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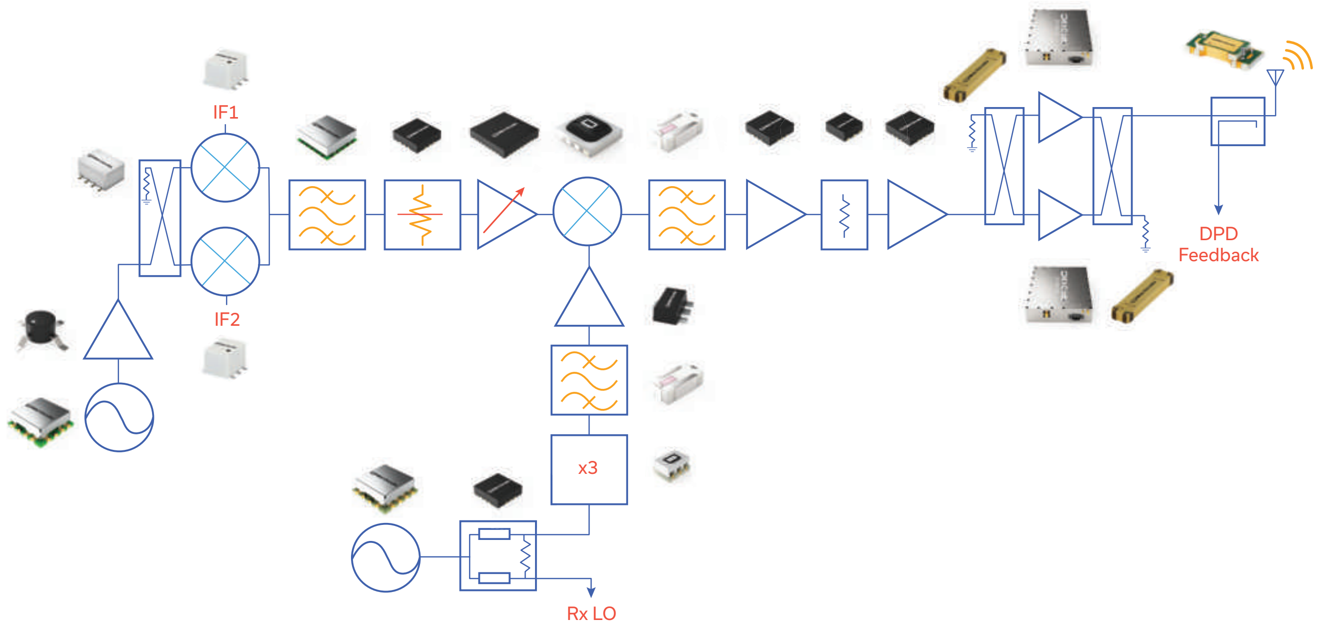

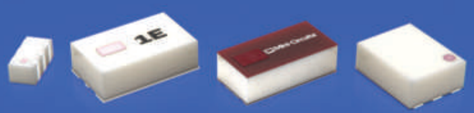

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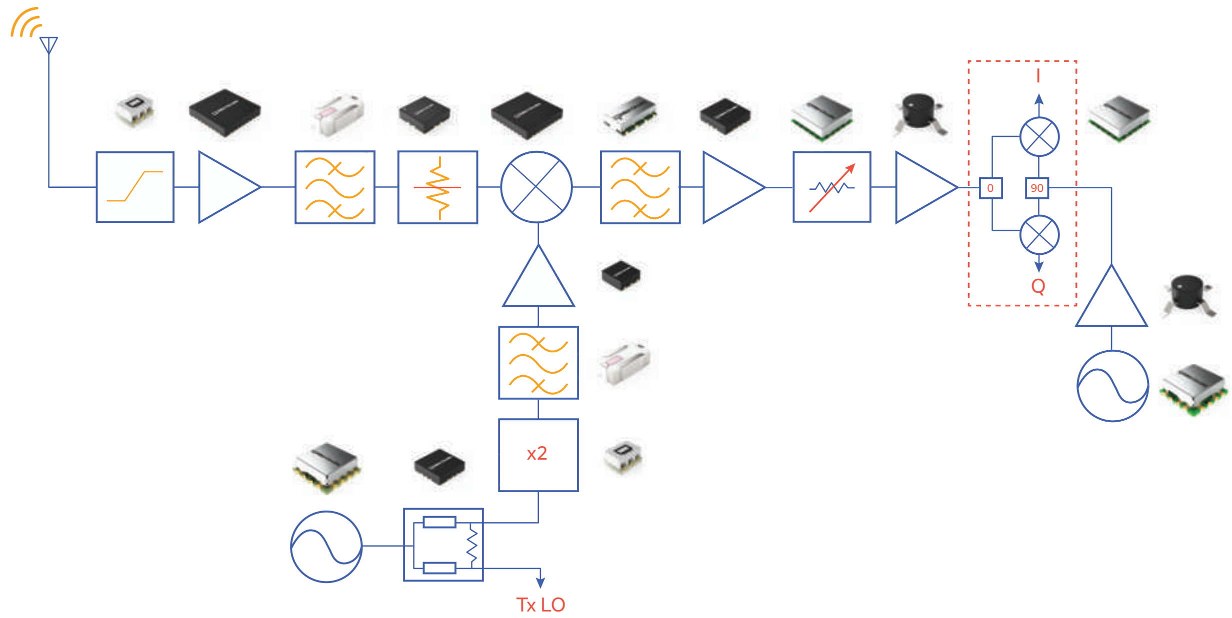

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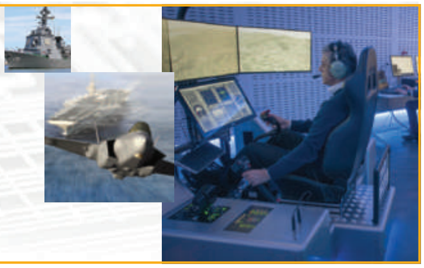

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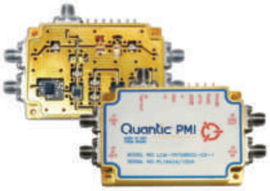

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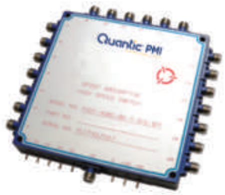

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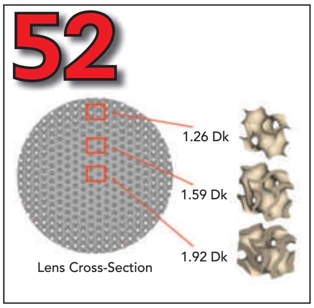

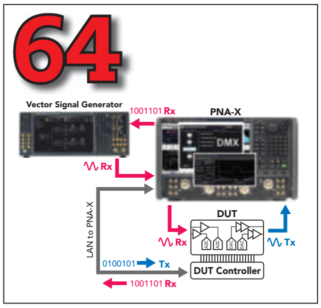

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In the TMYTEK article "Fast, mmWave Over-the-Air Testing," published in the November 2022 issue of Microwave Journal, Figure 1 was created by pSemi.

