply modulation and load modulation.

Waveform Engineering—The shape of the voltage and/or current waveform is modified, which is what happens when passing through the class A to C continuum. Harmonic content is introduced into the current, modifying its waveform, in a predictable but restricted way.[1] Alternatively, the ratio of the current's harmonic content may be modified by injecting harmonics from either the input side or output side. For the current's harmonic content to affect the voltage waveform, a non-zero impedance must be present at that harmonic frequency. In the limiting case, both current and voltage waveforms are square waves and antiphase. As one of them is zero at any instant in time, the power dissipation is zero. This zero dissipation applies at least to the device, but it could just be shifted elsewhere in the system.

Supply Modulation—The average or envelope supply voltage across the device, V_{supply}, is modified. With a perfect device, V_{supply} is the root-mean-square value of the voltage waveform, set so the minimum value of vd reaches zero.

Load Modulation—The Z_{load} presented to the device at the fundamental frequency is modified, ideally so the voltage (vd) swings from 0 to 2 times the supply.

Figure 3 illustrates these mechanisms using a class B waveform as the reference. The class B current waveform is half sinusoidal, compared to fully sinusoidal for class A operation. The fundamental current is equal in both classes A and B when the peak-to-peak current variation is equal. The reason for using a class B waveform as the baseline is because the efficiency can be enhanced by all three methods. Class A, on the other hand, cannot be improved with load modulation alone: class A power consumption remains constant regardless of the load impedance.

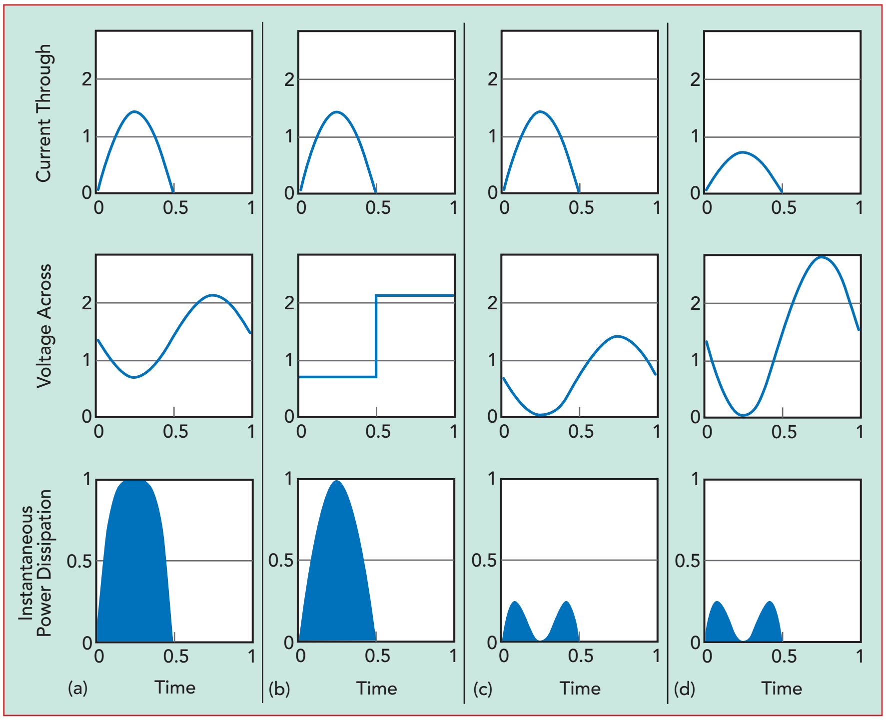

Fig. 3 **Efficiency enhancement mechanisms compared to a class B waveform at 6 dB back-off (a), waveform engineering (b), supply modulation (c) and load modulation (d).**

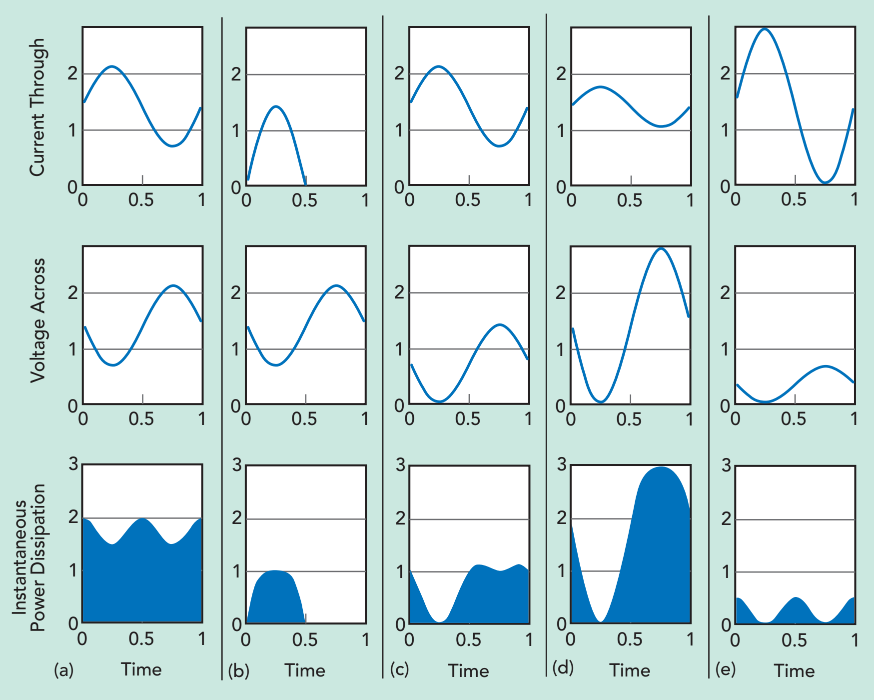

Fig. 4 Class A amplifier efficiency at 6 dB back-off (a) enhanced by waveform engineering (b), supply modulation (c), load modulation (d) and an unexpected improvement using a counter-intuitive hybrid (e).

TABLE 1
APPROACHES TO INCREASE CLASS A AMPLIFIER EFFICIENCY

Configuration	% Efficiency at 6 dB Back-Off (25% of Rated Power)
Class A Baseline	12.5
Waveform Engineered (Equivalent to Class B)	39.3
Supply Modulation	25.0
Load Modulation	12.5
Anti-Load & Supply Modulation	50.0

Class A Case Study

One of the goals of this article is to illustrate efficiency enhancement mechanisms so they can be used optimally. The class A case is not a lost cause. ***Figure 4*** shows the voltage, current and dissipation for a class A amplifier, illustrating that waveform engineering and supply modulation enhance efficiency, but load modulation does not. Waveform engineering can convert the class A sinusoidal current into the class B case of the half sinusoid in Fig. 4(b). Referring to Figure 3, class B efficiency could now be enhanced with load modulation.

What if the device could not be waveform engineered to add the required harmonics? For example, it might be operating close to its upper frequency limit and cannot support the harmonic currents. Supply modulation in Fig. 4(c) could be used, although combining it with load modulation would be counterproductive. Load modulation increases the peak-to-peak voltage, decreasing the range where supply modulation could be deployed. Turning the problem around, if load modulation degrades the effectiveness of supply modulation, what if "unload" modulation were applied? Instead of maximizing the load impedance to maximize peak-to-peak voltage, minimize the load impedance to minimize the peak-to-peak voltage and then use supply modulation. This is the case shown in Figure 4(e), the "anti-load modulation + supply modulation" case. The peak-to-peak values of current and voltage have been completely reversed from the load modulation case, and sup-

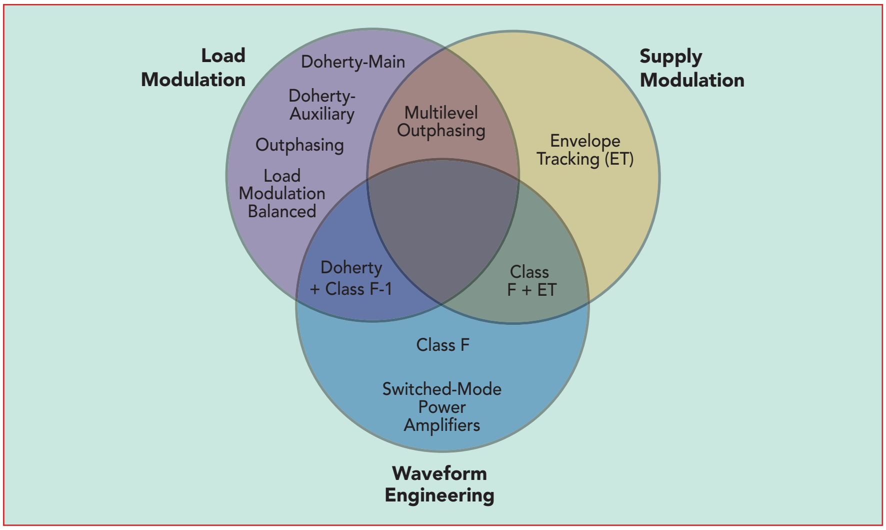

Fig. 5 **Efficiency enhancement mechanisms, their hybrids and possible areas for further improvement.**

Fig. 6 **Maury load-pull test system using the R&S®ZNA VNA.**

ply modulation has been applied—achieving a quite unexpected result: the efficiency at the output power back-off of the class A amplifier has been maintained at the theoretical maximum of 50 percent.

The respective efficiencies of the five scenarios of Figure 4 are summarized in ***Table 1***. Note that the waveforms all have the same output power.

POPULAR APPROACHES

Having classified various enhancement mechanisms and discussed their effects on theoretical amplifier blocks, including advantageous effects from hybrid approaches, the discussion moves from theory to practice, classifying the popular enhancement methods according to the mechanisms they use (see ***Figure 5***). Using a Venn diagram for classification helps identify where additional schemes are complementary and may further improve efficiency.

For example, the Doherty amplifier, which applies load modulation to its constituent amplifiers, can be improved by adding supply modulation, especially to the main channel, and/or waveform engineering, by modifying the design to incorporate class F^{-1} operation, for example.

Harmonic Load-Pull

A bottleneck is getting real world, practical devices to use the theoretical enhancements. For example, a typical GaN device may be sensitive to efficiency enhancement by load modulation over a 5–10:1 impedance range. However, when used as the main device in a Doherty architecture, it is typically exploited only over a 2–3:1 range. The Doherty scheme will fail to maximize the potential performance of the device.

Harmonic load-pull measurements over a range of bias conditions make it possible to establish the maximum performance envelope for the device technology. Load-pull data can be obtained using various setups, such as Maury Microwave's harmonic load-pull test bench with an R&S ZNA vector network analyzer (see ***Figure 6***). By comparing harmonic load-pull measurement data with the theoretical performance of a selected high efficiency technique, the performance gap can be quantified, answering the question of the difference between what has been built and the performance limit. Alternatively, if the device is assumed to be the bottleneck, the harmonic load-pull measurement data enables a

scheme to be designed to maximize its potential, using the optimal enhancement mechanisms in the correct proportions.

Thus there are several ways to use the data from a rigorous and repeatable setup for measuring load-pull. One is to create characterization and architectural databases for cross-referencing device performance with various circuit architectures and enhancement methods: Doherty, load modulated, balanced, outphasing, etc. The design flow of ***Figure 7*** shows possible steps for setting up and using a look-up table for assessing device performance and enhancement techniques. To illustrate the concept, a commercially available Wolfspeed GaN transistor (CG2H40010) was characterized at a fundamental frequency of 2 GHz and a bias current of 100 mA using a Maury harmonic load-pull test bench. The measurement data was analyzed to understand device performance in a Doherty amplifier, then compared with the maximum performance possible from the device. ***Figure 8*** shows the output power and drain efficiency as the input power, fundamental and harmonic terminations and supply voltages were swept. This scatter plot provides the performance limit of a single-ended device; to achieve drain efficiency greater than 50 percent, the dynamic range of the output power approaches 15 dB.

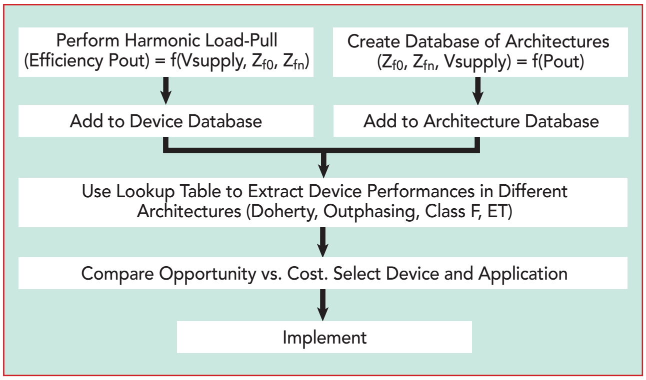

Fig. 7 **Process flow to achieve the best device-architecture pairing.**

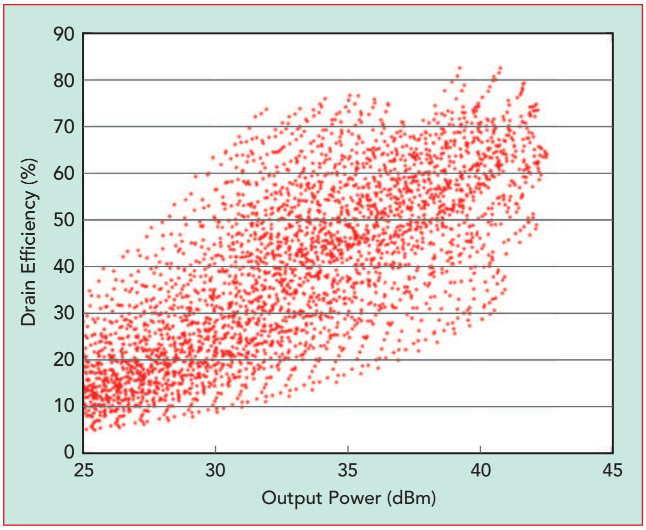

Fig. 8 **Single-ended GaN transistor drain efficiency and output power vs. swept input power, supply voltage (10, 20 and 28 V) and fundamental, second and third harmonic impedances.**

For a Doherty amplifier, the (simplified) relationship between output power and impedance is defined by:

$i_{aux} = 2i_{main} - 1$, where i_{main}, the normalized output current from the main transistor, varies from 0 to 1.

$i_{aux} = 0$ where $i_{aux} < 0$. i_{aux} is the normalized output current of the auxiliary device.

The normalized impedances presented to the main and auxiliary transistors are

$Z_{main} = 2 - i_{aux}/i_{main}$ and $Z_{aux} = 1/(i_{aux}/i_{main})$, respectively.

The output power contributions from the constituent amplifiers are given by

$P_{main} = i_{main}^2 \times Z_{main}$ and $P_{aux} = i_{aux}^2 \times Z_{aux}$

In this Doherty example, a theoretical output current relationship is used, although the equation relating i_{aux} and i_{main} can be changed, using a square law auxiliary relationship for example, where $i_{aux} = \sqrt{i_{main}}$. The impedance values Z_{main} and Z_{aux} may be

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AM100WN-CU-R	DC-6	14	44.5	46	28
AM025WN-BI-R	DC-8	16	38.9	40	28
AM012WN-BI-R	DC-10	17	36.1	37	28
AM005WN-BI-R	DC-12	15	32	33.5	28
AM050WN-00-R	DC-15	20	41.7	43.3	28
AM100WN-00-R	DC-15	19	44.5	46.1	28
AM025WN-00-R	DC-15	21	38.9	40.5	28
AM012WN-00-R	DC-15	22	36.1	37.7	28
AM005WN-00-R	DC-18	23	32	33.4	28

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AM024MX-QG-R	DC-6	13	28	39	5
AM036MX-QG-R	DC-6	12	29.5	42	5
AM048MX-QG-R	DC-6	11	31	43	5
AM072MX-CU-R	DC-6	11	34	46	7
AM100MX-CU-R	DC-6	10	35	48	7
AM150MX-CU-R	DC-6	10	36.5	50	7
AM200MX-CU-R	DC-6	10	38	48	7
AM300MX-CU-R	DC-6	9	39.5	51	7
AM005MH2-BI-R	DC-6	15	25	40	14
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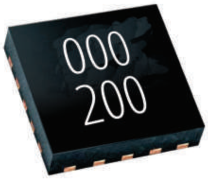
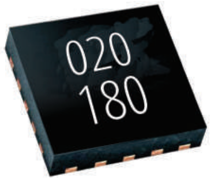
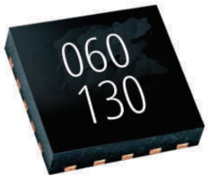


AMCOM's AM00020026WM-QN5-R is a broadband GaAs MMIC Distributed Power Amplifier which operates between DC and 20 GHz. This amplifier has 13 dB gain, and 26 dBm output power. The Amplifier Input and output are internally matched to 50 Ohms. The amplifier is packaged in a 5x5 mm 20-pins QFN package which suits automated assembly techniques.



AMCOM's AM02018026WM-QN5-R is a broadband GaAs MMIC Distributed Power Amplifier which operates between 2 and 18 GHz. This amplifier has 23 dB gain, and 26 dBm output power. The Amplifier Input and output are internally matched to 50 Ohms. The amplifier is packaged in a 5x5 mm 20-pins QFN package which suits automated assembly techniques.



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Phone 301.353.8400 - www.amcomusa.com - info@amcomusa.com scaled to any value in the dataset. In this case, 10 Ω is used as a multiplier prior to the look-up operation; fixed values for the harmonic impedances have also been chosen prior to look-up. With the definition for output power and impedance for the main and auxiliary devices, the look-up-table operation is performed on the measurement data to extract the drain efficiency, with interpolation of the measurements used to determine intermediate values.