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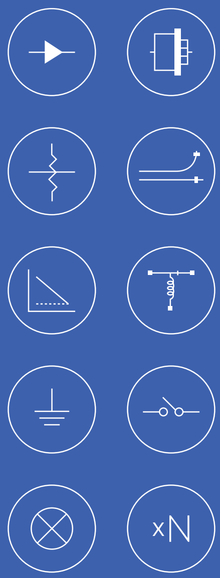

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Celebrating 65 Years

Carl Sheffres
Microwave Journal *Publisher*

This year marks the 65th anniversary of *Microwave Journal* (MWJ). We have seen many changes in that time, as microwave technology has evolved from a little-known electronics niche to a driving force in today's wireless communications. MWJ has evolved as well, expanding its digital offerings to include webinars, video, podcasts, blogs, panels, eBooks, white papers and numerous newsletters. This month we launch our redesigned website, which provides an enormous amount of valuable content in an easier to navigate format.

Live events are gaining traction and nearing their pre-pandemic levels of success. You will find *Microwave Journal* represented at many events this year, as usual, and in force at the major industry gatherings. The IEEE MTT-S International Microwave Symposium (IMS) will take place on 11-16 June at the San Diego Convention Center, and it is shaping up nicely. There are more than 400 companies already signed on to exhibit and attendance is expected to be high due to the attractive location and the large concentration of RF/microwave companies in Southern California. Book your hotel room while supplies last. Registration opens next month for IMS and the co-located and excellent RFIC and ARFTG conferences.

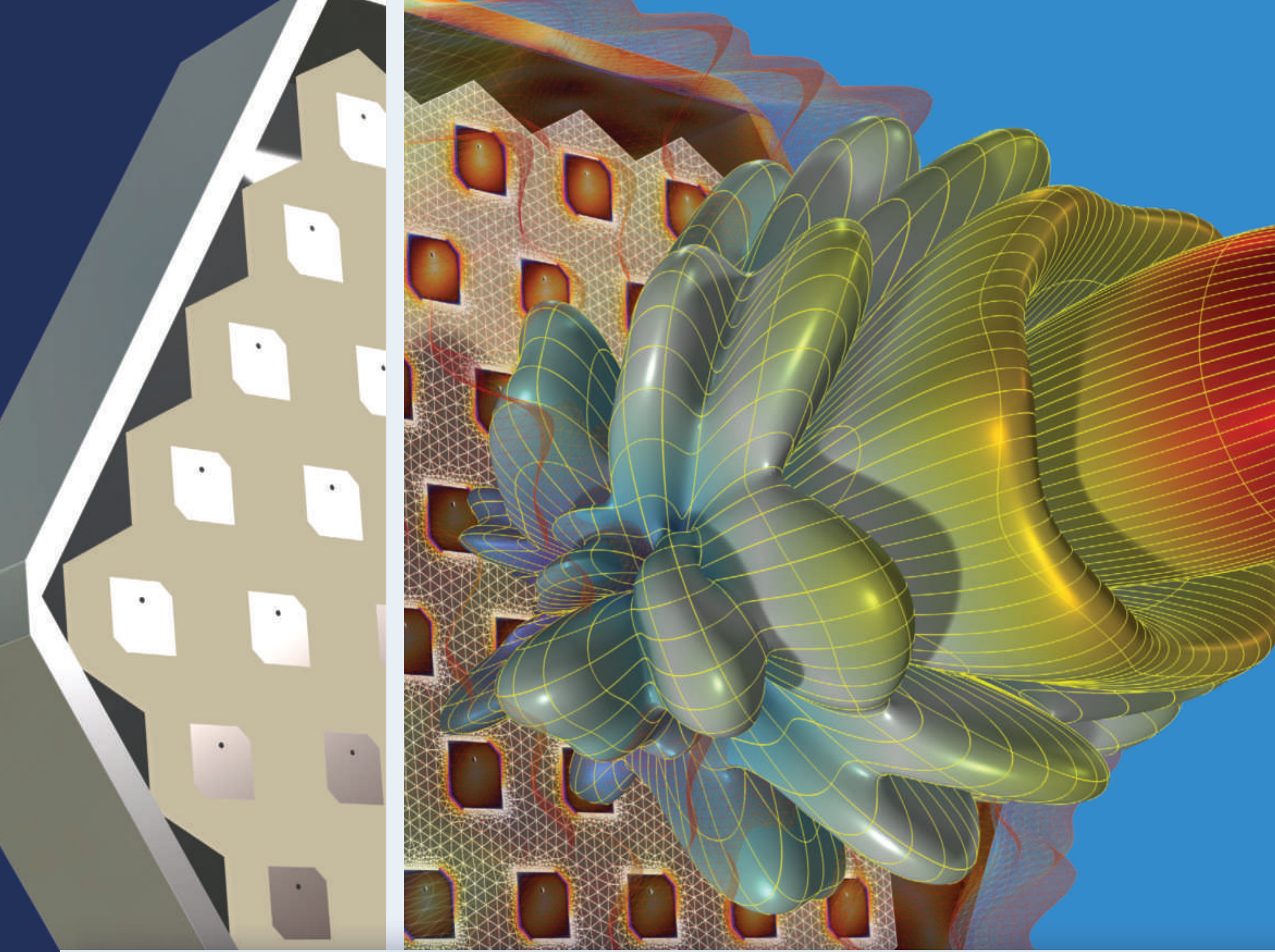
European Microwave Week (EuMW) ventures to a new venue in Berlin, Germany, on 17-22 September. Having attended the delayed EuMW in London last April and the 2022 edition in September in Milan, I found both events to be very worthwhile and truly enjoyed reuniting with our European colleagues. Having never been to Berlin, I am excited to experience that historic and vibrant capital city.

The Electronic Design Innovation Conference (EDI CON) attracted thousands of virtual attendees this past October and will take place every Wednesday in October of this year with dedicated tracks on "Signal Integrity," "5G/WiFi/IoT," "PCB/Interconnect/EMC-EMI" and "Radar/Automotive/SATCOM." The 2022 event featured 44 presentations with 51 speakers including four plenary keynotes, 18 technical sessions and 18 sponsored workshops. You can view all sessions on-demand at www.edicononline.com.

This issue of *Microwave Journal* is focused on our traditional "Radar and Antennas" theme; a fitting way to launch our 65th anniversary year. The cover feature is titled: "Gapwaveguide Technology: A Game Changer for Automotive Radars," provided by experts from Gapwaves. Additional articles this month are contributed by colleagues from Keysight Technologies, Rohde & Schwarz, Fortify and KVG. You will also find the latest news, products and insight from around the globe.

I hope that you enjoy this issue of *Microwave Journal* and take a minute to renew your subscription to ensure that you receive the publication every month this year. When convenient, please also check out our new website and let us know what you think. We are always interested in your input and suggestions on how we can better serve our loyal readers and followers. We may be 65, but we're not retiring any time soon.

Wishing all of you a healthy, happy and prosperous year ahead.



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Gapwaveguide Technology: A Game Changer for Automotive Radars

Carlo Bencivenni, Abolfazl Haddadi, Abbas Vosoogh and Marcus Hasselblad
Gapwaves AB, Göteborg, Sweden

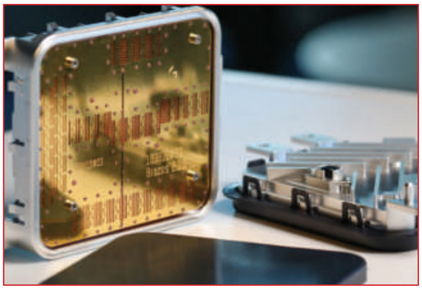
The shift to mmWave frequency bands and the demand for more reliable sensors are putting ever-increasing pressure on automotive radar capabilities, challenging what classical printed circuit board (PCB) antennas can provide. Gapwaveguide technology has established itself as an attractive solution by offering excellent performance and advanced features at a competitive price (see ***Figure 1****). This article gives an overview of the range of applications, solutions and relevant aspects of how this unique technology is enabling large and small players to make cost-effective high performance automotive radar a reality. An insight is given into the technical as well as the industrialization aspects.*

Despite the technical challenges, the microwave industry has constantly reached out to higher frequencies. On the one hand, motivations are connected to necessities, such as the congestion of the already exploited spectrum, as well as to advantages, such as larger bandwidth and smaller form factors. On the other hand, the obstacles have always been the lower performance of the circuitry and less favorable propagating conditions. Recently, modern telecommunication and radar systems have moved well into the mmWave frequency bands. While this fits within this larger trend and evolution, it is a significant leap that presents considerable challenges. As a result, the technology is pushing an evolution to several established solutions in the industry, from signal processing to hardware.

When it comes to RF distribution and radiation, planar solutions based on PCB technology have often been the preferred choice, offering adequate performance for most applications at low cost with simple integration. This has also been the case for automotive radar in previous lower frequency bands and the first generations of the new 77 GHz band. However, at mmWave frequencies, issues such as low bandwidth, high losses and expensive RF substrates become significant and the perceived PCB limitations create opportunities for other technologies. Some of the alternative candidate technologies include traditional waveguides, substrate integrated waveguides (SIW), low temperature co-fired ceramics (LTCC) and lens antennas.

AUTOMOTIVE RADAR APPLICATIONS

Automotive radars have completed the migration to the 76 to 81 GHz band, now also mandated by international regulatory bodies.[1] The main benefits are more accurate distance measurement due



▲ **Fig. 1** **Automotive imaging radar antenna with housing.**

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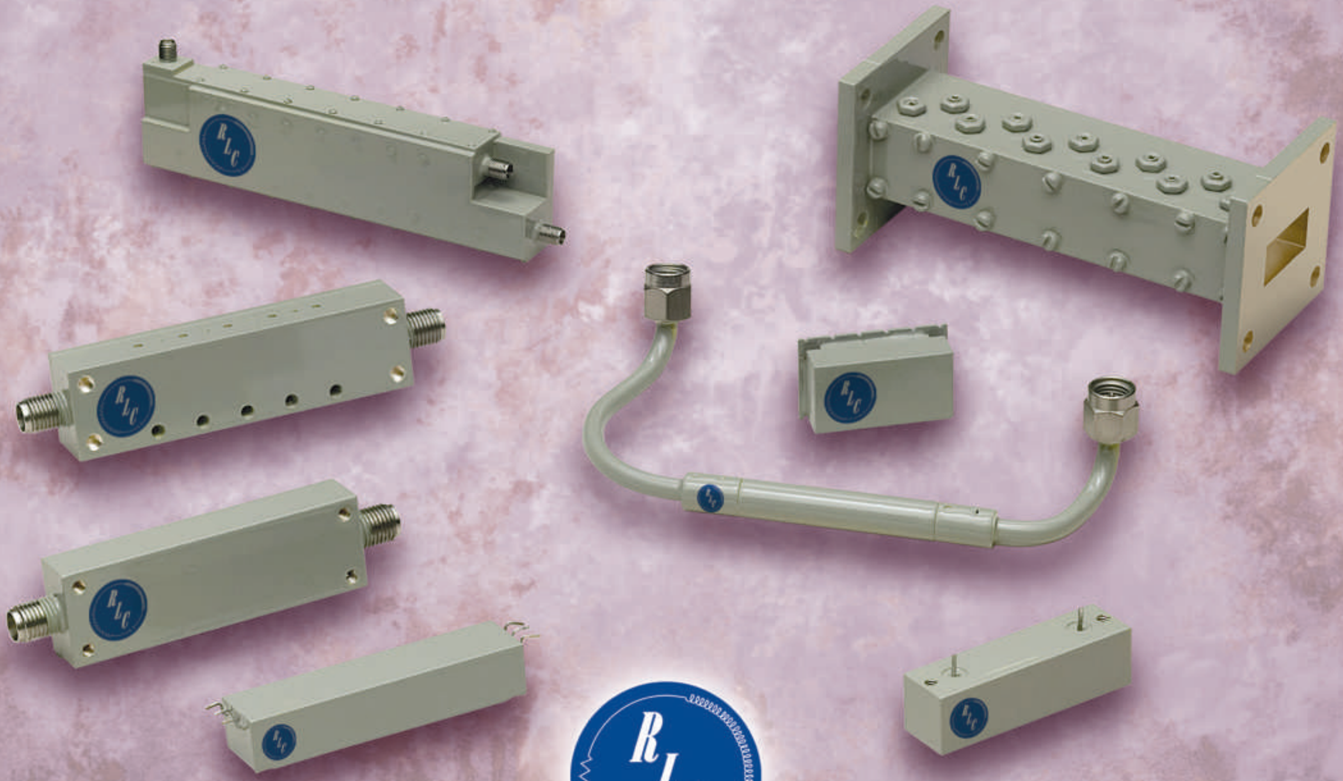

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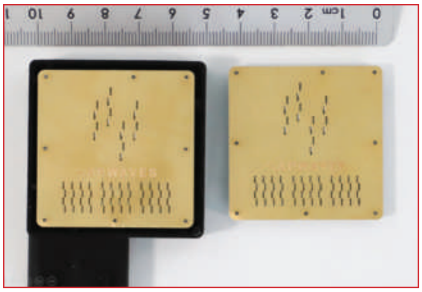

Fig. 2 Compact and low cost corner radar antennas for ADAS.

to the wider band and the easier integration of sensors on the car due to size reduction. Meanwhile, the increasing functionalities of advanced driver assistance systems (ADAS) and the rise of autonomous driving (AD) demand more capable and accurate sensors. Together with the other onboard sensors, such as cameras and lidars, radars are expected to continue having a significant role thanks to their low-cost and all-weather operation. However, to do so, radars must keep improving their performance while continuing to meet strict cost, size, thermal and reliability requirements.