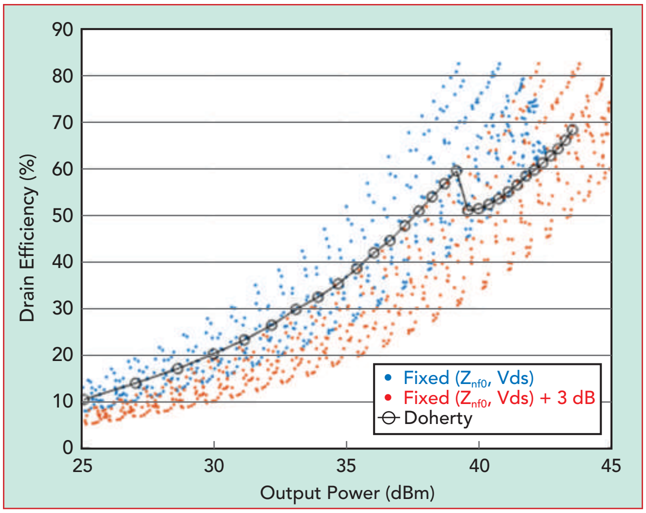

Fig. 9 **Calculated drain efficiency and output power vs. measured drain efficiency and output power with fixed supply voltage and harmonic impedances.**

With the output power and drain efficiency for the main and auxiliary known individually, the composite power consumption and output power can be calculated. The simulated output power and drain efficiency of the Doherty power amplifier is plotted in ***Figure 9***, using the measured data for the look-up operation. Because two devices are used in a Doherty, the output power capability is 3 dB higher, so a second scatter plot of the measured data, increased by 3 dB, is included. The second scatter plot represents the performance limit. The load modulation mechanism offered by the Doherty architecture—the limited 2:1 modulation range presented to the dominant main device, combined with the arbitrary impedance trajectory selected for this illustration—does not fully exploit the device's capability for load modulation. The device is, in effect, being driven in first gear. While the measurement space indicates a capability of 8 dB dynamic range achieving at least 50 percent drain efficiency, the Doherty only manages to exploit about 5 dB of that range, also missing a couple of dB of saturated output power. The same extracted Doherty performance plotted on the entire measurement space, including the full harmonic and supply variations, is shown in ***Figure 10***. For efficiency of 50 percent or greater, the output power dynamic range is now nearly 18 dB with the addition of the auxiliary transistor's 3 dB contribution. Clearly the performance of the Doherty in this example would benefit from the addition of supply modulation and/or waveform engineering.


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This model for the Doherty could be more sophisticated, including other effects without detracting from the basic flow. Alternatively, it could be that a different enhancement scheme offers a greater benefit for the device, whether tailored from the ground up or off-the-shelf. Other concepts can be analyzed using different equations and look-up parameters. For example, using the outphasing architecture, the impedances presented to the voltage source devices are derived from the cotangent of the inverse sine of the output amplitude.[1]

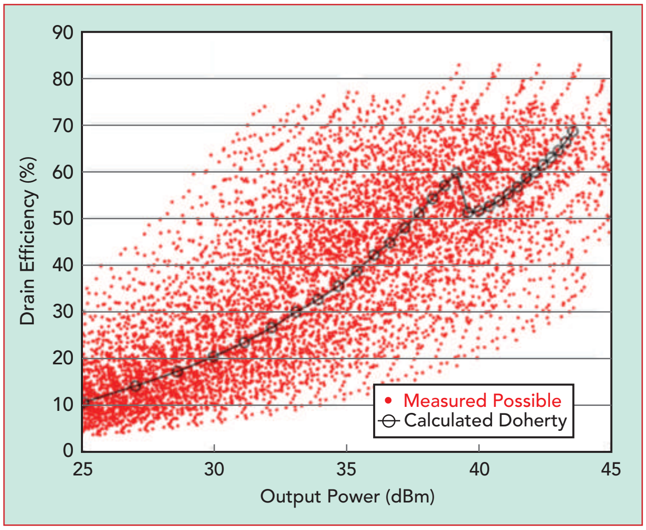


Fig. 10 **Calculated drain efficiency and output power vs. measured drain efficiency and output power showing full supply voltage and harmonic impedance variations.**

CONCLUSION

A classification of efficiency enhancement mechanisms has been proposed, and their effects on class A and class B amplifiers described, allowing for complementary mechanisms to be identified.

It is suggested that harmonic load-pull measurements, over a range of supply voltages, which are analogous to the mechanisms, can fully extract the performance potential of the device.

From those measurements, performance of the device in a range of architectures (e.g. Doherty) can be predicted.

State-of-the-art devices, such as the Wolfspeed device illustrated in this article, are capable of much better performance than state-of-the-art architectures.

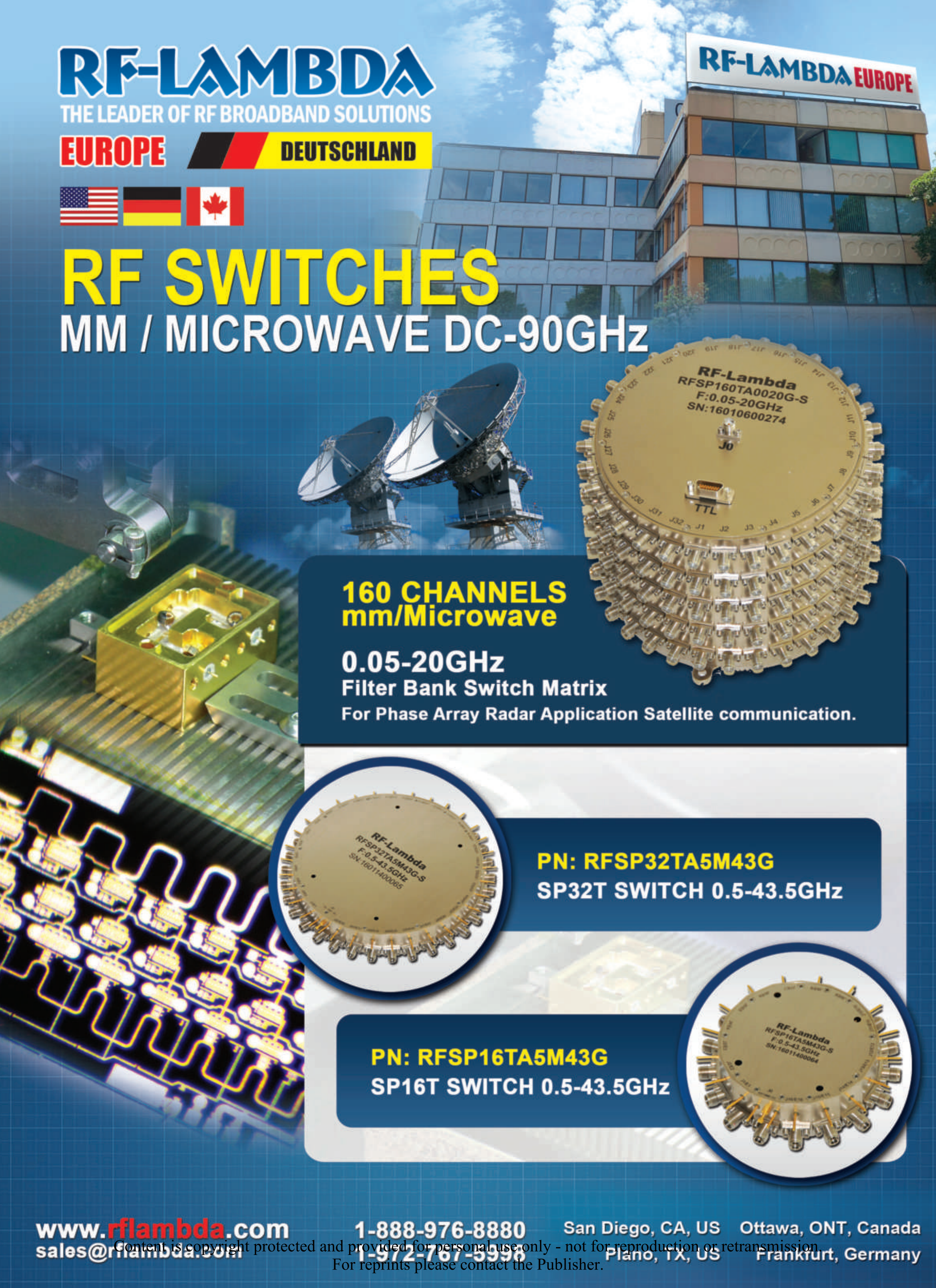
Therefore, that designing a "good enough" supply-modulated harmonic load-pull, appropriate for the application at hand, should be a goal for those responsible for developing power efficient RFFEs.■

ACKNOWLEDGMENT

The author would like to thank Maury Microwave for providing the measurement data.

Reference

1. Cripps, S. C., "RF Power Amplifiers for Wireless Communications," 2006, *Artech House*, Norwood, Mass., Chapter 3.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Insights Into Digital Predistortion System Design

Paul Turner
Systems4Silicon Limited, Bristol, U.K.

This article provides insight into the engineering of digital predistortion (DPD) systems for success, debunks some of the common misconceptions and gives real-world DPD performance examples.

In recent years advances in the performance of DPD for amplifier linearization have been largely driven by the cellular sector and the quest for higher power efficiency, spectral efficiency and data throughput with each successive generation of the standards. The complex modulations employed by standards such as 3G, 4G and 5G demand a level of transmission linearity significantly in excess of that offered by the power amplifier in isolation. This mandates linearization techniques to meet exacting out-of-band and in-band distortion levels as specified by the spectral emissions and modulation error requirements of the relevant standard.

DPD has particular relevance to 5G as the higher modulation bandwidths presented by many use cases that have the tendency to increase the level and complexity of non-linearity exhibited by a power amplifier (PA), the mechanisms for which are explored within this text. This puts a greater emphasis on ensuring that PAs are designed to maintain the extent of their non-linearities within the linearizer correction capabilities. Additionally, the very high data rates afforded by 5G consume significant power in transmission with respect to previous standards, notwithstanding the spectral efficiency of the modulation. Many wireless infrastructure sites have finite power supply networks that must still power the existing 2G/3G/4G infrastructure, to say nothing of the environmental implications of the power consumed. These factors place greater emphasis on a DPD's ability to enhance 5G transmitter power efficiency and consequential savings in capital and operating expenses.

The latest generation DPD solutions trailblazed by the cellular industry are now increasingly being deployed to other sectors including broadcast, satellite and private mobile radio as they in turn seek higher spectral efficiency through evolved, more sophisticated linear modulation.

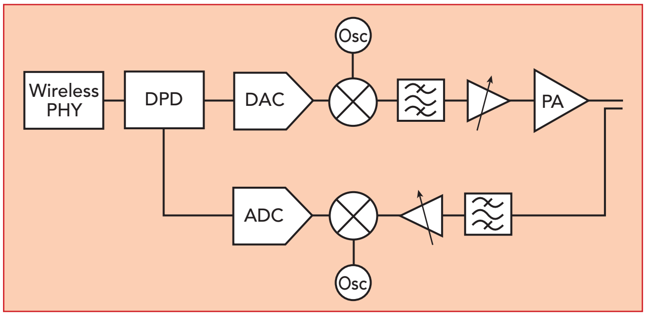

Fig. 1 Architecture of a PA with DPD.

DPD THEORY OF OPERATION

A simplified DPD system architecture is shown in ***Figure 1***. The forward path comprises the wireless physical layer (PHY), DPD, digital-to-analog conversion, RF up-conversion and the target PA, while the feedback or observation path comprises RF down-

conversion and analog-to-digital conversion.

In basic terms, DPD compensates for PA compression by expanding the input waveform. ***Figure 2*** shows a nominal amplifier compression characteristic, which demonstrates that for this characteristic an input signal at level P_{in} is subject to 1 dB output compression (P_{1dB}). Compensation of the compression characteristic requires 3 dB of input signal expansion, at which point the output power equates to that which would be provided by a linear characteristic ($P_{out(lin)}$).

Figure 3 illustrates the implications of now seeking an additional 0.5 dB of linear output power ($P_{out(lin)}$ + 0.5). This new operating point requires an additional 3.5 dB of expansion for a total input signal expansion of 6.5 dB and the output power is again restored to that which would be provided by a linear characteristic. However, the drive level is now increased such that the PA is at the point of saturation (the PA characteristic has a near-zero or zero gradient) and no amount of further signal expansion will increase the output power. This illustrates an important concept in predistorter design, that the required input signal expansion generally increases exponentially with drive level and that operation at, or close to, PA saturation is undesirable. Saturated operation can be problematic for the predistorter adaptation algorithm and the high level of signal expansion consumes digital dynamic range, raising the associated noise floor.

Perhaps the most common question to arise in predistorter design is how to determine correction (forward) path bandwidth. ***Figure 4a*** shows the two-tone unlinearized PA output spectrum with just third and fifth order intermodulation distortion products (IMD3 and IMD5) visible. Nonlinear theory of predistortion is outside the scope of this discussion, but it shows that full correction of an intermodulation product, in fact, requires a correction signal comprising an infinite series of odd-order products[1] as illustrated in ***Figure 4b***. Of course, an infinite correction bandwidth is not available in any practical system and a compromise is required. In reality, the ensemble of correction products above a certain order will have an insignificant performance benefit.

Figure 5a illustrates the unlinearized PA output for a broadband transmission. The effect of truncating the series of correction products within the PA input waveform is to introduce "bumps" of residual distortion within the output (see ***Figure 5b***). The optimum correction bandwidth reduces the level of this residual distortion to the point where it falls within the specification plus appropriate margins.

Typically, the baseband correction bandwidth may be 4 to 5x the composite modulation bandwidth (i.e. at 5× it encompasses all fifth order predistortion products), though this figure of merit can vary significantly according to application and performance requirements. The transmitter's digital and analog forward path must maintain this bandwidth to faithfully present the correction signal at the PA input. Therefore, for a 100 MHz modula-

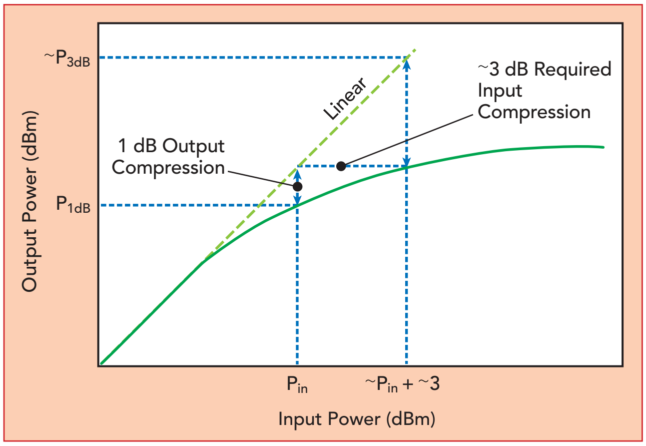

Fig. 2 PA output vs. input power, where P_{in} drives the PA to 1 dB compression.

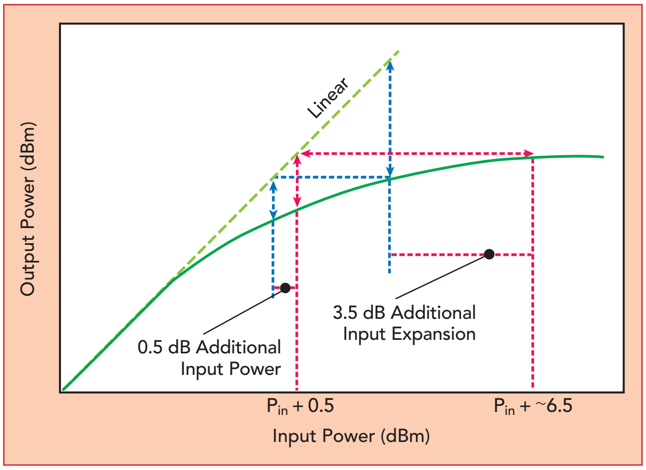

Fig. 3 PA output vs. input power, showing P_{in} + 0.5 dB.

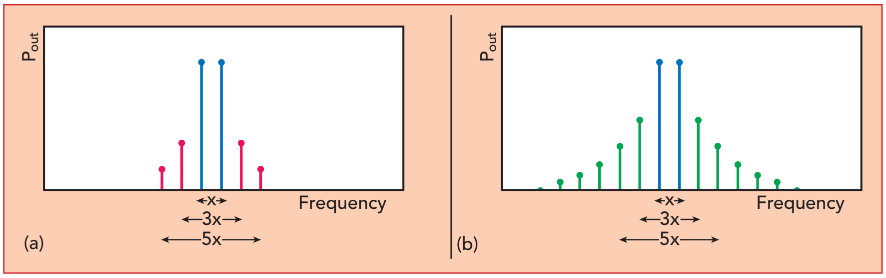

Fig. 4 PA two-tone output spectrum without linearization (a) and corresponding input correction signal (b).

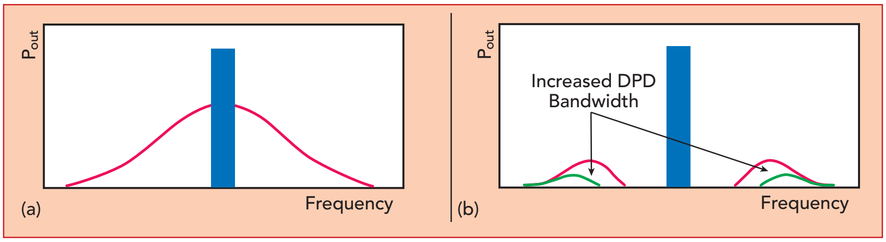

Fig. 5 PA spectrum without linearization (a) and linearized PA output, showing improvement with larger correction bandwidth (b).


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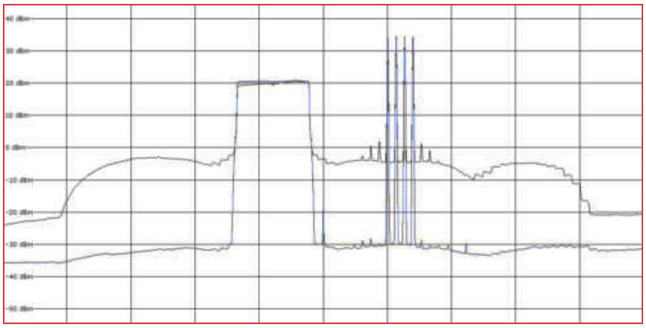

Fig. 6 Output of a Doherty PA with 4G and multi-carrier 2G signal, with and without DPD linearization. Frequency range: 841.6 to 1001.6 MHz. Mean output power: 46 dBm.

tion bandwidth the system may support a 400 to 500 MHz correction bandwidth from the baseband predistorter to the PA input, using the 4 to 5× guideline.