To reach an accurate and complete perception of the vehicle's surroundings, multiple radar sensor types exist.[2] In ADAS applications, one often distinguishes between short-, mid- and long-range radars, based on the distance and field of view (FoV) needed for the corresponding functions, such as blind spot detection, lane change assist and forward collision warning, respectively. These sensors are specialized and increasingly ubiquitous, with massive volumes captured by a few large TIER-1 suppliers. They typically have between eight to 16 channels in a compact form factor and cost is a key factor (see ***Figure 2***). The main performance challenge here is reaching the desired range and FoV. On the opposite end of the spectrum are the more powerful and flexible high-resolution sensors, used for example in AD systems. They are also referred to as imaging radars (see Figure 1) due to their ability to provide camera/lidar-like perception through high resolution. These more advanced and premium sensors, with 30 to 100 channels, target a young market with multiple players and smaller volumes. The main performance challenges are to realize low loss routing and complex large antennas with a massive number of channels. Clearly, the wide range of sensor types means a correspondingly broad range of priorities and optimal solutions that shall be addressed.

GAPWAVEGUIDE TECHNOLOGY

Traditional waveguides are one of the earliest and best performing RF technologies, but bulkiness and high cost have limited them to niche high-end applications, such as satellite and military. With the miniaturization at mmWave frequency bands, only cost remains as a major obstacle even more so since tolerances become increasingly stringent. In fact, one of the most challenging and costly manufacturing aspects is ensuring an accurate fit between parts. For this reason, high precision aluminum milling and many screws are typically used. More scalable solutions exist, such as dip brazing, soldering and 3D printing, however they remain expensive and technically demanding, so not suitable for mass production.

Meanwhile, gapwaveguide technology has risen as a solution to reach the same performance in a robust and cost-effective way.[3] In the most typical implementation, an equivalent transmission line can be obtained simply by replacing the waveguide side walls with an artificial magnetic conductor (AMC) texture, typically in the form of periodic posts of appropriate dimensions. Then, even in the presence of mating defects in the manufacturing or assembly of the parts, the fields remain well confined in the waveguide channel, unlike traditional hollow waveguides which instead suffer a field breakdown, as shown in ***Figure 3***. In theory, gapwaveguide technology works for gaps up to a quarter of wavelength, 0.9 mm (about 0.04 in) at E-Band, but it is used to relax tolerances and thus lower the cost.

GAPWAVES AUTOMOTIVE SOLUTIONS

Back in 2018, amid initial skepticism in the industry on waveguide solutions, Gapwaves released an automotive reference antenna,[4] shown in ***Figure 4***. Rather than an

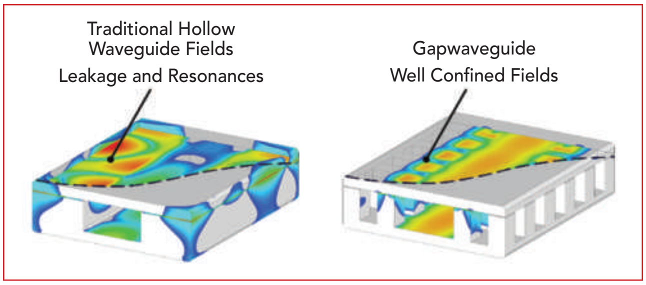

Fig. 3 **With small assembly defects, the fields in a standard waveguide can break down (left) while a gapwaveguide operates as designed (right).**

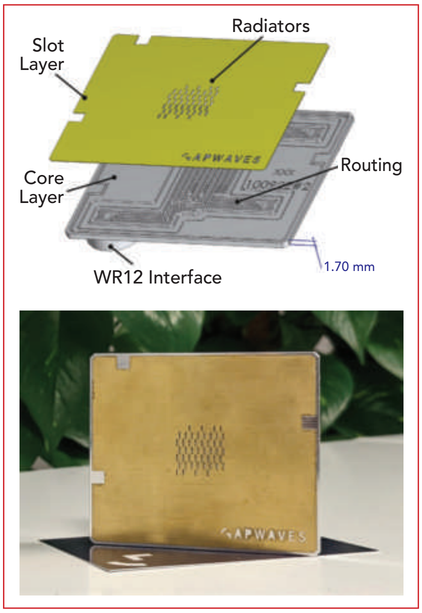

Fig. 4 **Gapwaves automotive reference antenna fabricated and assembled (bottom); exploded view (top).**

actual product, the purpose was to allow customers' engineering teams a quick firsthand evaluation of some key capabilities through standard WR12 interfaces. From a form factor point of view, the design sported a minimalistic 1.5 layers (one core layer and a flat 2D metal one), sub 2 mm (about 0.08 in.) thickness and assembly by non-conductive glue. Performance-wise, the six channels supported the full 76 to 81 GHz band, half-wavelength spacing, narrow elevation coverage and wide and moderate in azimuth plane, using a series slotted waveguide end-fed design and optional grouping. Interestingly, despite being such an early demonstrator, several of these aspects have not yet been matched by competing technologies.

Today, Gapwaves offers a range of technical and manufacturing solutions to best address nimble mass-volume corner sensors as well as large premium imaging radars. One of the advantages of this technology is the flexibility in manufacturing and functionality. While each application has diverse needs, the main benefits are typically linked to RF performance improvement, sensor size reduction and advanced functionalities such as thermal handling and EMC shielding.

RADAR PERFORMANCE

The main RF performance benefits are three-fold: powerful pattern control, wideband operation and high efficiency. Waveguide antennas can achieve remarkably well both very wide and focused patterns, as well as shaped ones. Vertically aligned resonant series-fed slotted waveguide antennas are an ideal building block due to their flexibility, simplicity and low profile.[5] They have naturally very wide and stable radiation patterns in the horizontal E-plane (as shown in ***Figure 5a***), beyond that of patch antennas, and enable easy control in elevation by their length and number of slots. This is ideal for short-range radars where a large azimuth FoV is critical and spacing down to half-lambda is often needed. For applications that require focusing on the azimuth plane, such as for maximum range in long-range radars, columns grouping or hard surfaces are used. Shaped beams, such as in corner radar where the direction of the maximum range is at about 40 degrees, can be obtained by careful phase and amplitude control.