While simulation has its place in determining the required correction bandwidth for a given scenario, the nonlinear hardware-in-the-loop nature of the problem means that the only reliable way to establish the bandwidth with certainty is by empirically evaluating the PA hardware within the DPD control loop. This approach provides a definitive answer as to what correction bandwidth achieves the desired spectral emission and modulation error levels. Fortunately, it is often possible to achieve this using off-the-shelf signal processing and radio transceiver evaluation cards without committing to the cost of prototype development.

Figure 6 illustrates the level of performance available from a latest generation digital predistorter. The mixed-mode signal (4G plus multi-carrier 2G) has a total instantaneous bandwidth of 40 MHz. It is illustrative of the current cost-driven push to share radio infrastructure and represents a challenging composite signal use case for any digital predistortion system. The Doherty amplifier has 46 dBm mean output power and the traces show performance with and without linearization enabled. For this scenario the level of third order intermodulation distortion is improved by up to 30 dB, from a highly nonlinear starting point. Of note is the DPD's in-band equalization of the amplifier gain slope apparent on the 4G signal prior to linearization; this is one of the side benefits of DPD systems supporting this capability.

While Figure 6 shows the predistorter's action on out-of-band spectral emissions, ***Figure 7*** illustrates the concurrent improvement of in-band distortion that results from linearization. The figure shows the transmitted constellation for a 64 QAM carrier before and after linearization. The predistorter removes the AM-to-AM and AM-to-PM distortion introduced by the PA which would otherwise increase the modulation error as shown in Figure 7a. For this example the modulation error ratio is improved by approximately 6 dB.

While DPD enhances power efficiency, the linearizer subsystem

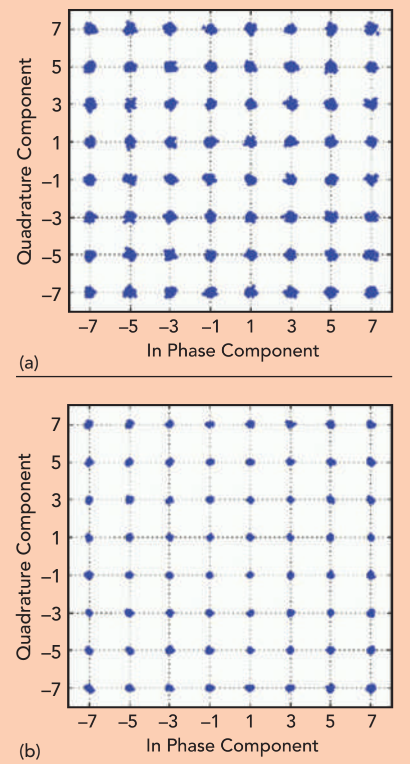

Fig. 7 64-QAM constellation before linearization, MER = 33.1 dB (a) and linearized, MER = 39 dB (b).

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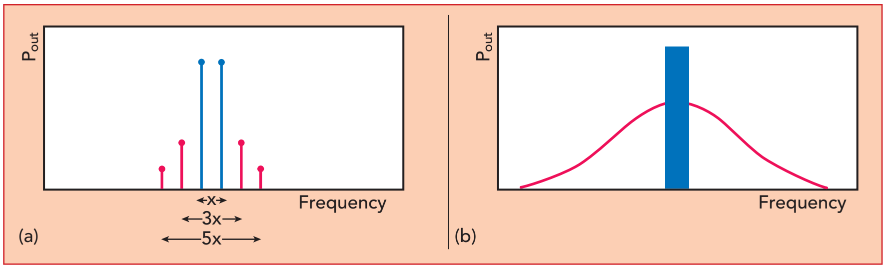

Fig. 8 Two-tone (a) and wideband (b) intermodulation distortion spectra.

does of course consume additional power associated with the correction engine, adaptation processing, enhanced forward path bandwidth and feedback path. The power consumed by the predistortion system varies significantly according to the transmission standard, target technology and performance level sought; though, for wideband 4G/5G applications a very rough estimate might be 3 W. For lower transmit power applications such as small cell and MIMO this figure should be established to confirm that predistortion provides a net efficiency improvement (assuming DPD is not mandated by other considerations such as spectral emissions compliance).

FEEDBACK PATH

An unavoidable fact in predistorter design is that the linearity of the feedback path represents a limit on available performance. Because the feedback path falls within the control loop, the predistorter introduces a correction signal for the feedback path nonlinearity, which in turn is imposed upon the transmit output. During hardware design careful attention to feedback path linearity, including that of the data converter is required to ensure it does not compromise performance. In contrast to a conventional receiver design the feedback receiver path linearity tends to be a more important consideration than SNR.

Similar considerations apply to any linear feedback path distortion such as gain and phase variation which may be superimposed on the transmit path if not addressed. Digital linear equalization of the feedback path can be used to mitigate this effect, though characterizing the response of the feedback receiver in isolation can be tricky.

It is a common misconception that the feedback path bandwidth should be equivalent to the forward path correction bandwidth. In fact, the design requirement is that the feedback path should span sufficient distortion orders to facilitate construction of the forward path correction signal, which may be less than the forward path bandwidth. ***Figure 8*** shows two waveforms, both with the same instantaneous bandwidth. The image in Figure 8a comprises two narrow-band carriers and it is apparent that the third and fifth order distortion products occur at discreet locations. To capture IMD5 information, the feedback path must be 5× the instantaneous bandwidth. In this case it is necessary for the feedback bandwidth to equal that of the forward path.

Now consider Figure 8b showing a wideband noise-like carrier with distortion products that are diffuse, falling both within and outside of the modulation bandwidth. If a feedback bandwidth of less than 5x the modulation bandwidth is employed it will still capture a proportion of IMD5 (and higher) products. For this scenario it may be possible to use a feedback bandwidth less than that of the forward path. In practice the feedback path bandwidth should be designed empirically as restricted bandwidths can reduce algorithmic convergence time, which may or may not be a consideration.

PERFORMANCE OPTIMIZATION

To obtain optimum performance from a digital predistorter, it is necessary to account for and address hardware deficiencies and non-idealities (in addition to the PA nonlinearity) that would otherwise degrade the correction level achieved. Non-flat

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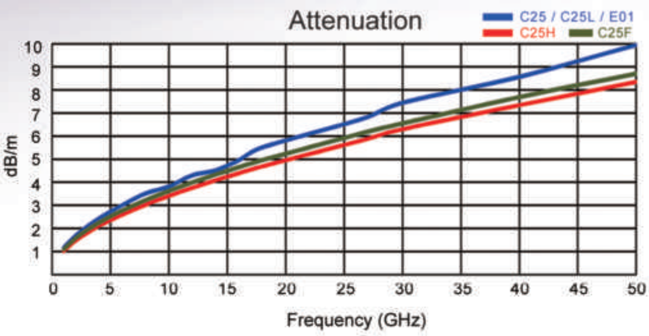
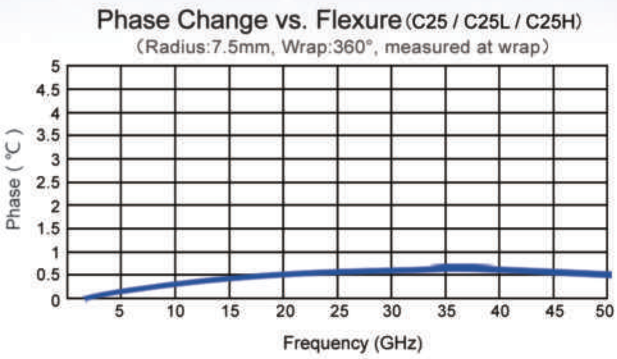
38	SMP Right Angle Female	26.5	<1.40
40	2.92mm Straight Male	40	<1.35
46	2.92mm Straight Female		<1.40
0C	SSMP Right Angle Male		<1.45
24	SSMP Straight Female		
39	2.4mm Straight Male	50	
48	2.4mm Straight Female		

*Same Connectors at both ends





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gain and phase slopes across the analog forward and feedback paths, local oscillator phase noise, direct conversion gain and phase imbalance, carrier leakage, PA gain variation and control loop timing variability can all degrade performance. The more sophisticated DPD solutions incorporate subsystems to correct the majority, if not all these non-ideal characteristics. Indeed, one of the greatest challenges to successful predistorter design is to orchestrate the operation of these correction subsystems to avoid adverse interaction between them and to allow the primary nonlinear correction engine to be deployed solely against the PA nonlinearity.

Worthy of specific mention are amplifier memory effects, where the PA output is a function of current input signal and its past history. Sources of memory effect are numerous and include:[2]

- Gain variation with frequency across the modulation bandwidth.
- Transistor power supply variations (e.g. non-deal response of the drain circuitry at the modulation frequency).
- Thermal effects whereby device junction temperature changes modify the nonlinear characteristic at the modulation envelope frequency.
- Charge trapping effects. All semiconductor materials and interfaces tend to capture and later emit charge (holes and electrons) within the transistor channel, causing changes in current flow that are dependent upon not only the instantaneous device voltage but also the history of the voltage signal. Of relevance to 5G is the increasing popularity of gallium nitride (GaN) transistors for wideband transmission. Compound semiconductors such as gallium arsenide (GaAs) and GaN have greater susceptibility to charge trapping than conventional silicon laterally diffused metal oxide semiconductor transistor.

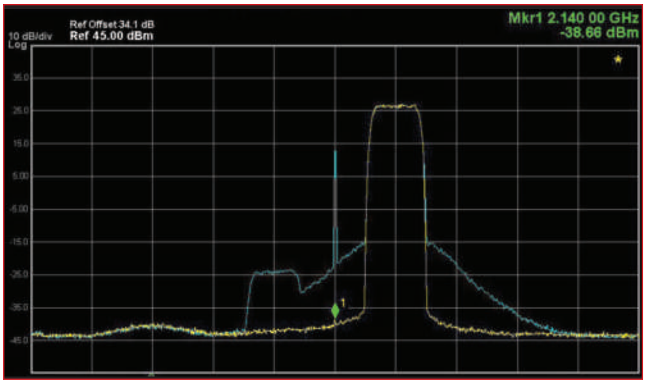

Fig. 9 Suppression of the carrier image and LO using DPD.

Linearized performance is substantially degraded if the hardware exhibits memory effects that exceed the correction capability of the DPD. This is an area where scalable (field-programmable gate array (FPGA)-based) DPD has an advantage as there is the potential to increase the complexity of the correction engine to accommodate the PA's memory depth. This does, however, consume additional signal processing resources and designing PAs to minimize memory effect is the preferred approach, where feasible.

Figure 9 illustrates the operation of a correction subsystem in the form of a predistorter with the capability to automatically suppress the carrier image from the gain and phase imbalance of the analog quadrature modulator (AQM) of a direct conversion transmitter. It is apparent that the correction algorithm also has the capability to suppress the local oscillator (LO) leakage of the AQM to a high level. The best DPD systems have the capability to independently correct carrier images and LO leakage associated with the forward and observation paths, thereby preventing the observation path correction signal from being imposed upon the transmit output.

Care is required when positioning ancillary digital correction engines within the forward path as the nonlinear nature of the system means that superposition may not apply. For example, the above compensator intended to address AQM deficiencies should be located after the predistorter, and not before, to ensure that the compensated correction signal is not subject to a nonlinearity.


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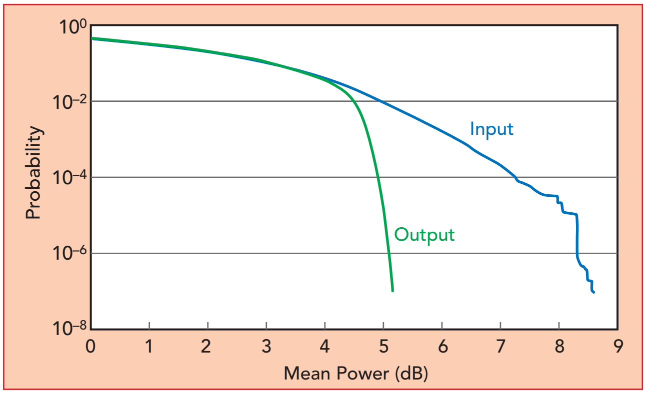

Fig. 10 CCDF of a 64-QAM signal (input) showing CFR (output) to achieve 5 dB PAPR at 10^{-5} probability.

A sophisticated, latest generation predistorter can provide system benefits beyond linearization by virtue of the control loop formed by the feedback path. In addition to the above examples of linear equalization, carrier image and LO suppression, the DPD may also integrate compensation for PA gain variation with temperature. Furthermore, in multi-transmitter applications, such as beamforming or MIMO it is possible to commutate a common feedback path between the predistorter associated with each transmit chain and thereby achieve gain and phase alignment between channels.

CREST FACTOR REDUCTION

Crest factor reduction (CFR), like DPD, is a technology that can be used to enhance PA efficiency. It is, therefore, worth a brief summary here. CFR modifies the input signal to reduce its peak-to-average power ratio (PAPR), trading a reduction in signal peak power level for increased in-band modulation error (within system requirements). Since a PA is defined by its peak power handling capability, this enables operation at a higher mean power level for improved efficiency. CFR invariably requires a knowledge of the underlying transmission standard and carrier configuration.

The capability of CFR is illustrated in ***Figure 10***, which shows the simulated complementary cumulative distribution function for a 64 QAM satellite bearer where the CFR has been configured to provide 5 dB PAPR at 10^{-5} probability. Modern, noise-like linear modulations can have a very high PAPR for which CFR can provide peak reductions in excess of 5 dB for significantly enhanced efficiency.

In contrast, DPD improves efficiency by providing a level of PA linearity that would otherwise require the PA to be significantly backed-off or overspecified, with associated implications for transistor size and cost. DPD is more indifferent to the underlying modulation than CFR and derives a correction signal from the characteristics of the composite signal applied without a knowledge of the specific transmission standard. CFR and DPD are separate yet complementary technologies and may be used together or individually.

SUMMARY

It is important to appreciate that DPD system design is a co-design exercise between the predistorter (CFR, if employed), radio platform and in particular, the PA. While the latest generation DPDs are cable of correcting complex nonlinearities and hardware deficiencies, this consumes digital resources (FPGA or ASIC memory, registers and multipliers) which may be at a premium. Hence maintaining PA characteristics such as memory effect within the correction capabilities of the predistorter is desirable. PA saturation at the maximum anticipated signal drive level should also be avoided as no amount of signal expansion within the predistorter can compensate for a saturated nonlinearity. The PA need not be linear, but it should be designed to handle the input peak power, which will be dictated by the CFR, if used. The best outcomes are achieved when a PA is designed to be linearizable (i.e. system designed), rather than attempting to apply the technology to an arbitrary amplifier.■

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2. J. Vuolevi and T. Rahkonen, "Distortion in RF Amplifiers," *Artech House*, 2003, pp. 43-68.

INVITED PAPER

Choosing the Best Method for mmWave De-Embedding

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Yuenie Lau
OML Inc., Morgan Hill, Calif.

As higher frequency mmWave measurements are increasingly needed, there is a corresponding need for robust de-embedding techniques to reach device-under-test (DUT) reference planes accurately and to account for fixture, radiator and launcher behaviors. While most lower frequency techniques still work in principle, connection repeatability becomes much more of a challenge at higher frequencies, and greater bandwidths are available as well, so optimal techniques may change. This article examines some popular choices and experimentally looks at performance in some WR5 fixtures from 140 to 220 GHz.

Many classical de-embedding extraction techniques rely on explicitly solving for the S-parameters of the fixture or interposing networks.[1-5] These can work very well, particularly at lower microwave frequencies if the standards that are used at the DUT plane are adequately defined and connection repeatability is sufficient. Examples of these techniques include generalizations of adapter removal,[6] where a pair of full calibrations at inner and outer planes solve for the network parameters; one-port removal, often termed Bauer-Penfield[1] from an early paper, where one-port calibrations are used to complete the solution; and traditional calibration methods such as thru, reflect, line (TRL).[7,8]

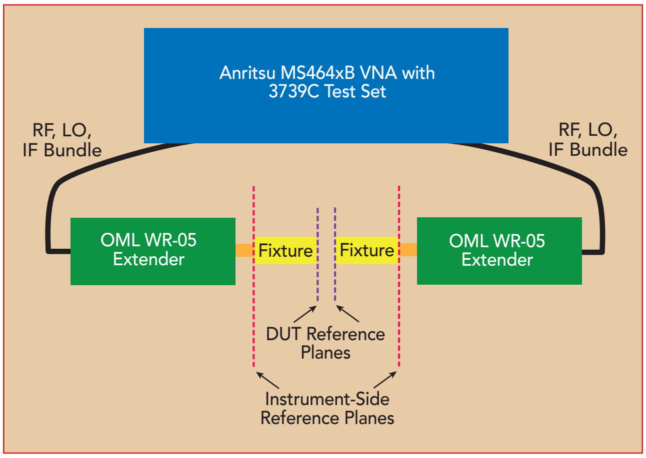

Fig. 1 De-embedding measurement setup.

At higher mmWave frequencies (greater than 100 GHz), these methods face increased challenges as standards definition is affected more by machining tolerances and repeatability. If the reference planes are based on variations of the common UG387 flange, alignment tolerances are such that repeatability degrades rapidly above a few hundred GHz.[9-11] This has led to a class of de-embedding methods where assumptions about the fixture are used to substitute for some of the measurements. The argument is that by using less repeatability-sensitive data, while keeping the less sensitive measurement data that is still important, net

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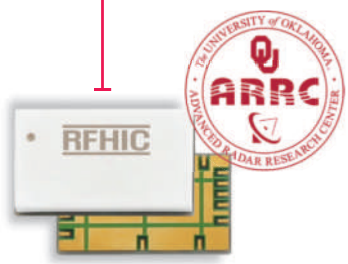

▲ [redacted]

TX Specifications

Parameter	Unit	data		
		Min	Typical	Max
Frequency	MHz	2,700	-	3,000
Duty Cycle	%	10		
Pulse Width	us	100		
Input Power	dBm	-	17	-
Output Power	dBm	41	-	42
Power Gain	dB	24	-	25
Efficiency	%	-	45	-
Input VSWR	-	-	-	2

RX Specifications

Parameter	Unit	data		
		Min	Typical	Max
Frequency	MHz	2,700	-	3,000
Duty Cycle	%	-	10	-
Pulse Width	us	-	100	-
Main Path Gain	dB	-	21	-
Main Path NF	dB	-	-	32
Bypass Gain	dB	-	-20	-
Main Input VSWR	-	-	-	2.5
Main Output VSWR	-	-	-	2.2
Bypass Input VSWR	-	-	-	2.2
Bypass Output VSWR	-	-	-	1.5

Fig. 2 Waveguide calibration components, left to right: load, offset short shim, flush short.

accuracy is improved. The assumptions can include symmetry—and almost always include reciprocity—and that mismatch centers are not located too close together.[12-16] The latter is addressed in this article, where the phase resolution afforded by wide waveguide bands allows the extraction process to separate out dominant mismatch mechanisms and create something between a black box analysis and a pure model fit to the fixture.

The measurement setup is shown in ***Figure 1***. It comprises a vector network analyzer (VNA), the Anritsu MS464XB and mmWave extension heads, the WR05 from OML, to allow measurements from 140 to 220 GHz. Most of the conclusions apply to other mmWave bands, with the repeatability condition becoming more important at higher frequencies. The fixtures that are extracted all have standard UG387 flanges on the instrument side and modified flanges on the DUT side, to support DUT mounting. Short, short, load (SSL) and short, short, short (SSS) calibration standards are used in most cases, with modified offset shorts being used at the DUT plane.

CALIBRATION STANDARDS CONSTRUCTION

Due to the influence of the calibration and de-embedding standards on the extracted results, it is useful to look at how the waveguide calibration standards at the instrument reference planes are fabricated. Three essential waveguide calibration standards are needed for TRL error correction in calibrating the VNA: waveguide load, waveguide offset line and waveguide short, which are representative of needs for many other calibration methods (see ***Figure 2***). Precision alignment hole locations, waveguide aperture dimensions and

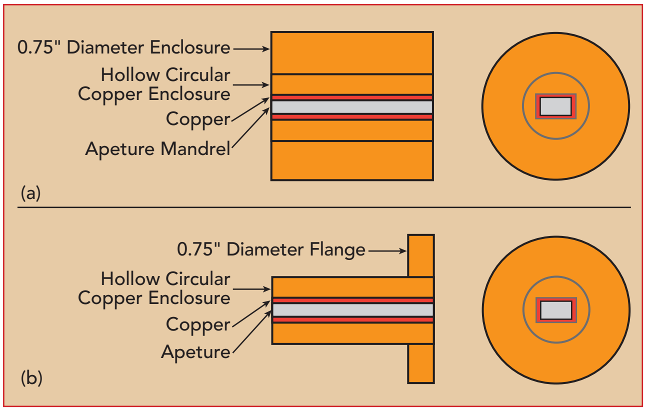

Fig. 3 Offset line (a) and precision load (b) construction.

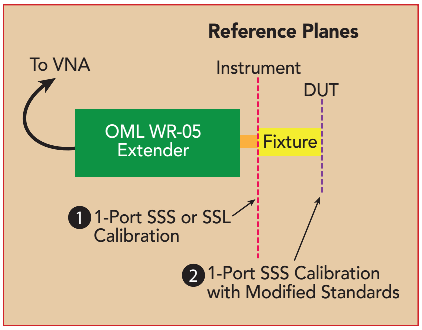

Fig. 4 One-port BP method calibration.

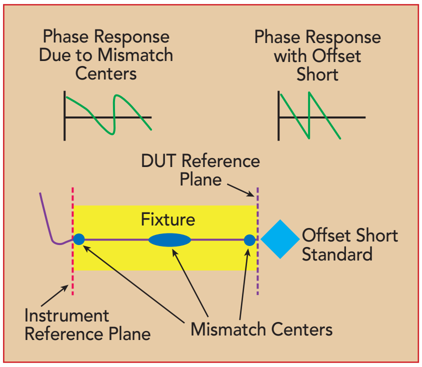

Fig. 5 Reflection-based, phase localized extraction calibration.

offset line length are critical parameters for defining these standards.

Quality calibration load and offset line waveguide apertures are often manufactured using an electroforming technique. The electroforming process starts with a precision machined waveguide aperture mandrel, with the mandrel tolerance usually better than 0.0005 in. and a 16 µin. finish is possible. With polishing, the surface finish can be less than an 8 µin. mirror finish and a 0.0002 in. or better accuracy. Once the mandrel passes mechanical inspection, it is submerged in a copper solution where copper attaches and thickens around it through a chemical process. It is rinsed and cleaned after reaching the desired copper thickness and is brazed into a hollow circular copper or brass enclosure. For offset lines, the brazed part goes through another brazing step for a final 0.750 in. diameter (see ***Figure 3a***). Similarly, one end of the waveguide load goes through another brazing stage to attach a 0.750 in. diameter flange (see ***Figure 3b***). The machined aperture mandrel is chemically removed. The part is cleaned, the interface flange is machined per MIL-DTL 3922/67 and OML precision anti-cocking flange specification control drawings. The waveguide offset line is cut to λ/4 at the center of the waveguide band of interest, and the waveguide precision load is cut to a predetermined length. Both the offset line and the waveguide precision load interface are polished to a 16 µin. finish or less. The part is then gold plated after passing mechanical inspection. The waveguide short is a machined part, with its flange configured per MIL-DTL 3922/67 and precision flange specification drawings. The waveguide short flange interface is polished to an 8 µin. mirror finish or better.

Once gold plated, the parts must pass final mechanical inspection. In addition, the aperture dimensions and the offset line length must be within ±0.0002 in. tolerance. Machining and process precision help to reduce uncertainties at the instrument reference planes of Figure 1, resulting in a low insertion loss—often on the order 0.1 dB—with a correspondingly high return loss. Such mechanical precision at the inner fixture DUT reference planes may be much more difficult to achieve, which drives the need for an optimal technique for de-embedding.

ONE-PORT TECHNIQUES

One-port methods are among the simplest to execute, since an interconnection between ports is

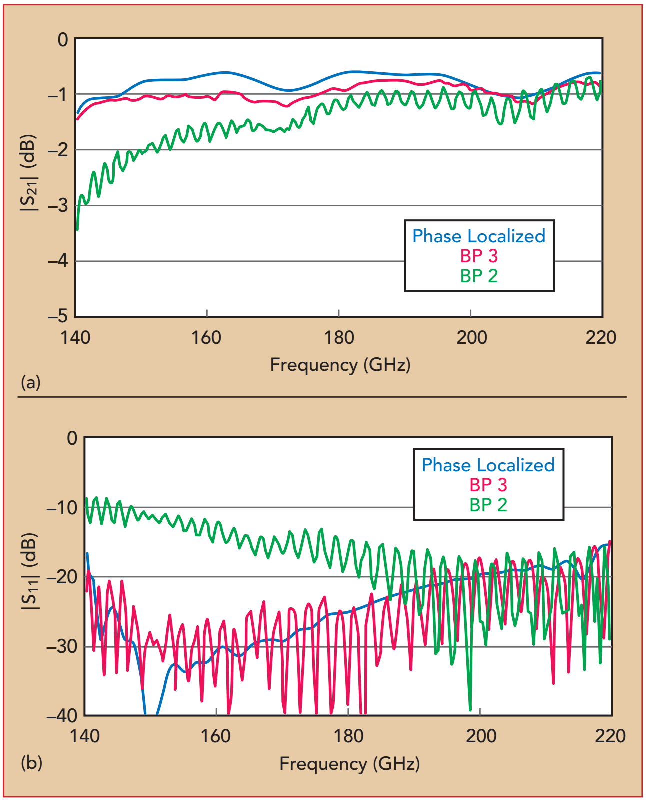

Fig. 6 Extracted fixture $|S_{21}|$ (a) and $|S_{11}|$ (b) comparing the phase localized, BP2 and BP3 one-port methods.

not required. A common classical family often goes by the name Bauer-Penfield (BP).[1] As shown in ***Figure 4***, a full one-port calibration is performed at the instrument side of the fixture, and another calibration is performed at the DUT side. Assuming reciprocity, the fixture S-parameters are then explicitly determined. In the following, this is labeled BP3, as in three standards are used at the DUT plane. As discussed in the literature,[6] the DUT side match of the fixture is somewhat sensitive to standards quality, but the losses in the fixture here are low, so the input and output match behaviors convolve. Insertion loss extraction is derived from the two reflection tracking terms, so the high reflection standard behaviors are particularly important. By using an SSL kit on the instrument side plane, the load standard has little impact on loss extraction. By using an SSS kit on the DUT side, all the standards have roughly equal sensitivities.

A variation on the basic BP approach is to use two standards—often two different high reflections—if insertion loss is the primary quantity of interest. There are some variations on this, including those that assume symmetry and those that assume the fixture is electrically short, as in the on-wafer case.[3] The fixture used in these measurements is not electrically short, i.e., greater than 10λ at mid-band, so symmetry is assumed used and labeled BP2 in the plots to follow. A partial information method used in this work is based on a single reflection measurement through the fixture[14,16] after a full calibration at the instrument plane. The reflection coefficient of the standard at the DUT plane, an offset short in this case, is assumed known. The measured reflection data through the

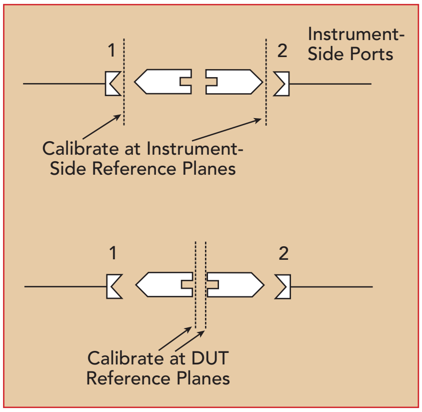

Fig. 7 Adapter removal method two-port extraction.

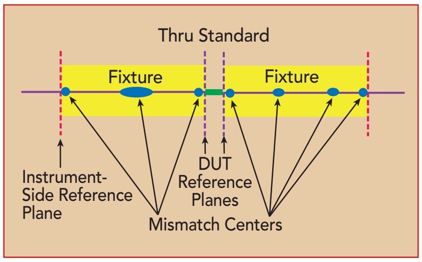

Fig. 8 Transmission based, phase localized, two-port extraction.

fixture is correlated with a series of propagation kernels to separate the portions of the response due to the reflection standard from those due to the internal mismatch centers (see ***Figure 5***). Because the separate identification of the centers is based on phase resolution, there is a limit when a mismatch center near the DUT interface cannot be separated from the reflection standard. The resolution is proportional to the reciprocal of the sweep width, which is 12.5 ps for the WR5 waveguide band. The results from this approach are labeled "phase localized" in the measurements to follow. Related approaches using time-domain processing also exist.

ONE-PORT MEASUREMENTS

Using the test setup of Figure 1, all three methods were used to extract the fixture parameters. |S21| is plotted in ***Figure 6a***. BP2 produces the least physical result which might be expected since the fixture is not particularly symmetric, and the match is not excellent. The phase localized and BP3 methods produce similar results. BP3 has a 2σ repeatability of the extracted $|S_{21}|$ of ±0.25 dB. The 2σ repeatability of the phase localized result is ±0.11 dB.

Extracted $|S_{11}|$ on the instrument side is plotted in ***Figure 6b*** for the three methods. The BP2 result is again clearly deviant, most likely because of the assumption of underlying symmetry. Again, the BP3 and phase localized methods agree reasonably well within repeatability and calibration kit uncertainties: ~5 dB at -20 dB reflection.

TWO-PORT TECHNIQUES

A popular classical approach for two-port analysis, where two fixture arms are extracted simultaneously, is sometimes termed adapter removal (see Martens[6] and the references therein); although this term is sometimes used specifically for the case where a single fixture is moved from being attached to one instrument port to being attached to the other instrument port. This discussion generalizes to two fixture arms. While the concept has several different implementations, one is essentially a doubling of the BP analysis with the thru information not actually used. Other implementations use the thru data to augment the fixture transmission terms, often in a least-squared sense that is reflected in this article; the method is illustrated in ***Figure 7***. Since a calibration is being performed at the inner reference plane, why is extraction needed? This is sometimes done so the fixture parameters can be recalled in conjunction with a simpler instrument calibration for future measurements, when the DUT plane calibration may not be practical.

A simple partial information technique does a gross match assignment by using only the instrument side reflection data and, assuming the inner interface is perfect, assigns the measured mismatch to S_{11} and S_{22} of the fixture arm, either with symmetry or, usually, all mismatch assigned to one side or the other of the fixture. Symmetry is

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LM-30M3G-C3-1 https://www.pmi-rf.com/product-details/lm-30m3g-c3-1	30 MHz - 3 GHz	1.2	5 W CW @ +25°C	10	1 µs	1.314"x 0.375" 2.92mm (M/F)
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LM-10M9G-100CW-1KWP-SFF https://www.pmi-rf.com/product-details/lm-10m9g-100w-1kwp-sff	10 MHz - 9 GHz	2	100 W CW Max (10 MHz to 8 GHz), 80 W CW Max (9 GHz), 50 W CW Max (10 MHz to 9 GHz)	20	60 ns	1.86" x 0.65" x 0.38" SMA (F)
LM-10M18G-16-20W-AL https://www.pmi-rf.com/product-details/lm-10m18g-16-20w-al	10 MHz - 18 GHz	2	20 W Max @ -55°C to +85°C, 1 kW Peak Max (1 µs Pulse Width, 1% Duty Cycle), 100 W Peak (10 µs Pulse Width, 10% Duty Cycle)	17	250 ns	0.90" x 0.38" x 0.38" SMA (M/F)
LM-100M20G-18-10W-SFF-MAH https://www.pmi-rf.com/product-details/lm-100m20g-18-10w-sff-mah	0.1 - 20 GHz	3	10 W Pulsed, 100 µs Pulse Width, 10% Duty Cycle, 1 W CW	18	115 ns	0.50" x 0.50" x 0.22" SMA (F) Field Removable
LM-20M18G-100W-15DBM https://www.pmi-rf.com/product-details/lm-20m18g-100w-15dbm	20 MHz - 18 GHz	2.6	100 W CW Max @ -55°C to +85°C, 1 kW Peak Min +85°C (1 µs Pulse Width, 0.1% Duty Cycle), 100 W (1 µs, 1% Duty Cycle, 10 kHz), 100 W (10 µs, 0.1% Duty Cycle, 100 Hz), 100 W (1 µs, 0.1% Duty Cycle, 1 kHz), 100 W (40 µs, 10% Duty Cycle, 2.5 kHz)	15	100 ns	0.90" x 0.38" x 0.38" SMA (M/F)
LM-20M20G-18-20WP-5W-MAH https://www.pmi-rf.com/product-details/lm-20m20g-18-20wp-5w-mah	20 MHz - 20 GHz	2.5	20 W Pulsed, 100 µs Pulse Width, 10% Duty Cycle, 5 W CW	18	25 ns	0.50" x 0.50" x 0.22" SMA (F) Field Removable
LM-1G18G-16-4W-SMF https://www.pmi-rf.com/product-details/lm-1g18g-16-4w-smf	1 - 18 GHz	2.3	4 W CW Min @ +85°C, 1000 W Peak Min @ +85°C (1 µs Pulse Width, 0.1% Duty Cycle)	16	24 ns	0.90" x 0.38" x 0.38" SMA (M/F)
LM-1G18G-15-3W-500WP-SFF https://www.pmi-rf.com/product-details/lm-1g18g-15-3w-500wp-sff	1 - 18 GHz	2.5	3 W CW 500 W Peak	17	33 ns	1.00" x 1.00" x 0.40" SMA (F) Field Removable
LM-2G18G-18-20W-1KWP-SFF- https://www.pmi-rf.com/product-details/lm-2g18g-18-20w-1kwp-sff	2 - 18 GHz	2.6	+43 dBm CW Max, +50 dBm (10% Duty Cycle, 40 µs Pulse Width) Max Peak	18	10 ns	1.00" x 1.00" x 0.40" SMA (F) Field Removable
LM-18G40G-18-1W-292FF https://www.pmi-rf.com/product-details/lm-18g40g-18-1w-292ff-	18 - 40 GHz	4	1 W CW	18	10 ns	0.5" X 0.5" X 0.22" 2.92mm (F) Field Removable

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assumed in this analysis. The insertion loss is simply the square root of the measured insertion loss of both fixture arms together. In dB, it is a halving of the measured loss; hence, this method is sometimes termed "divide by 2." Because of the match handling coarseness, this approach is best suited to a well-matched fixture[12] and is labeled D1 in the following measurements. A more recent partial information scheme also goes under the "phase localized" label used in the one-port section, but here the correlation with phase kernels is applied to transmission as well as reflection data, and fixture insertion loss is derived from processing on the measured transmission data.[14] This process is illustrated in *Figure 8*, with the results labeled PLD in the following measurements. A calibration exists at the instrument reference planes—short, short, load, thru (SSLT) in this case—and transmission and reflection data through the fixture pair are correlated against a range of phase kernels.

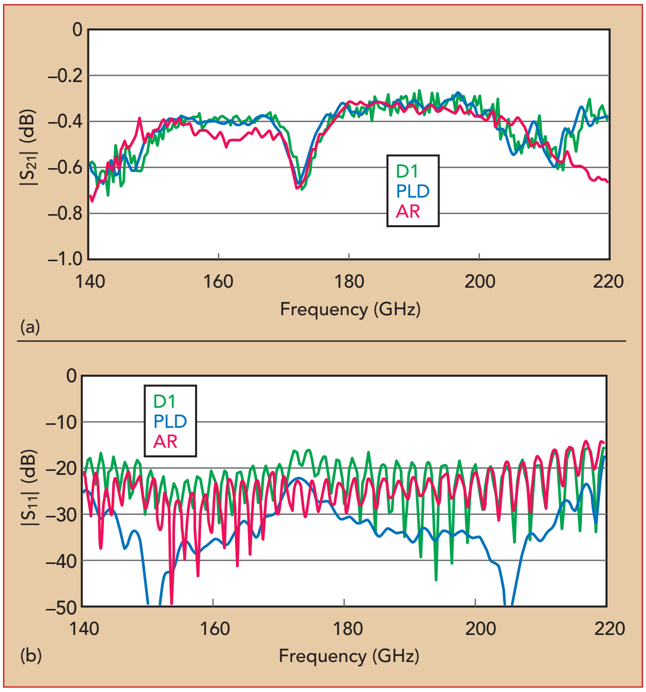

Fig. 9 Extracted fixture $|S_{21}|$ (a) and $|S_{11}|$ (b) comparing the D1, PLD and AR two-port methods.