When it comes to operational bandwidth, unlike PCB patch solutions, waveguides can easily support the full 76 to 81 GHz automotive band. This gives flexibility in frequency allocation and more accurate distance measurement. For this purpose, both impedance and, more importantly, radiation patterns must be well-behaved, which is more challenging the narrower the beamwidth. ***Figure 5b*** shows the pattern response across the full band of a long antenna with a beamwidth of 10 degrees.

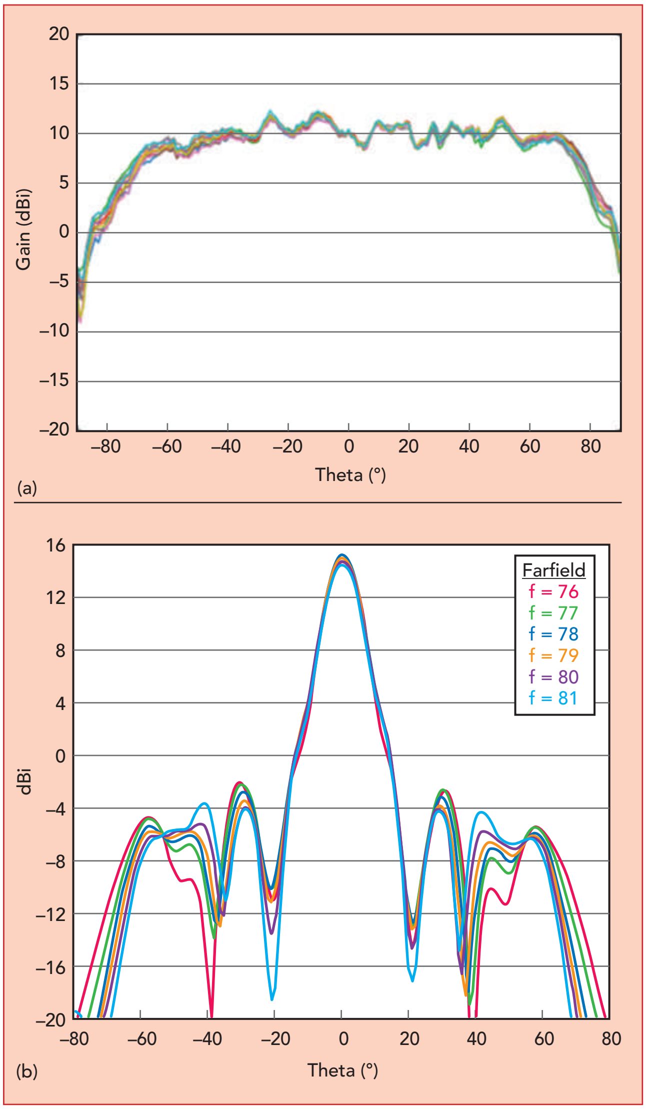

Fig. 5 **Wide and consistent azimuth radiation patterns of eight samples (a) and narrow elevation patterns across 76-81 GHz (b).**

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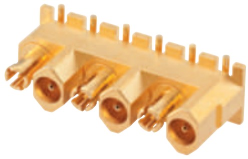

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High efficiency is the most well-known advantage of the technology. At the antenna level, losses are the most negligible even for high gain elements. When it comes to routing, typical losses at E-Band are around 0.01 to 0.02 dB/mm (0.25 to 0.5 dB/in.) depending on the design and material characteristics, about an order of magnitude lower than typical microstrip solutions. This is particularly beneficial for large and multi-layer sensors such as imaging radars, as shown in ***Figure 6***, where the antenna size and layout may require tens of centimeters long routing lines, including crossovers. Of course, designing and manufacturing large sensors with several channels is a challenge.

INTEGRATION

Waveguide antennas enable sensor size reduction with respect to PCB counterparts. The antenna is located above the PCB with a clearance to host components underneath. This frees the area otherwise occupied by the antennas and removes any component influence on the radiation characteristics. However, a simple, robust and high performance integration is a key aspect since the entirety of the electronics live on the PCB and within the sensor assembly. Consequently, a portfolio of readily available transitions for a wide range of feeding configurations and substrates, from high- to low-end ones have been designed. Most typical solutions have simple via-less PCB designs and losses in the lower part of a dB, as shown in ***Figure 7a***. Alternatively, drop-in launcher-in-package interfaces are available for the main chip manufacturers, as shown in ***Figure 7b***. These unique chips inject the signal directly into the antenna with integrated launchers, entirely bypassing the PCB.[6] This further reduces the losses and completely removes the need for the RF substrate. In all of these cases, gapwaveguide technology is used to allow a robust interface where no electrical contact is needed between the antenna and the PCB and hundreds of microns in tolerances in all directions are supported.

Moreover, waveguide integration can provide additional functionalities. Often RF systems are thermally limited, due to the low power efficiency of high frequency electronics, compact dimensions and typical high temperature environments. Thus, the thermal design aspects are often critical and challenging to overcome. In those cases, the antenna body can offer an additional heat dissipation path by using thermally conductive materials in direct contact with the electronics. Another challenging aspect in sensors is electromagnetic compatibility (EMC), where the device must not infringe regulations on radiated out-of-band emissions. Again, an antenna made of electrically conductive material can suppress the emission by closely surrounding the critical part of the circuitry and shielding them. ***Figure 8*** shows a die cast metal antenna layer that serves both of these functions in addition to the electrical ones: the protruding square area at the cen-

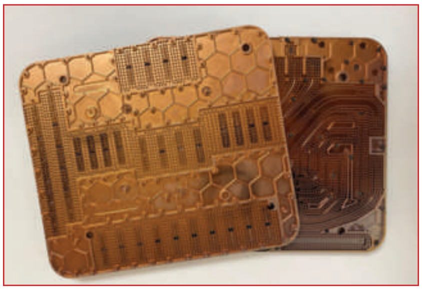


Fig. 6 Imaging radar antenna showing long and complex routing.

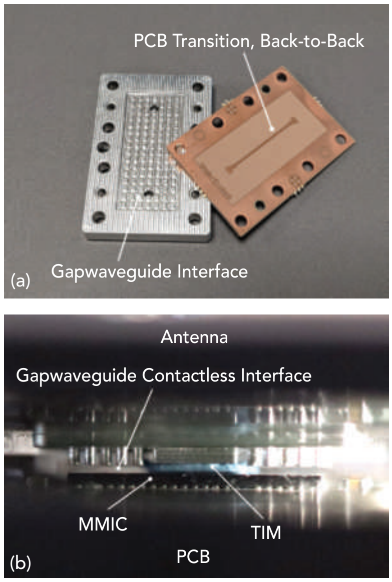
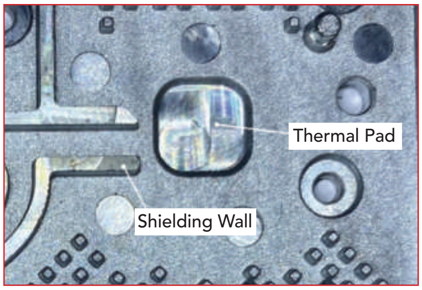


Fig. 7 Gapwaves antenna interface to a PCB (a) and direct launch-in-package (b).