TWO-PORT MEASUREMENTS

The two fixture setup is measured using all three methods, and both fixture arms have similar parameters. $|S_{21}|$ is plotted in *Figure 9a*, and all methods agree within about 0.1 dB except above 215 GHz. The D1 method shows higher spatial frequency ripple, which appears to arise from the misallocation of mismatch centers. Separation by phase localization is cleaner with PLD, and the bandwidth enables this separation since the dominant centers are separated by about 250 ps. The adapter removal method misses some structures, and adds one of its own, presumably because of repeatability issues on the many connections. On repeated extractions, the 2σ repeatability for the adapter removal approach is ±0.2 dB, while those for D1 and PLD are both under ±0.1 dB. All methods identify the resonant structure at about 172 GHz, caused by a support structure near the DUT plane.

The extracted $|S_{11}|$ on the instrument side is plotted in *Figure 9b* for the three methods, with a bit more variance here, although return loss levels are relatively high. Based on simulation, the D1 method appears to underestimate return loss, but the allocation is forcibly symmetric, so it is not surprising there are some variances. The adapter removal method shows higher reflections at some frequencies, likely due to heightened sensitivity to the characterization of the standards used at the DUT plane.

CONCLUSION

In repeatability-challenged fixtures used at higher mmWave frequencies, classical extraction approaches for de-embedding may have suboptimal performance due to repeatability or the ability to fabricate and characterize standards to use at the DUT plane. Partial information methods that place

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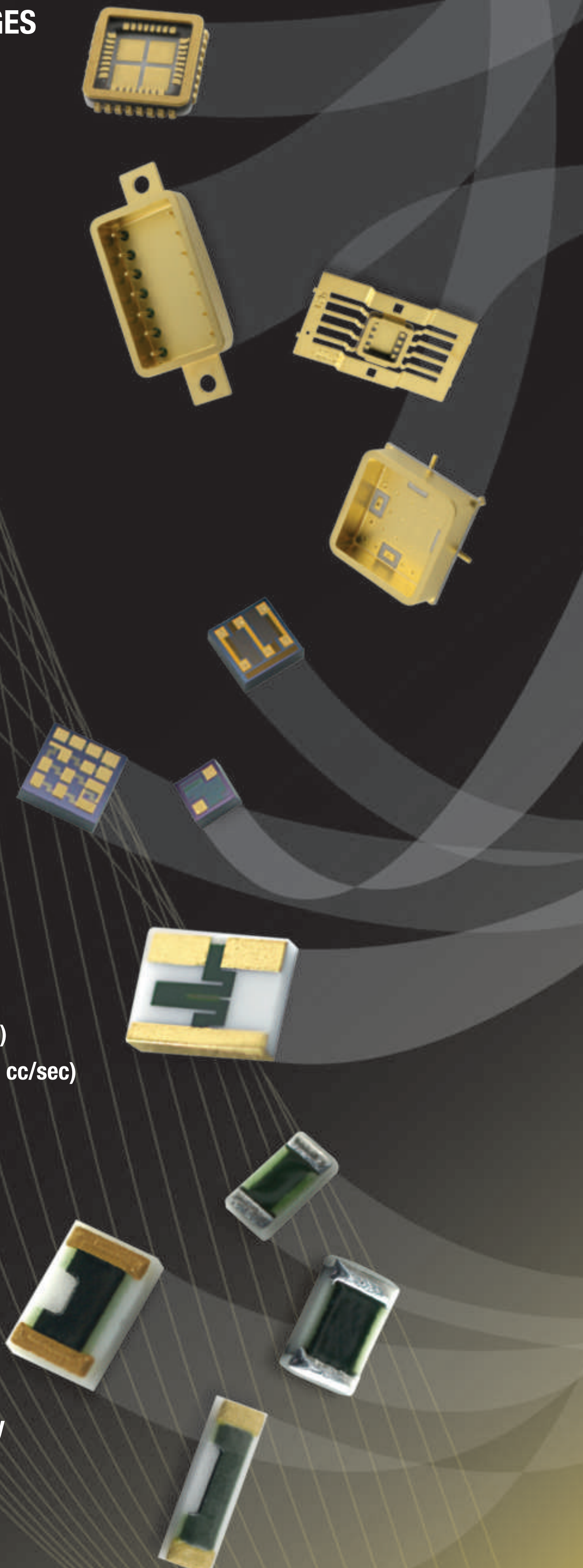

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less stress on those standards and more stress on fixture assumptions have evolved over the years and can produce improved results if the assumptions are met. Some of the more recent algorithms that make assumptions about locations of mismatches in some mmWave fixtures may yield better results than measurements that ignore mismatches or assume symmetry.■

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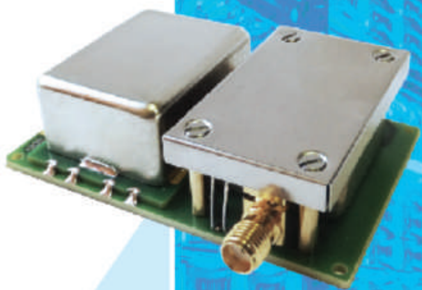
100 Hz	<-160	<-135
1 kHz	<-165	<-160
10 kHz	<-170	<-175
100 kHz	<-170	<-180



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Using GaN power amplifiers (PA), the compact and lightweight RIU256K0-40T generator operates from 2.4 to 2.5 GHz, combining four, 1.6 kW GaN PAs into a stand-alone, rack mounted solid-state power amplifier (SSPA) that is modular and fault tolerant (see ***Figure 1***). The SSPA supports both CW and pulse operation and can be customized to application requirements. With an adjustable power range from five to 100 percent of rated output, the RIU256K0-40T utilizes RFHIC's technology enabling high system efficiency at both low and high power levels (see ***Figure 2***).

Each of the four GaN PAs in the generator uses RFHIC's high performance GaN on SiC transistor technology, which provides wide bandwidth, high efficiency, high breakdown voltage and reduces the overall size of the

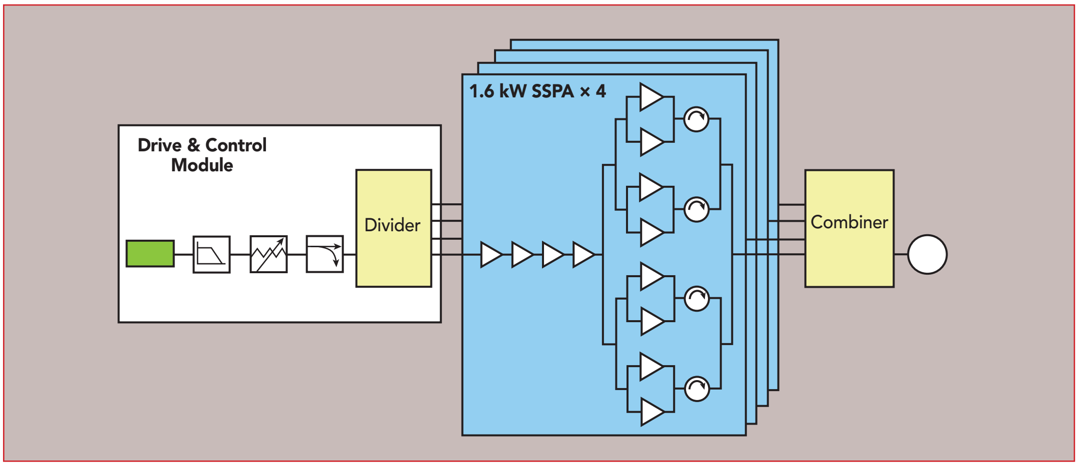

Fig. 1 SSPA head.

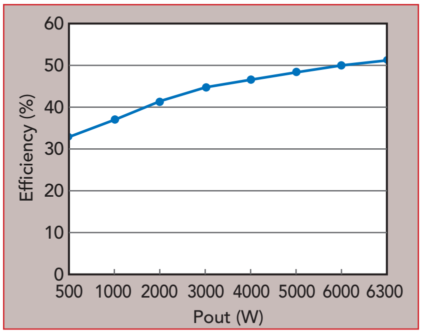

Fig. 2 System efficiency vs. output power.

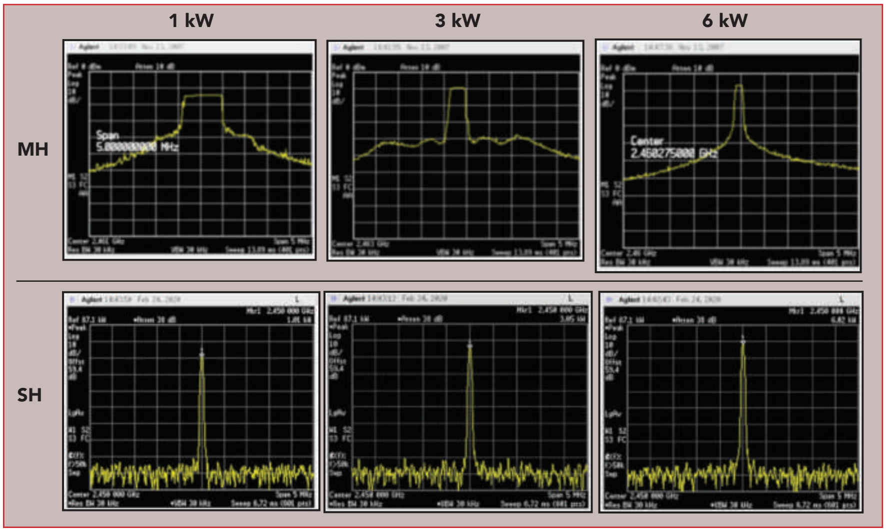

Fig. 3 Signal purity of the SSPA head (SH) compared to a magnetron head (MH).

system. The RIU256K0-40T uses 200 W transistors (IE24200P), which have a saturated output power of 230 W and 74 percent drain efficiency at 50 V bias. The fully matched transistors are integrated with DC blocking capacitors on both RF ports to simplify SSPA integration.

SSPA VS. TUBE

Many historic RF energy applications use vacuum tubes or magnetrons as the core power source. Such systems have significant disadvantages controlling the frequency, power and phase. The RIU256K0-40T includes RFHIC's drive and control module to precisely set the output frequency and power, and the generator delivers a clean signal with low noise and spurious compared to a magnetron (see ***Figure 3***). Another advantage is the capability to generate full power without any warm-up time.

Tubes have short lifetimes—often less than 6,000 hours—causing down time and increasing operating cost. The RIU256K0-40T's lifetime is between 50,000 and 100,000 hours, depending on the operating conditions, which yields significant cost savings. Unlike magnetrons and

other tube-based systems with a single power source, the RIU256K0-40T combines four rugged GaN SSPAs, enabling the system to degrade gracefully if one of the PAs fails. Tube-based systems require high voltage power supplies inside the generator, which are susceptible to arcing. The SSPA operates at a safer voltage of 50 V.

The RIU256K0-40T uses water cooling to eliminate large metal heat sinks and reduce generator size. With water cooling, the SSPA can be compatible with the existing cooling infrastructure for a tube-based system, which reduces installation and operating costs for the customer. The system has multiple sensors to detect water flow rate, SSPA temperature and VSWR. In case of abnormal operation, the system will automatically shut down and alert the user, ensuring the generator is not damaged. The RIU256K0-40T has an LCD touchscreen and jog wheel, providing full access to the system controls, sensors and alarms; full monitoring and control is also accessible using a laptop or remote PC. Controlling the system remotely via PLC, CAN or Bluetooth is available as an option.

MODULAR DESIGN

The RIU256K0-40T is a standalone, rack mounted system with two parts:

- SSPA head with isolator, which is 42.4 cm wide, 74.7 cm long, 25.6 cm high and weighs 41 kg.
- Power supply, which is 48.3 cm wide, 43.2 cm long, 17.7 cm high and weighs 29 kg. The power supply uses three-phase, 380 V AC and generates the 50 V bias for the GaN transistors. The power supply contains six, 3 kW rectifier modules designed to load share, be hot-swappable and n+1 redundant, meaning the SSPA will continue to operate if one of the power modules fails. The failed module can be replaced without replacing the entire generator.

Four 1.6 kW SSPAs are combined to produce the 6 kW CW output, using RFHIC's four-way waveguide combiner. From 2.4 to 2.5 GHz, the WR340 combiner has a maximum insertion loss of 0.1 dB with 1.1:1 VSWR and less than 3 degrees imbalance among the ports. The generator is scalable, meaning users can add RFHIC's commercial off-the-shelf PAs without manual phase synchronization. This flexibility maximizes amplifier utilization, reduces capital expense and shortens development time.

RFHIC Corp. is semi-vertically integrated, the only company with a portfolio from GaN transistors and PAs to full systems, from commercial off-the-shelf products to custom module and sub-system designs with output power to multi-megawatts. RFHIC's extensive capabilities ensure low cost and quality products, with fast lead times and after-care service.

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Advances in Temperature Stable, Low Power Consumption OCXOs

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Cesson-Sévigné, France

The choice of the local oscillator in an RF/microwave system is a significant decision affecting the performance of the system. In the case of an embedded application, where power is limited by battery operation, for example, optimizing the performance for the lowest dissipation is an important requirement. ***Figure 1*** shows the frequency stability versus power consumption of several categories of quartz oscillators. The most basic use MEMS, while the most efficient are the oven controlled quartz oscillators (OCXO), where the quartz resonator is stabilized at a specific temperature.

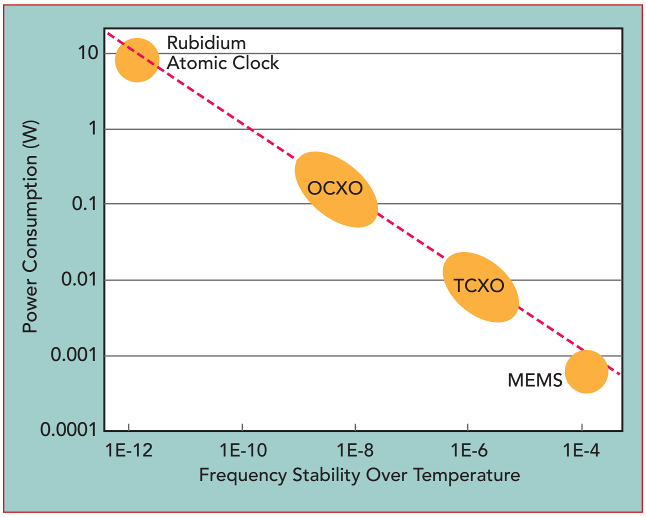


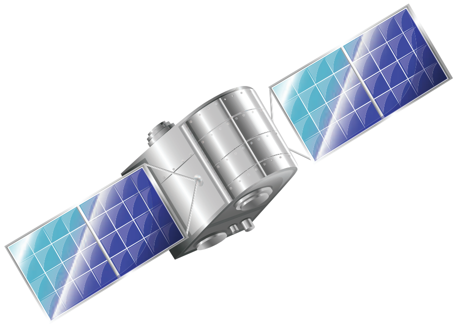
Fig. 1 **Oscillator frequency stability vs. power consumption.**

The performance of an OCXO is primarily determined by two factors: the quality of the quartz resonator and the variation in quartz temperature with ambient temperature changes external to the OCXO. The frequency of any quartz oscillator will drift with temperature. For a 10 MHz oscillator, for example, the frequency drift between -40°C and +85°C can reach ±250 to ±500 Hz. Maintaining the quartz at a precise temperature will reduce the OCXO drift to between ±0.05 and ±0.5 Hz, depending on the OCXO.

The quartz crystal in an OCXO is chosen to operate at an ultra-stable point, called the turnover point, where a small excursion in temperature does not significantly affect its frequency. The turnover point temperature must be higher than the maximum ambient temperature of the OCXO, so the internal heating mechanism and thermal regulation of the OCXO can be effective. To limit the power dissipation, the heated quartz must be well insulated from the outside, meaning the packaging must have the highest possible thermal resistance.

AT OR SC CUT?

Using an OCXO requires choosing the type of quartz cut, AT or SC, and whether a simple or double oven is necessary to achieve the required stability. ***Figure 2*** compares the frequency stability of AT and SC cut crystals. The difference can be signifi-



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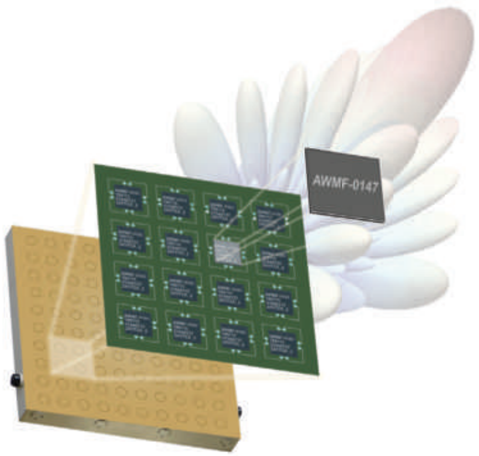

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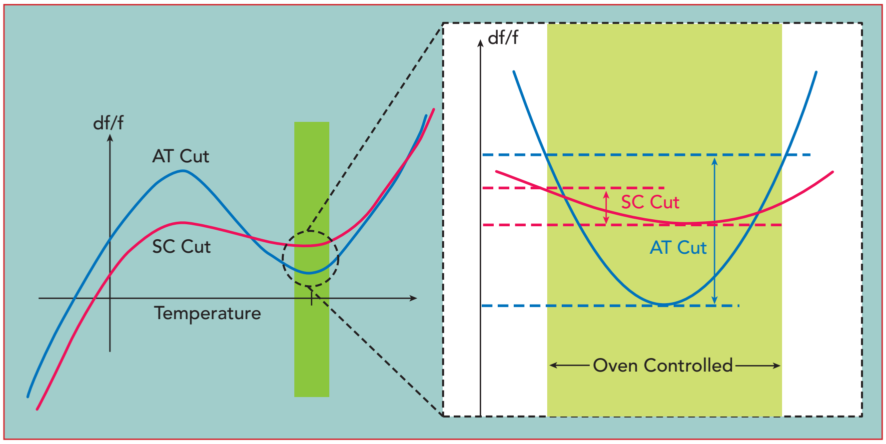

Fig. 2 **Frequency stability of AT and SC cut crystals.**

cant, with SC cut crystals more stable than AT cut at a given turnover point. However, OCXOs using AT resonators are more common and, for low volume applications, provide an excellent trade-off between overall frequency performance and low power consumption. OCXOs using SC cut resonators represent the state-of-the-art and are used for the most demanding applications, those requiring very low long-term aging, precision ranging or satellite positioning. SC cut resonators are traditionally bulkier than AT cut.