▲ Fig. 8 Using metallic layers improves the thermal and EMC performance of the radar sensor.

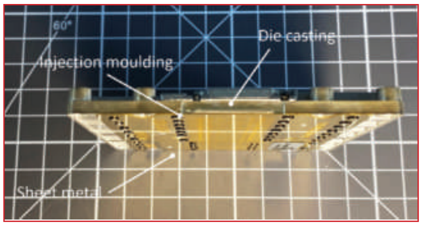
ter is offering a thermal connection to the active component while the surrounding walls improve the EMC shielding.

MANUFACTURING AND SUPPLY

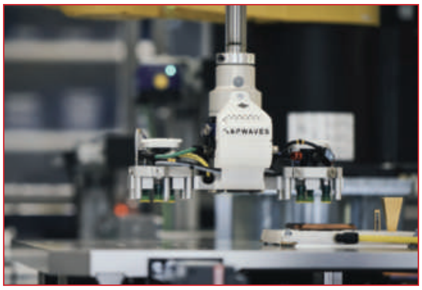
Gapwaves has developed a variety of manufacturing processes. Low volume prototyping is mostly handled by metal or plastic CNC machining, due to its speed and accuracy. This has proved to be a sensible first verification and a reliable benchmark for the actual parts which have greater lead times and deviations. For high volume production, Gapwaves currently employs three main processes: plastic injection molding, metal die casting and sheet metal stamping.

Plastic injection molding produces complex, lightweight parts and is often the first choice for automotive applications. Non-conductive plastic parts are then coated with a thin metal layer, typically copper by physical vapor deposition for the best performance to cost ratio. Alternatively, die casting can be used to produce bulk aluminum or zinc parts. This solution offers superior thermal and EMC handling and greater flexibility on some geometries. Finally, sheet metal manufacturing produces accurate thin 2D parts. Unlike other processes, this is cost-effective both at low and high volume by choosing between laser cutting, chemical etching or stamping. For this reason, it is often preferred for simple parts since it lowers the cost with respect to a fully 3D product. Given the differences between each process, it is important to choose the best one according to the application. Moreover, it is quite common to combine them, for example, metal casting close to the electronics, molding for other 3D parts and sheet metal for simple layers such as the radiating one, as shown in ***Figure 9***.

When it comes to the supply chain, Gapwaves has partnered globally to manufacture its parts in the most flexible and cost-effective way. For low to mid volumes, antennas can be delivered directly from Gapwaves facilities, while for large volumes, partners are extensively used. Gapwaves's philosophy is to team up with large and established suppliers for volume scaling and expertise in cost-effective manufacturing. The company leverages its expertise in manufacturability by assisting partners in getting the critical dimensions correct for proper performance. The company has also developed the required equipment for the non-readily available processes needed to transform loose parts into a complete antenna, such as assembly and test.



▲ Fig. 9 Antenna fabricated using multiple volume manufacturing processes.



▲ Fig. 10 Gapwaves rapid inline antenna test system.

RELIABILITY AND TESTING

As with any technology in a new market, building a reputation of maturity is crucial. For this reason, extensive testing and qualification are desired for ensuring defect-free manufacturing and reliable field operation. Interestingly, unlike PCB-based antennas, waveguides enable easy and direct testing with their accessible interface. Measuring early at the antenna level has the advantage of unambiguously tacking its performance and catching faulty units without scrapping the entire assembled sensors. Seeing this upcoming need and opportunity, Gapwaves has developed an inline test system for the production lines as shown in ***Figure 10***. The system is fast and flexible, measuring any type of antenna in a few seconds.

Reliability is an aspect of paramount importance. The automotive industry typically requires demanding environmental standards, including harsh temperature, humidity, shock and vibration tests. These products have been fully qualified to automotive standards, such as IEC60068-2, and perform tailored qualifications at the customer's request. The ruggedness of a product is the result of several design and manufacturing aspects and is challenging to master. Over the years the company has developed strong expertise to support customers and supply partners.

CONCLUSION

Gapwaves' unique waveguide technology offers automotive radars unprecedented performance capabilities. Thanks to the robustness and relaxed manufacturing tolerance, advanced antennas are now a reality for low-cost, mass-volume markets. Some of the key benefits are powerful pattern control, full band support, minimal losses as well as sensor size reduction, thermal dissipation and EMC shielding. Moreover, leveraging the technology's flexibility, a wide range of building practices and manufacturing processes are available for every application and volume. From nimble mass-volume to complex premium sensors, gapwaveguide technology offers superior tailored solutions. These benefits enable any radar sensor to improve performance and help sensor manufacturers to meet the demands required by modern driver assist and autonomous systems. ■

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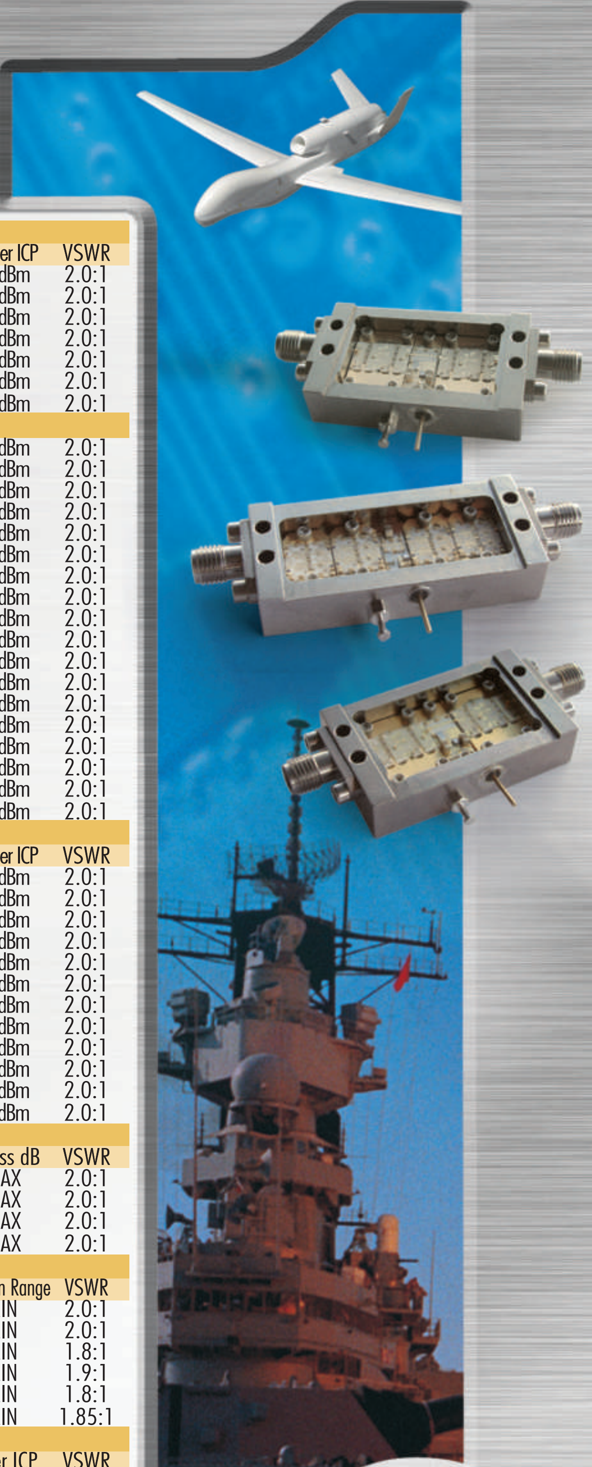