OCXOs guarantee high frequency accuracy, typically ±1 ppm. To achieve this, the OCXO manufacturer sorts the crystals and adds a trimming step during production. This adjustment, called frequency tuning, is important to guarantee the frequency precision when the OCXO is shipped. For example, if an OCXO is specified at 10 MHz, the frequency must be within a few Hertz—difficult to achieve without trimming. Yet, even with this accuracy, designers often want to adjust the frequency of the OCXO slightly; to enable this, a Vtune input is provided to tune the OCXO to the nearest milliHertz. For maximum precision, Syrlinks provides an internal, thermally-controlled reference voltage, Vref, which does not vary with the ambient temperature. This enables adjusting Vtune with a simple resistive divider, and the Vref ensures the maximum precision.

BATTERY-POWERED APPLICATIONS

To counter the generally higher power consumption of an OCXO compared with a temperature compensated crystal oscillator (TCXO), Syrlinks has developed a range of OCXOs combining low power consumption with small size and weight. The EWOS ™ range covers frequencies between 10 and 40 MHz, with thermal sensitivities between ±5 and ±250 ppb and power consumption between 50 and 400 mW at 25°C, about 10× lower power consumption than comparable OCXOs. Small size is achieved by adding an ASIC at the core of the OCXO to control all oscillator functions and manage the thermal behavior.

Syrlinks has developed a new timing module built using its OCXO and very low power digital electronics. The Syrlinks GNSS Timing Module (SGTM) precisely aligns the frequency and phase of the EWOS OCXO with the GPS signal. If the GPS reference is not available, the SGTM maintains accurate time, relying on the stability of the embedded OCXO. Without modifying the system, the SGTM can be used in some applications as an alternative to a chip-scale atomic clock (CSAC): its footprint enables quick pre-testing and deployment in production, making it an alternate second source if the CSAC is not available. The digital electronics of the SGTM provide advantages over the OCXO alone. The alignment of the OCXO's phase and frequency with the GNSS signal is fully automated and achieves 0.5 to 1.0 ns jitter compared to the pulse-per-second (PPS) signal. This performance is linked to Syrlinks' proprietary algorithm and hyper-

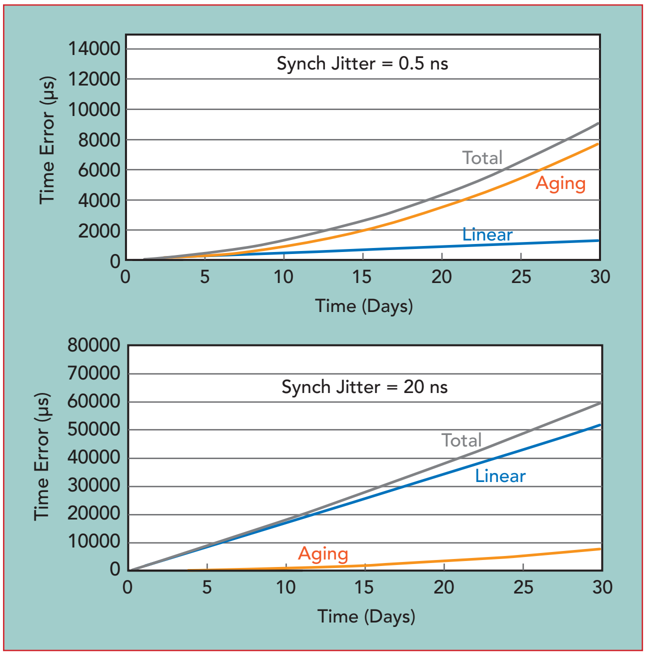

Fig. 3 Accumulated time error of the low jitter SGTM (top) with an oscillator with initial synchronization of 20 ns (bottom).

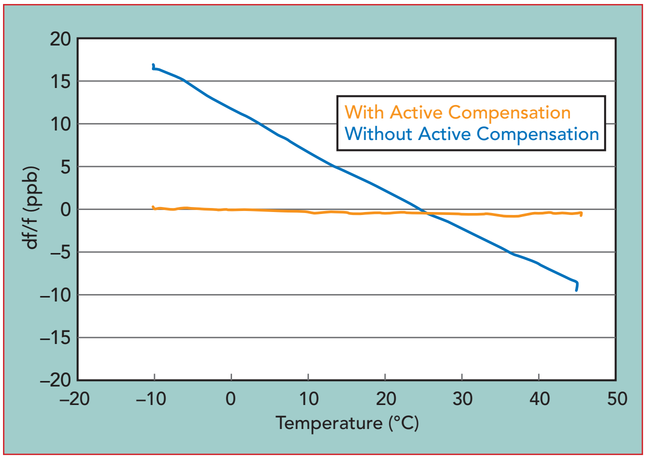

Fig. 4 Improved OCXO thermal stability with active compensation.

fine tuning of the OCXO frequency using the Vref output.

The reduction of the residual initial synchronization error with the GNSS signal makes it easier to reveal secondary parabolic drifts related to long-term aging or thermal drift. ***Figure 3*** compares the accumulated time error for a case where the initial synchronization is not close—the jitter is 20 ns—vs. the SGTM with 0.5 ns jitter. In the first case, the linear accumulated error masks the other types of drift, which must be post-processed to obtain better resolution of oceanic subsoils, for example.

In addition to generating a PPS signal from the OCXO frequency, the SGTM enhances key OCXO parameters such as thermal sensitivity. Understanding the thermal behavior of the EWOS10HP, Syrlinks developed a predictive algorithm for its OCXOs. Using the type of cut, AT or SC, each SGTM module is individually calibrated to compensate its intrinsic and natural thermal drift. For an EWOS10 AT cut resonator in a DIL14 enclosure, the algorithm reduces the thermal sensitivity from an initial value of around ±100 ppb to ±2 ppb. For Syrlinks' most efficient OCXO with an SC cut resonator, the frequency stability over temperature can be improved to ±1 ppb. The thermal drift compensation technique has also been implemented on inherently more stable OCXOs, which are dedicated to underwater applications. For example, from -10°C to +45°C, the thermal sensitivity of the SGTM16HP-UW is reduced by 20×, from ±15 ppb without compensation to ±0.5 ppb, the thermal noise of the OCXO (see ***Figure 4***).

OCXOs are essential for many RF/microwave applications. Syrlinks has combined its long-term understanding of crystal oscillator technology with digital electronics and algorithms to push OCXO performance to new frontiers.

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Cesson-Sévigné, France
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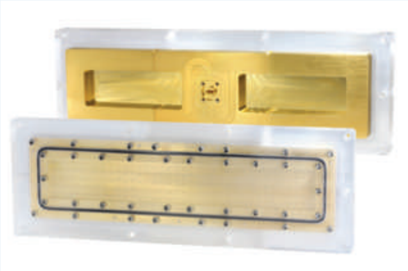

Slotted Waveguide Array Antenna

Slotted antennas, a complement to dipole antennas, have slots λ/2 long and a fraction of a wavelength wide. The antenna propagates based on Babinet's principle of a resonant radiator. The key difference between a dipole and a slotted antenna is the field components are interchanged in orientation. Because of the vertical electric field in horizontal orientation, slot arrays can fit on the surface of moving objects without introducing much aerodynamic drag and wind load. For the same size, slotted waveguide array antennas are more efficient than any other planar antenna. Versatility in slot feeding options, ease of weather-proofing and mechanical stability make slotted antennas well-suited for military and defense applications.

For radar and communication systems, Eravant, formerly SAGE Millimeter, has developed the SAW-3533532716-28-L2-WR, a slotted waveguide array antenna operating at 35 GHz with 500 MHz bandwidth. The bandwidth can be increased by increasing the slot width, with cross-polarization increasing as a trade-off. The SAW-3533532716-28-L2-WR slot array supports linear, vertically polarized signals with high aperture efficiency and low VSWR. The antenna has 27 dBi gain with a half-power beamwidth of 16 degrees in the E-plane and 2 degrees in the H-plane. A radome of LEXAN polycarbonate makes the antenna suitable for outdoor applications. Its 1 lb. weight and small size—measuring 11.84 in. x 3.85 in. and just 0.93 in. thick—eases mounting and minimizes the dynamic load to the overall structure. A groove for an O-ring in the standard WR28 waveguide flange (UG-599/U) pressure seals the connecting interface. Integrating the antenna with a T/R diplexer, a dual channel I/Q receiver and an oscillator makes a complete package for many system applications, such as traffic management, law enforcement, communications and military surveillance.

The slot array antennas offered by Eravant span WR90 to WR10 and are designed with MIL-F-3922 designated standard flanges as the microwave connector interface.

Eravant, formerly SAGE Millimeter
Torrance, Calif.
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High Reliability, Precision Thin Film Resistors

Susumu's RG series of thin film resistors was developed to have extraordinary environmental resistance and durability in high temperature and high moisture applications, maintaining the excellent performance properties of thin film resistors. RG resistors, which stands for "resistors great," were developed for applications such as automotive electronics, test and measurement and medical equipment, where high reliability and accuracy are essential to achieve "zero" defects.

The RG series has an inorganic protective coating to maintain high reliability and durability to heat and moisture and offers excellent performance, with tight tolerance, low temperature coefficient of resistance (TCR), low current noise and high linearity for high frequency circuit applications. Resistor precision is typically ±0.02 percent, with a TCR of ±5 ppm/°C. Subjected to a 10,000 hour reliability test, the RG series drifts less than ±0.1 percent. The four types in the series have maximum voltage ratings from 75 to 200 V. Various power ratings are available within each type, up to 0.25 W, with power handling derated above +85°C. The overall operating temperature range of the RG series is from -55°C to +155°C.

Since 1964, Susumu has been developing innovative and high-quality thin film resistors for the electronics industry. As a specialist in thin film technology and one of the world's largest manufacturers, Susumu offers a wide range of high-quality components: chip resistors, chip networks, precision resistor networks, chip inductors, delay lines, power inductors and current sensors.

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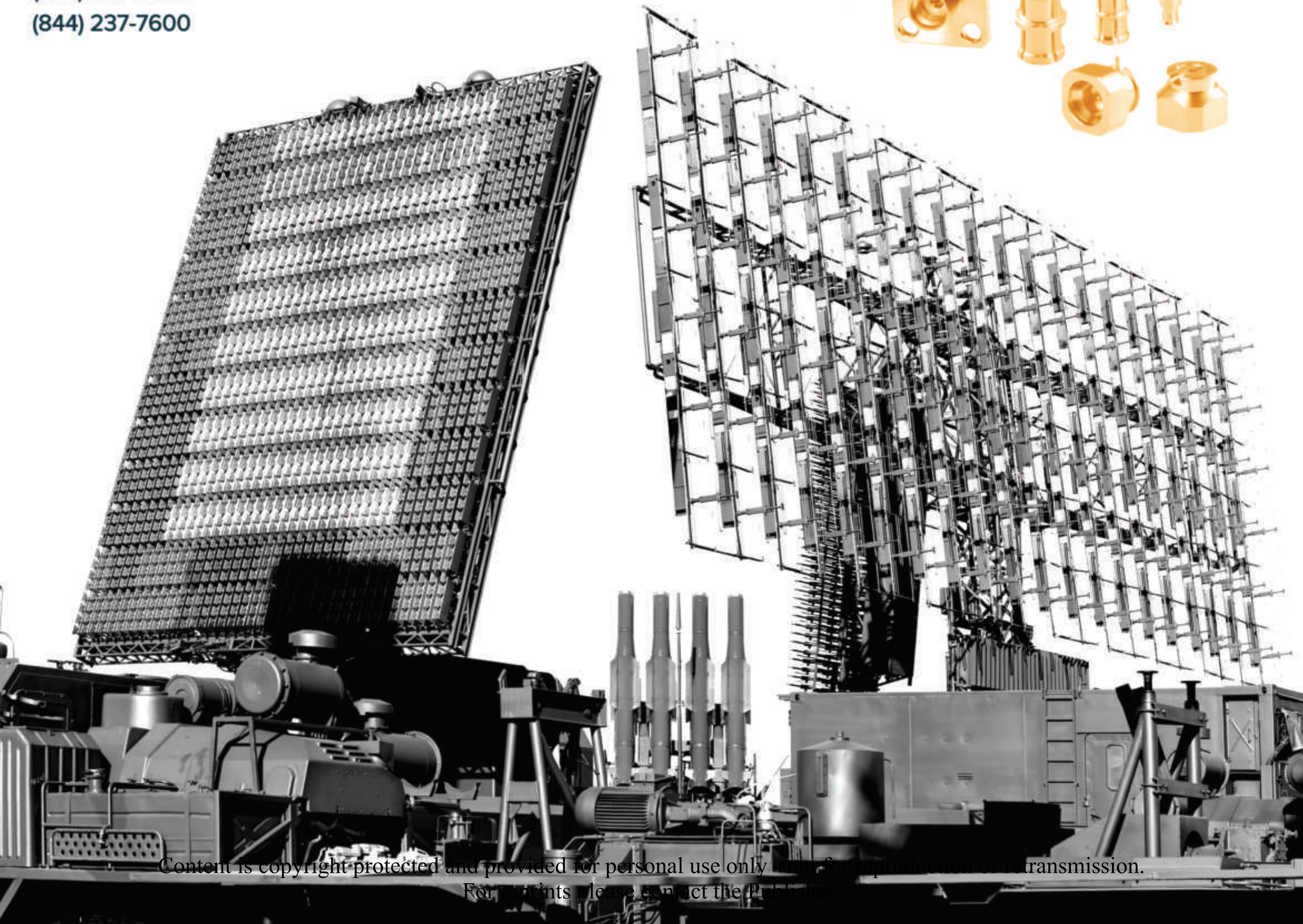

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New Product Guide

VENDORVIEW

The new MilesTek product guide is filled with detailed technical information and specifications covering a host of MIL-STD-1553B, Ethernet, fiber-optic products and more. Featured product lines include 1553B data bus couplers, bus and stub cables, relay devices, Twinaxial and Triaxial cables and connectors, mil/aero and harsh environment Ethernet cables and connectors and a range of rugged fiber optic product solutions.

MilesTek
www.milestek.com/t-catalog.aspx

New Product Guide

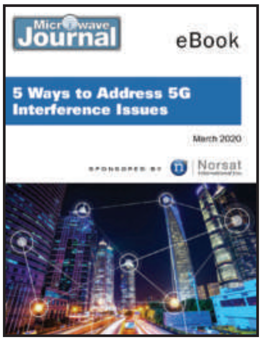
VENDORVIEW

Mini-Circuits continues to release new products at a record pace. The Q4 2019 New Product Guide showcases some of the company's latest model releases including ultra-wideband coaxial amplifiers up to 43.5 GHz, MMIC splitter/combiners with multi-octave bandwidths from DC to 43.5 GHz, connectorized passives up to 65 GHz, new LTCC products and more.

Mini-Circuits
www.minicircuits.com

5 Ways to Address 5G Interference Issues

VENDORVIEW



As the RF spectrum becomes more crowded, the chance for interfering signals greatly increases as frequency bands become very close to each other and sometimes even overlap. These situations have caused more interference issues than ever in the RF and microwave spectrum, so it is important to understand how to avoid interference. This eBook examines several solutions to the ever increasing problem of interference using techniques such as frequency sharing, frequency cancelation and filtering.

Norsat International
mwjournal.com/ebooks

New 2020 Product Guide

VENDORVIEW

Pasternack, an industry-leading manufacturer and supplier of RF, microwave and mmWave products, has recently released their 2020 RF Product Guide. The company's latest 264 page catalog contains thousands of in-stock products including RF cable assemblies, RF amplifiers, an expanded portfolio of waveguide components, 60 GHz modules and systems and hundreds of other active and passive RF components that are all available for same-day shipping worldwide.