OCTAVE BAND LOW NOISE AMPLIFIERS

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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Pentagon Debuts its New Stealth Bomber, the B-21 Raider

America's newest nuclear stealth bomber made its debut after years of secret development and as part of the Pentagon's answer to rising concerns over a future conflict with China.

The B-21 Raider is the first new American bomber aircraft in more than 30 years. Almost every aspect of the program is classified.

As evening fell over the Air Force's Plant 42 in Palmdale, the public got its first glimpse of the Raider in a tightly controlled ceremony. It started with a flyover of the three bombers still in service: the B-52 Stratofortress, the B-1 Lancer and the B-2 Spirit. Then the hangar doors slowly opened and the B-21 was towed partially out of the building.

The B-21 is part of the Pentagon's efforts to modernize all three legs of its nuclear triad, which includes silo-launched nuclear ballistic missiles and submarine-launched warheads, as it shifts from the counterterrorism campaigns of recent decades to meet China's rapid military modernization.

China is on track to have 1500 nuclear weapons by 2035, and its gains in hypersonics, cyber warfare and space capabilities present "the most consequential and systemic challenge to U.S. national security and the free and open international system," the Pentagon said in its annual China report.

"We needed a new bomber for the 21st Century that would allow us to take on much more complicated threats, like the threats that we fear we would one day face from China, Russia," said Deborah Lee James, the Air Force secretary when the Raider contract was announced in 2015.

While the Raider may resemble the B-2, once you get inside, the similarities stop, said Kathy Warden, chief executive of Northrop Grumman Corp., which is building the bomber.

"The way it operates internally is extremely advanced compared to the B-2, because the technology has evolved so much in terms of the computing capability that we can now embed in the software of the B-21," Warden said.

Other changes include advanced materials used in

B-21 (Source: AP Photo/Marcio Jose Sanchez)

coatings to make the bomber harder to detect, Austin said. "Fifty years of advances in low-observable technology have gone into this aircraft," Defense Secretary Lloyd Austin said. "Even the most sophisticated air defense systems will struggle to detect a B-21 in the sky."

Other advances likely include new ways to control electronic emissions, so the bomber could spoof adversary radars and disguise itself as another object, and use of new propulsion technologies, several defense analysts said. "It is incredibly low observability," Warden said. "You'll hear it, but you really won't see it."

Six Raiders are in production. The Air Force plans to build 100 that can deploy either as nuclear weapons or conventional bombs and can be used with or without a human crew. Both the Air Force and Northrop also point to the Raider's relatively quick development: The bomber went from contract award to debut in seven years. Other new fighter and ship programs have taken decades.

Raytheon Intelligence & Space Demos Multidomain Advanced Tactical Comms

Raytheon BBN, a subsidiary of Raytheon Technologies, recently showcased its Robust Information Provisioning Layer (RIPL) solution during an Air Force Research Laboratory exercise at their Stockbridge Test Site in Rome, N.Y.

During the exercise, the RIPL system allowed seamless and secure access to content for all users in the network, ensuring users received only what they requested and what they were authorized to see. By combining advances in artificial intelligence and machine learning with advanced disruption tolerance protocols, RIPL was able to overcome the type of limited and intermittent connectivity expected in contested environments, rapidly getting critical content to those who needed it.

Brian Holmes, program manager, AFRL Advanced Planning and Autonomous C2 Systems Branch, said the demonstration, which included three of the four mission divisions with AFRL/RI and two geographically separated locations was "executed flawlessly."

BBN's RIPL technology was successfully used to enable secure multidomain interoperability and information dissemination at the tactical edge. It was demonstrated using multiple waveforms and hardware platforms, as well as numerous data formats with both real and emulated components.

RIPL enables the Air Force Combat Cloud vision, which in turn will be a key enabler of the U.S. Air Force's Advanced Battle Management System and the Department of Defense's Joint All Domain Command and Control vision.

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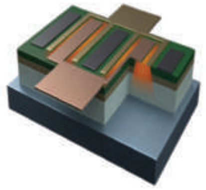
Cranking the Power on Radar Capabilities

Military and civilian uses for radar range broadly, and the possibilities for radar applications expand almost every day. Whether they are being used to navigate, control air traffic, track weather patterns, carry out search-and-rescue missions, map terrain or countless other functions, radar technologies are constantly advancing.

As RF systems, radar capabilities hinge on the ability to sense and communicate across long distances while maintaining signal strength. Powerful RF signal capabilities extend mission-critical communications and situational awareness, but the microelectronic technologies that strengthen RF output—specifically, high power density transistors—must overcome thermal limitations to operate reliably and at significantly higher capacity.

DARPA looks to build on previous success in RF power output with its new transistor-focused THREADS program. THREADS aims to overcome the thermal limits inherent to internal circuitry operations in general, and to critical power-amplifying functions specifically. Today, RF systems operate well below the limits of electronic capacity simply because the transistors, the basic building blocks of RF amplifiers, get too hot. With new materials and approaches to diffusing the heat that degrades performance and mission life, THREADS targets thermal management challenges at the transistor level.


Transistor (Source: DARPA)

Central to this effort will be reducing the thermal resistance involved in dissipating internal heat without degrading performance or increasing the footprint of the transistors key to advancing radar capabilities. To that end, the work under THREADS in overcoming thermal limits can help realize robust, high power density transistors that operate near their fundamental electronic limit—achieving new levels in amplifying RF output power.

"Wide bandgap transistors, such as GaN, were developed specifically to improve output density in power amplifiers—and GaN does provide a greater than 5x improvement compared to previous-generation transistor technology. We also know that a further order-of-magnitude increase in power output is possible in GaN, but it cannot be realized in sustained operation today due to excessive waste heat," said Thomas Kazior, DARPA program manager for THREADS. "If we can relax the heat problem, we can crank up the amplifier and increase the range of radar. If the program is successful, we're looking at increasing the range of radar by a factor of 2x to 3x."