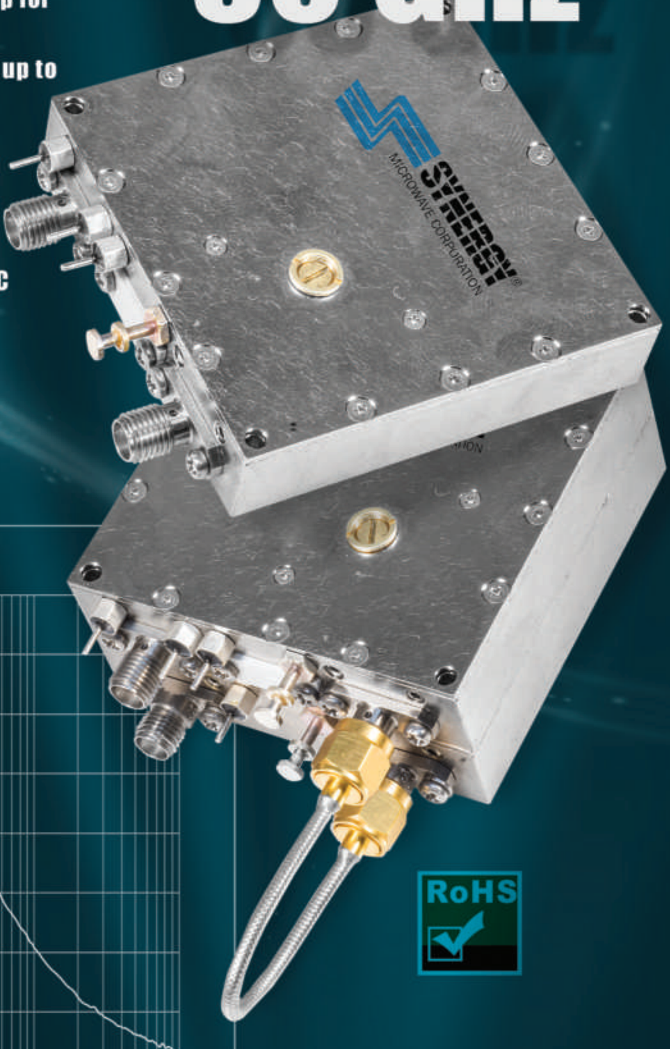
Pasternack
www.pasternack.com

DUAL or SINGLE LOOP
SYNTHESIZER & PLO MODULES

Up to 30 GHz*

Features:

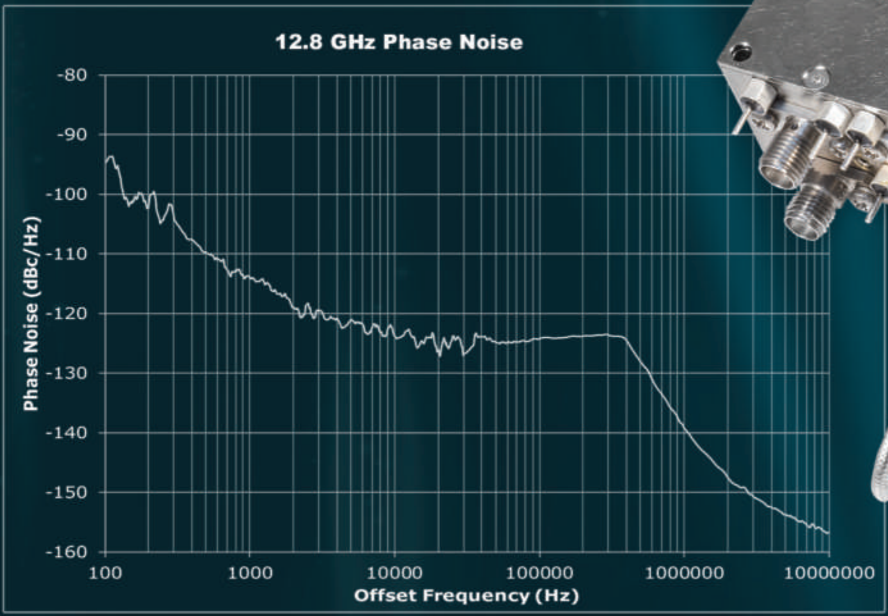
- Proprietary digital Integer and Fractional PLL technology
- Lowest digital noise floor available -237 dBc/Hz figure of merit
- Output frequencies from 100 MHz locked crystal to 30 GHz
- Available with reference clean up dual loop, or single loop for very low noise reference
- Parallel fixed band stepping or SPI interface synthesized up to octave bandwidths
- Reference input range 1 MHz to 1.5 GHz
- Dual RF output or reference sample output available
- +12 dBm standard output power +16 dBm available
- Standard module size 2.25 X 2.25 X 0.5 Inches (LxWxH)
- Standard operating temperature -10 to 60 °C, -40 to +85 °C available



Applications:

- SATCOM, RADAR, MICROWAVE RADIO

* 16 - 30 GHz with added x2 module < 1" in height.



Talk To Us About Your Custom Requirements.

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E-mail: sales@synergymwave.com
Web: WWW.SYNERGYMWAVE.COM
Mail: 201 McLean Boulevard, Paterson, NJ 07504

CatalogUpdate

Wi-Fi Convergence with IoT and 5G

This eBook presents a number of products and technologies that enable Wi-Fi, IoT and 5G wireless systems to work together without interference. New filter and front-end modules are key products that enable these wireless technologies to work together seamlessly. The first two articles feature products that allow these wireless technologies to work together with excellent performance; followed by a short update on the release of Wi-Fi 6; and it finishes with a thorough article covering the various Wi-Fi and IoT deployment synergies.

Qorvo
mwjournal.com/ebooks

New Product Guide

VENDORVIEW

Go anywhere Arbitrary-Waveform-Generators (AWGs) with 24V output swings! In the catalog 2020, Spectrum Instrumentation features four brand new LXI-based AWGs for high amplitude signals. Using the latest 16-bit DACs, the DN2.657 models offer up to 125 MS/s and the DN2.654 units work with up to 40 MS/s. Both speeds are available with four or eight fully synchronous channels. An optional 12V or 24V power supply is available.

Spectrum Instrumentation
www.spectrum-instrumentation.com/en/news

New SPINNER Air Traffic Control Catalog

VENDORVIEW

Today's high air traffic densities can only be managed with the aid of extremely reliable components that fully exploit the potential of digitization. The new RF rotary joints from SPINNER are virtually maintenance-free when equipped for contactless transmission of data and power. Their features include real-time gigabit Ethernet for handling the steadily expanding data volumes involved. They are also well-known for the exceptionally high quality and precision of their mechanical parts and their excellent signal transmission properties. Learn more in our new ATC Catalog.

Spinner Group
www.spinner-group.com

NEW PRODUCTS

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

COMPONENTS

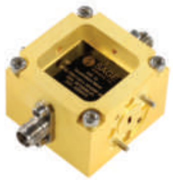
75 Ohm Terminations

BroadWave Technologies Inc. introduced two new lines of 75 Ohm terminations. Model 572-375-001 features an N male RF connector and model 572-376-001 features an N female RF connector. Both devices are 75 Ohm, DC-4 GHz, 1 W average power, exhibit 1.35:1 maximum VSWR with an operating temperature range of -55°C to +100°C. Delivery for up to 25 pieces is from stock to 1 week ARO.

BroadWave Technologies Inc.
www.broadwavetechnologies.com

Quadrature Mixer

Model SFQ-75311415-1010SF-N1-M is a W-Band quadrature mixer that covers the frequency range of 75 to 108 GHz. The typical conversion loss of the quadrature mixer is 15 dB with an LO driving power of +15 dBm. Since the IF port of the quadrature mixer is DC coupled, the mixer can be used as a phase detector.



In addition, the mixer can be readily configured into an image rejection mixer or single sideband modulator by adding an IF quadrature coupler.

Eravant
www.eravant.com

Right Angle SMA Attenuators

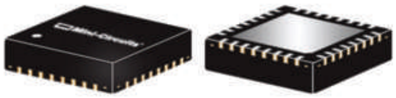
VENDORVIEW

MECA expands its series of 2 W SMA right angle attenuators to include non-standard/odd dB values from 1-32 dB. The 662-dB-1RA series attenuators cover all wireless applications from Hz to 4.0 GHz Made in the U.S., 36 month warranty.

MECA Electronics Inc.
www.e-meca.com

Front-End Module

VENDORVIEW



Mini-Circuits' model DVGA3-122+ is a miniature front-end multichip module with a wide 31.5-dB gain-control in 0.5-dB steps from 900 to 1200 MHz. It combines a low-noise amplifier, voltage-controlled attenuator with 6-b serial control, and reflectionless lowpass filter in a low-profile, 32-lead MCLP package that measures 5 × 5 × 0.89 mm and is a good fit for densely packaged printed-circuit boards. It operates from a single 5-V DC supply and provides +15.6 dBm output and +28 dBm third-order intercept (IP3) at 1 GHz.

Mini-Circuits
www.minicircuits.com

5.0 to 10.0 GHz Hybrid Coupler

VENDORVIEW

PMI Model No. QC-5010-NFF is a 5.0 to 10.0 GHz hybrid coupler. It has a maximum insertion loss of 1.1 dB; a minimum isolation of 16 dB; Amplitude Balance: ±0.75 dB Max. - Measured ±0.5 dB; Phase Balance: ±5 Max; VSWR: 1.50:1 Max: and Power Handling: Average: 75 W Max and Peak: 3 kW Max. Contains N female connectors in a housing that measures 1.870" × 1.315" x 0.787."

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

75Ω Absorptive Switch

The QPC4270 is a high isolation Silicon on Insulator (SOI) single pole single throw (SPST) 75Ω absorptive switch designed for use in CATV, satellite set top and other high performance communications systems, provided in a low cost small 6-pin DFN package.

Qorvo
www.qorvo.com

Miniature SPDT Switch Line

RLC Electronics introduced an addition to its miniature SPDT switch product line. This switch is offered in a unique package with connectors in a "T" configuration for ease of connection/mating at the system level, and is a perfect drop-in replacement for pin diode switches. The switch is offered in both surface mount and connectorized versions and operates from DC-18 GHz. Standard options are available include Indicators and TTL Drivers. The switch measures 1"× 1"× 0.90."

RLC Electronics Inc.
www.RLCelectronics.com

SpaceNXT™ MWC Series

VENDORVIEW

Addressing the need to create a stream-lined procurement experience by shifting the testing responsibility away from the customer, Smiths Interconnect announced the release of its SpaceNXT™ MWC Series of high reliability multi-way isolated splitters in high-frequency Ku bands. The SpaceNXT™ MWC Series is specifically designed for a variety of space applications from MEO/GEO satellites to deep space probes. It can be supplied to recognized testing sequences, so simplifying the specification and definition process.

Smiths Interconnect
www.smithsinterconnect.com

CABLES & CONNECTORS

UltraPhase / Phase 3 / Vast Array

MegaPhase designs and manufactures a wide variety of cable assemblies through 110 GHz. Best known for test and measurement products, including RF Orange®, Killer Bee™, and VNA test port extension cables lead the lineup. MegaPhase offers much more than test cables. MegaPhase is a leading provider of cables for applications such as space, airborne radar, advanced EW and communications. Leading the lineup are UltraPhase™ to 110 GHz with linear phase versus temperature. Also ultra low loss Phase3™ through 70 GHz.

MegaPhase
www.megaphase.com

MiCable

Butler Matrices for WiFi & Base Station Test

- ☑ Fully Support WiFi 6E, 5G/4G/3G Base Stations
- ☑ Diversified Phase Distributions & I/O Structures, up to 64x16 Matrix Crossover
- ☑ Excellent Phase Accuracy, Amplitude Balance, VSWR & Insertion Loss
- ☑ High Power Handling: 20W
- ☑ Custom-design Available

Typical I/O Structures

• 4x4 • 8x8 • 16x16 • 32x16 • 64x16

Typical Frequency Range (GHz)

• 1.7-2.2 • 2.3-2.7 • 2-6 • 2-8
• 3.3-3.8 • 4.4-5 • 5.2-6 • 24-52

Typical Performance

Frequency (GHz)	Structure	Phase Accuracy (Max.)	Insertion Loss (Max.)
1.7-2.2	16x16	±4°	15 dB
2-8	4x4	±6°	7.8 dB
2-8	8x8	±12°	12.5 dB
2.496-2.696	32x16	±4°	19 dB

More Information-
Scan the QR Code

affiliated with SSi Cable Corp.

Fuzhou MIcable Electronic Technology Co., Ltd,
Tel: +86-591-87382856 Email: sales@micable.cn Website: www.micable.cn

Low PIM Series of Armored Test Cables

MIcable developed a series of DC-6 GHz low PIM armored test cables. As an example, for 1 meter N/male to 4.3-10/ male connector cable, specification is PIM -165 dBc max. (tested at -173 dBc), VSWR < 1.25:1 and insertion loss 1.5dB max. The cable is flexible with 50 mm mini. bend radius and Ø10 mm armor diameter. MIcable sells at $105 each with stock to four weeks delivery. Other available connectors include 4.3-10/female, L29/ male and SMA/male.

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

Cable Assembly with 2.40 mm Connectors

Samtec announces a new high-performance cable assembly with performance up to 50 GHz using both Male and Female 2.40 mm connectors. The RF23C Series uses cable manufactured in their Wilsonville, Oregon facility, which is a flexible low-loss alternative to RG405 semi-rigid cable. According to their on-line characterization report, 12-inch assemblies typically exhibit less than 1.3:1 VSWR and just over 2 dB of insertion loss up to 50 GHz.

Samtec
www.samtec.com

AMPLIFIERS

Gallium Nitride (GaN) Amplifier

COMTECH PST introduced a new Gallium Nitride (GaN) amplifier for applications in the X-Band radar market. The AB linear design operates over the 9.0-10.0 GHz frequency range intended for use in radar applications. The amplifier design features include pulse width and duty factor protection as well as thermal and load VSWR fault monitoring. Consistent with its planned technology development roadmap, Comtech is leading the field with the latest in GaN-based RF device performance and advanced amplifier development.

COMTECH PST
www.comtechpst.com

4 KW S Band SSPA

VENDORVIEW

Empower's model 2176 is a compact high power GaN on SiC solid state CW amplifier. Standing 27 in. tall, it is less than half the size of the typical legacy uplink HPA's that it replaces. The slightly broader band brings flexibility to transmit in either of the two uplink channels. Besides the dramatic size reduction, the upgrade from legacy design to a next generation SSPA from Empower RF brings greater reliability and improved spectral purity for increased data rates.

Empower RF Systems
www.EmpowerRF.com

Solid State Power Amplifier System

VENDORVIEW

Exodus AMP4072 is designed for broadband EMI-Lab, Comm. and EW applications. Class A/ AB linear design for all modulations & industry standards. Covers 26.5 to 40.0 GHz, nominal powers 10W rated, 6W P1dB, with a minimum 40dB Gain. Excellent gain flatness, optional monitoring parameters for forward/reflected power, voltage, current and temperature sensing for superb reliability and ruggedness. Integrated in a compact 2U chassis weighing <10 Kg.

Exodus Advanced Communications
www.exoduscomm.com

Tri-Band RF Power Amplifiers

Microwave Amps offer its AM4 range of wideband GaN amplifiers in a convenient chassis for general purpose high-power test and measurement, and where wideband RF power is needed in ECM systems. The AMR offers three bands which can be used separately or simultaneously, each having dedicated input and output ports. Standard bands are 20-500 MHz, 500-2500 MHz and 2000-6000 GHz, but the AMR can be configured with any combination of its AM4 models spanning the 20 MHz to 12 GHz range, with output power levels of 25 W or 50 W.

Microwave Amps Ltd.
www.maltd.com

Class AB High Power Amplifiers

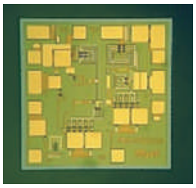
VENDORVIEW

Pasternack, an Infinite Electronics brand and a provider of RF, microwave and millimeter wave products, has just launched a new series of high power, Class AB broadband amplifier modules that incorporate GaN, LDMOS or VDMOS semiconductor technology. The combination of high linearity and efficiency with low distortion over a wide dynamic range make them ideal for a variety of applications including communications systems, military radio, radar, signal jamming, test and measurement and base stations.

Pasternack
www.pasternack.com

Gain Block

VENDORVIEW



RFMW announced availability of a broad-band gain block from Microwave Technology. The MMA-062020 GaAs MMIC gain block provides nearly 20 dBm of saturated output power over its full 6 to 22 GHz frequency range. Optimally designed for broadband applications requiring flat gain with excellent input and output port matches, the MMA-062020 provides 14 dB of gain with typical gain flatness of ± 0.8 dB. P1dB output power measures >18 dBm with OIP3 of 28 dBm. Operating from a 5 V drain-supply, this general purpose amplifier is offered as a 0.92 × 0.92 mm DIE.

RFMW
www.rfmw.com

SEMICONDUCTORS

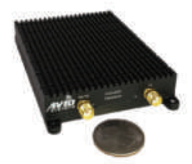
650 V SiC Schottky Diodes

Richardson RFPD Inc. announced the availability and full design support capabilities for the sixth generation family of SiC Schottky diodes from Wolfspeed, a Cree Company. The C6D family of 650 V SiC Schottky diodes is based on Wolfspeed's innovative, robust and reliable 150 mm SiC wafer technology. The latest C6D technology offers low forward voltage drop (VF = 1.27 V at 25°C) that has a significant impact on the reduction of conduction losses.

Richardson RFPD
www.richardsonrfpd.com

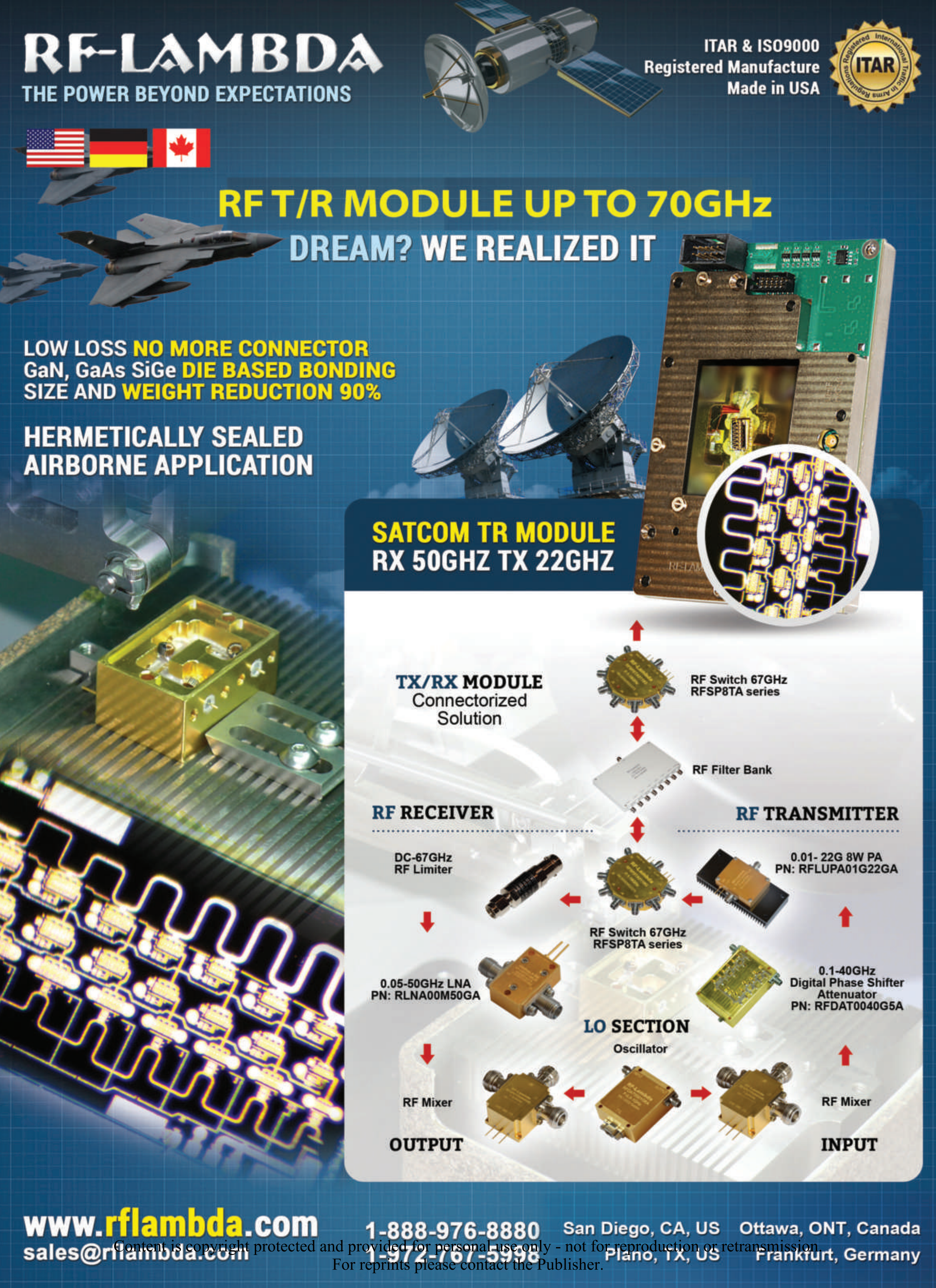
SYSTEMS

AVS-4000 Software Defined Radio



Avid Systems Inc. announced the AVS-4000 Software Defined Radio. The AVS-4000 is a USB type C radio that has independent transmit and receive capability from 1 MHz to 6 GHz with over 50 MHz of bandwidth. The AVS-4000 uses Vita 49 transport and includes accurate time stamping. The AVS-4000 is packaged into a rugged 2.5"×3.5" aluminum chassis, draws 2.5 W typical and weighs 4.5 ounces. The AVS-4000 has an integrated GPS receiver that is used to discipline the local oscillator, provide timing and location. In addition, the AVS-4000 has an external 1PPS and 10 MHz inputs. The AVS-4000 has five selectable RX and TX preselection filters.

Avid Systems Inc.
www.avid-systems.com


RF-LAMBDA
THE POWER BEYOND EXPECTATIONS
ITAR & ISO9000
Registered Manufacture
Made in USA
ITAR
RF T/R MODULE UP TO 70GHz
DREAM? WE REALIZED IT
LOW LOSS NO MORE CONNECTOR
GaN, GaAs SiGe DIE BASED BONDING
SIZE AND WEIGHT REDUCTION 90%
HERMETICALLY SEALED
AIRBORNE APPLICATION
SATCOM TR MODULE
RX 50GHZ TX 22GHZ
TX/RX MODULE
Connectorized
Solution
RF Switch 67GHz
RFSP8TA series
RF Filter Bank
RF RECEIVER
RF TRANSMITTER
DC-67GHz
RF Limiter
0.01- 22G 8W PA
PN: RFLUPA01G22GA
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

NewProducts

77 GHz FMCW Radar Warning Receiver

VENDORVIEW

Today's automotive and transportation systems rely on high-reliability/high-performance radar. Target tracking, collision threat prediction, configurability and cost along are critical. In conjunction with Mobile Technology Solutions, RFE developed a 77 GHz frequency-modulated continuous wave radar system that exceeds the standards in the marketplace. With over 150 meters of range, RFE's automotive radar platform is unaffected by vehicle glass and a custom designed antenna/lens system eliminates the alignment issues common with strip-line configurations.

RFE
www.rfe-mw.com

SOURCES

Ultra-Small Low Noise Low Power OCVCSO

IQD Frequency Products has launched a range of high frequency Oven Controlled Voltage Controlled SAW Oscillators (OCVCSOs). Three frequencies are currently available in the OCVCSO series, 400 MHz, 800 MHz and 1.2 GHz and they are packaged in a 25.4 × 22 × 13.2 mm industry standard SMD package. These OCVCSOs have a noise floor of 10 dB to 15 dB lower than an OCXO at the same frequency, enabling a much improved phase noise performance for applications such as radar detection systems.

IQD Frequency Products
www.iqdfrequencyproducts.com

XO9095 OCXO Series

MtronPTI introduces a small form factor high frequency XO9095 OCXO series that has multiplier stages to generate high frequency signal between 200 MHz to 6 GHz. XO9095 OCXO series offers exceptional stability, low phase noise and low-g sensitivity. Key features include standard frequencies: 1 GHz, 1.28 GHz, 2 GHz, 4 GHz, 6 GHz, various custom output frequencies available up to 6 GHz, low phase noise, low aging and low spurious. Applications include radar, GPS, test equipment, EW and satcom.

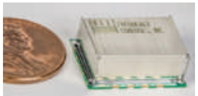
MtronPTI
www.mtronpti.com

Dual Output Frequency OCXO Module

Morion MV359 integrates two precision, ultra-low phase noise OCXOs at 10 MHz and 100 MHz. It utilizes a phase locked loop (PLL) to lock the 100 MHz OCXO to the 10 MHz OCXO. This configuration simultaneously facilitates exceptional frequency stability over temperature, long term frequency stability (aging), low "close-in" phase noise and excellent short term stability (Allan Deviation-ADEV) that is inherent in low frequency crystal oscillators (10 MHz), as well as excellent phase noise floor provided by a high-frequency crystal oscillator (100 MHz).

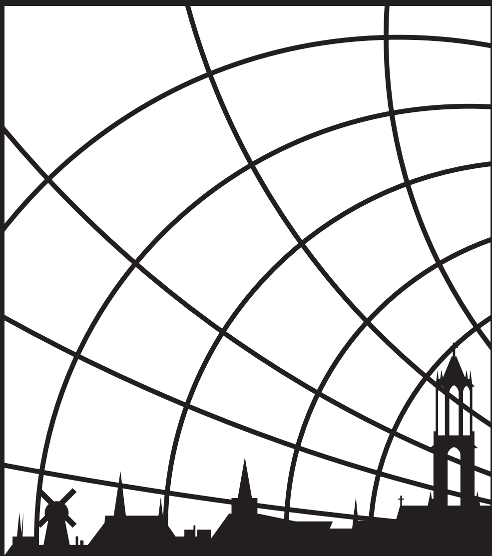
Morion US
www.morion-us.com

ULPN Surface Mount OCXO



The ULPN surface mount OCXO is ideal for applications that include instrumentation, radar, high end synthesizers, telecommunication systems and data communications.

NEL Frequency Controls Inc.
www.nelfc.com



Arbitrary Waveform Generators

VENDORVIEW

The ability of Arbitrary Waveform Generators to recreate virtually any waveshape makes them especially useful as signal generators in today's sophisticated electronic systems. Spectrum Instrumentation recently released four new models in its generatorNETBOX family with output swings of up to 24 volts on up to eight channels, to cover even the most demanding test applications. The new units use the latest 16-bit Digital-Analog-Converters and offer two different speed ranges; the DN2.657 models output waveforms at rates up to 125 MS/s while the DN2.654 units have a 40 MS/s capability.

Spectrum Instrumentation GmbH
www.spectrum-instrumentation.com/en

Voltage Controlled Oscillator

VCO's featuring excellent phase noise and available in planar, ceramic or SAW resonator construction. Most of these products utilizes its patented REL-PRO®technology surface mount footprint design. Synergy can also customize an oscillator according to your specific requirements.

Synergy Microwave Corp.
www.synergymwave.com

ANTENNAS

Sectorial Antenna

In order to meet optimum network performance and capacity enhancement, HUBER+SUHNER provides multi-band, multi-beam as well as multi-port antenna solutions with best in class electrical performance for different cellular applications and various deployment scenarios (urban, sub-urban, rural, etc.). The wide product range of Sectorial, In-Building and Distributed Antenna Systems is complemented by radio frequency jumpers, cables, connectors and RF components. In addition to DAS, ODAS or Small Cells, HUBER+SUHNER is capable of doing customized cost effective designs of compact and light weight antenna with optimum wind load capacity, with fast turn-around time for samples.

HUBER+SUHNER AG
www.hubersuhner.com

TEST & MEASUREMENT

IEEE 802.11ax Compliant WLAN Signaling Test Solution

VENDORVIEW

The greatest innovation in IEEE 802.11ax (Wi-Fi 6) compliant WLAN transmission technology is the introduction of orthogonal frequency-division multiple access (OFDMA) technology, a multi-user variant of the orthogonal multiplexing scheme previously used in wireless LANs. By sharing the available bandwidth, multiple users can be active at the same time. This technology presents new challenges for developers of WLAN devices and significantly expands the scope of testing for the certification of Wi-Fi 6 devices.

Rohde & Schwarz
www.rohde-schwarz.com

MICRO-ADS

IndustryWorkshops

June 23, 24, and 25, 2020,
Los Angeles Convention Center

IMS LOS ANGELES 2020 CONNECTIVITY MATTERS

The **Industry Workshops** are a unique conference track at the IMS that focusses on the practical talks that help working engineers solve complicated problems in the microwave field

Tuesday

- COTS Phased Array Radar System Design and Measurement Using Model-Based Engineering
- Analytical vs. numerical techniques for beamforming optimization in phased arrays
- Automotive Radar IQ Data Simulation for Performance Analysis

- Multi-Channel mmWave EW Receiver Workshop
- Understanding 5G System-Level Evaluation
- Hybrid Beamforming for 5G Systems

- Optimizing System Performance for Emerging Wideband mmWave Applications
- RF and mmWave Frontends: efficient RF power amplifiers and affiliates
- Achieving Electromagnetic Compatibility (EMC) for 5G Devices

- Phase-Noise Theory and Measurement Workshop
- Integrated Passive Devices (IPD) for 5G RF Front-end Designs
- Enabling Technologies for Silicon Beamformers for 5G and Satcom Systems

Wednesday

- Learn 5G Signals, Demodulation and Conformance Tests with the VSA
- Addressing Calibration and Measurement Challenges of Broadband On-wafer VNA Measurements up to 220 GHz
- High Power Solid State Amplifier Advances in Technology

- Cryogenic measurement challenges for quantum applications
- Design Tutorial for a High-Efficiency GaN Doherty Power Amplifier
- Redefine OTA: Innovative testing solution for 5G NR mmWave

- Understanding 5G New Radio (NR) Release 15-16 Standards
- Designing GaN on SiC MMIC Power Amplifiers Using the Cree-Wolfspeed MWO PDK
- System-level and Module-level RF/microwave design flows integrating circuit/EM and thermal analysis

Thursday

- Best practices for thermal on wafer S-parameter measurements
- Challenges of Modern Wireless Devices
- mmWave Over-the-air (OTA) test - best practices for fast and reliable results

- Measuring S-Parameters and Power with Uncertainty
- Practical GaN Power Amplifier Design - Modeled vs Measured Performance, Tricks and Tips for Avionics and Satcom Applications
- Best Practices for Efficient EM Simulation

For additional information visit ims-ieee.org

Participating companies include:

ANALOG DEVICES — AHEAD OF WHAT'S POSSIBLE™
Anokiwave — mmW Solutions. Enabling a new world
Anritsu — envision : ensure
cadence®
Wolfspeed. A CREE COMPANY
EMPOWER RF SYSTEMS, INC.
ETS-LINDGREN® An ESCO Technologies Company
KEYSIGHT TECHNOLOGIES
Lake Shore CRYOTRONICS
MathWorks®
Maury Microwave
MPI CORPORATION
NATIONAL INSTRUMENTS™
OPTENNI
MYTEK
X microwave
XPEEDIC ACCELERATE YOUR IC DESIGN

IMS
Connecting Minds. Exchanging Ideas.

New!

LOS ANGELES 2020
CONNECTIVITY MATTERS

Technical Lectures at IMS and RFIC 2020!



"FUNDAMENTALS OF PHASED ARRAYS"
Marinos Vouvakis - *University of Massachusetts Amherst*

"QUANTUM COMPUTING: AN RF CONTROL PERSPECTIVE"
Evan Jeffrey - *Google Inc.*

"N-PATH MIXERS AND FILTERS: CONCEPT, THEORY AND APPLICATIONS"
Alyosha Molnar - *Cornell University*

"TRENDS IN AUTOMOTIVE RADARS: WAVEFORM, SYSTEM IMPLEMENTATION, AND IC TECHNOLOGIES"
Cicero Vaucher - *NXP Semiconductors*

"SILICON-BASED MILLIMETER-WAVE PHASED ARRAY DESIGN"
Bodhisatwa Sadhu - *IBM T. J. Watson Research Center*

"UNDERSTANDING OSCILLATOR PHASE NOISE AND LOCKING"
Ali Hajimiri - *Caltech*

"INTUITIVE MICROWAVE FILTER DESIGN WITH EM SIMULATION"
Daniel Swanson - *DGS Associates, LLC*

"TAXONOMY OF RF RECEIVERS: FROM BASICS TO LATEST TECHNIQUES"
Peter Kinget - *Columbia University*

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MTT-S

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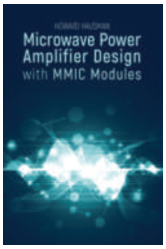

Microwave Power Amplifier Design with MMIC Modules

Howard Hausman

> "Hausman, a microwave engineering consultant and professor of engineering, outlines the theory and technology needed to select, integrate and optimize the design of solid state power amplifiers (SSPAs) using microwave monolithic integrated circuit (MMIC) modules configured on microstrip transmission lines. He explains SSPA applications, configurations, specifications and documentation used to start the product design; microwave design concepts and microwave theory relating to the design of microwave power amplifiers using MMIC modules; the design of power amplifiers using MMIC modules; and the interface of an SSPA with other system components, including issues with DC power supplies, monitoring circuits and electromagnetic interference compatibility."
>
> ***Protoview***

SSPAs are a critical part of many microwave systems. Designing SSPAs with MMICs has boosted device performance to much higher levels focused on PA modules. This cutting-edge book offers engineers practical guidance in selecting the best power amplifier module for a particular application and interfacing the selected module with other power amplifier modules in the system. It also explains how to identify and mitigate peripheral issues concerning the PA modules, SSPAs and microwave systems.

This authoritative volume presents the critical techniques and underpinnings of SSPA design, enabling professionals to optimize device and system performance. Engineers gain the knowledge they need to evaluate the optimum topologies for the design of a chain of microwave devices, including power amplifiers. Additionally, the book addresses the interface between the microwave subsystems and the primary DC power, the control and monitoring circuits and the thermal and EMI paths. Packed with 240 illustrations and over 430 equations, this detailed book provides the practical tools engineers need for their challenging projects in the field.

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FABS and LABS

Ramping up Capacity at BAE Systems

In the spring of 2019, when the ribbon was cut signifying the official grand opening of BAE Systems' Microwave South (MWS) factory in Nashua, N.H., another important milestone in the Ramp 2 Rate initiative was achieved–adding state-of-the-art capability and capacity to an already impressive suite of microelectronic assembly and test automation.

The Ramp 2 Rate initiative spanned over two years, and $100 million of investment in new capital and facilities, expanding BAE Systems' Electronic Warfare Integrated Manufacturing Center (EW-IMC) and Class 100,000 cleanroom footprint, as well as increasing the number of microwave lines from three to 10 in anticipation of the unprecedented growth in demand for the radio frequency electronic warfare product lines.

The new MWS facility added 16,000 square feet of Class 100,000 cleanroom space, bringing the total to nearly 60,000 square feet. The facility is home to two microwave lines dedicated to high volume manufacturing of integrated microwave assemblies (IMA) and contributed significantly to the more than 700 percent growth of complex IMAs completed over the last two years in support of the warfighter.

The state-of-the-art microwave lines in all BAE Systems microwave facilities employ automation for epoxy dispense, bare die pick and place of GaAs and GaN MMICs and other passive components containing air bridges, gold wire and ribbon bonding, as well as inspection and electrical test. Everything is designed to minimize touch times, unit variation, potential for defects, tuning and test times, while improving overall process repeatability and quality.

To meet the demand growth and staff the facilities and capital expansion, as well as ensure that BAE Systems' microelectronics workforce is continually trained to the latest quality standards and operations processes, the company established a Microwave Training Center that resides in MWS. This provides operators access to train on the exact same equipment that they will be using to manufacture BAE Systems' advanced products.

To develop the necessary workforce skills, a few years ago company officials joined forces with Nashua Community College and created the Microelectronics Boot Camp. The 10-week, non-credit course is designed to help people learn the skills needed to work in the advanced manufacturing field. The intensive program teaches students basic military standards and assembly techniques for radio frequency and microwave electronic assemblies.

In addition to providing both compliance and hands-on training to the workforce that assembles, inspects and tests the products, BAE Systems employs teams of technical experts in the process and test engineering disciplines within the product lines to drive continuous improvement activities through a combined approach. While improved capability and scalability were targeted in the microwave expansion, forward-looking re-configurability was also planned to enable flexibility as demand profiles and product mix changes. The ability to shift equipment within product lines or shift entire product lines was built into the facility infrastructure via a grid array of ceiling locations for electrical power and gas connectivity.

The Microwave West renovation in process is planned for completion this year–and leverages the work done in MWS and other prior microwave facility and capital upgrades, resulting in a set of five scalable state-of-the-art, highly automated BAE Systems microwave facilities. BAE Systems is at the forefront of technology and innovation in manufacturing and design of RF/microwave products and able to ramp out quickly to meet new demand and reconfigure for new projects.

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