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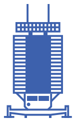
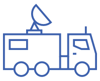


Long-Range Surveillance

Battlefield Management



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What Is the Status of 5G and What Can We Expect From 6G in the Future?

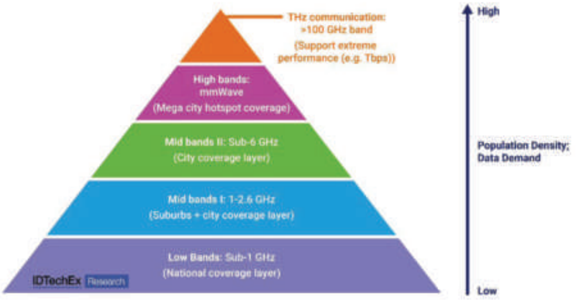
Adding a new spectrum is key to each new generation of telecommunications. The two new frequency bands in 5G are sub-6 GHz (3.5 to 7 GHz) and mmWave (24 to 71 GHz). The initial wave of 6G development looks at expanding the spectrum to the THz area, with a special focus on the sub-THz range (100 to 300 GHz).

The advantages of going up to a higher frequency band are obvious: substantial bandwidth (translating to large data throughput) and extremely low latency. These two key benefits enable the exploration of new applications that past generations of telecommunications were unable to explore. Nonetheless, severe signal attenuation when encountering obstacles, such as raindrops or walls, is a crucial bottleneck in the high frequency spectrum.

The characteristics of different frequency bands will lead to drastically different deployment strategies. The foundation of mobile networks will still be based on low and mid bands I. On the other hand, higher bands will be deployed in regions with high population densities. For instance, the sub-6 GHz band is largely deployed for cities, where the majority of mmWave deployment is limited to population-dense venues such as stadiums and metro stations.

IDTechEx has examined the global 5G commercial and precommercial services by frequency. According to their findings, sub-6 GHz frequency bands dominate more than 50 percent of 5G services. Another 38 percent is based on the low and mid bands I, while mmWave accounts for just 9 percent. Sub-6 GHz frequency ranges are more desirable for deployment for 1) a better balance of coverage and capacity and 2) proximity to 4G frequency bands. It is not surprising that mmWave accounts for only 10 percent of the global 5G service deployment, given how economically unviable it would be to deploy mmWave at a large scale for public networks.

5G is recognized as an important infrastructure for both developed and developing countries. As of September 2022, 98 nations have commercialized 5G or are conducting 5G trials, compared to 79 at the end of 2021. The majority of countries deploy 5G sub-6 GHz frequency bands, and only a few countries, including the U.S., South Korea, Japan, Italy, Australia, South Africa, etc., have commercialized 5G mmWave.



"Frequency Bands" (Source: IDTechEx)

Though 5G is commercialized, there is still a lot of ongoing technical development. In addition, 6G research has already started. IDTechEx discusses the five key points regarding technical development in 5G and 6G: Power management for sub-6 GHz MIMO radio, smart electromagnetic environment and small cell deployment, Open RAN development, mmWave development and 6G development.

LoRa Alliance® Expands Certification Program to Include SCHC over LoRaWAN® Enabling IPv6 Solutions

The LoRa Alliance, the global association of companies backing the open LoRaWAN® standard for IoT low-power wide-area networks, announced that LoRaWAN certification is now available for end-devices using static context header compression (SCHC). Certification is based on the LoRa Alliance technical specifications for IPv6 published last May, which enable the deployment of IPv6 over LoRaWAN solutions.

As previously announced, the first applications to leverage SCHC for IPv6 over LoRaWAN are smart metering and IoT applications in the smart grid, just two of many applications requiring the use of IPv6-based standards. Solutions using LoRaWAN for metering include proactive consumption monitoring, leak detection warnings and automatic shutoffs and solutions for balancing electricity supply and demand. Easy and cost-effective to deploy, LoRaWAN is ideal for identifying and managing unmeasured losses, which currently reach into the billions of dollars each year, in addition to helping to conserve energy. Similar benefits can be realized for water and gas metering, with LoRaWAN CertifiedCM devices communicating over open standards enabling scale to address these growing markets.

> **Drives digital industrialization across a wide variety of new markets and applications, enabling massive IoT.**

"As deployments continue to grow to the tens or hundreds of millions of devices, the importance of using open standards has never been greater," said Donna Moore, CEO and chairwoman of the LoRa Alliance. "Certifying IPv6 over LoRaWAN for end-devices gives

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end users the level of certainty needed to deploy and benefit from IP-based solutions. With vendors now able to certify LoRaWAN end-devices using SCHC, customers can confidently commit to massive utilities deployments. This will further drive digital industrialization across a wide variety of new markets and applications, which will in turn enable massive IoT."

Bluetooth SIG Targets 6 GHz Frequency Band

The Bluetooth Special Interest Group (SIG), the trade association that oversees Bluetooth® technology, announced a new specification development project to define the operation of Bluetooth Low Energy (BLE) in additional unlicensed mid band spectrum, including the 6 GHz frequency band. With over 5 billion products shipping each year, Bluetooth technology is the most widely deployed wireless standard in the world. A core reason for its unmatched adoption and success is the continual evolution of the technology in key areas, including higher data throughput, lower latency and greater positioning accuracy. The new spectrum expansion project will help ensure that these Bluetooth performance enhancements can continue well into the future.

> New specification defines BLE operation in unlicensed mid-band spectrum.

"Over the last 20 years, Bluetooth technology has made our lives more productive, safer, healthier, and joyful," said Mark Powell, CEO of the Bluetooth SIG. "The Bluetooth SIG community is constantly evolving the technology to meet ever expanding market demands for wireless communications. Expanding into the 6 GHz spectrum band will ensure the community can continue to make the enhancements necessary to pave the way for the next 20 years of Bluetooth innovation."

"The global allocation of additional spectrum for unlicensed use is vital to ensuring that wireless technologies can continue to meet growing connectivity demands," said Kevin Robinson, president and CEO of Wi-Fi Alliance. "Designating 6 GHz for unlicensed use creates a valuable spectrum resource that is recognized globally for its ability to bring tremendous socioeconomic benefits. Wi-Fi Alliance looks forward to collaborating with the Bluetooth SIG to ensure our successful co-existence in the band."

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GaN MMIC's to 40W

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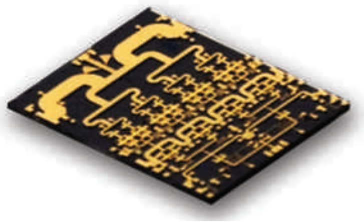

Packaged MMICs to 35W

Nxbeam offers its Ka-band MMICs in leaded flange packages for easier system integration

PRODUCTS:
NPA2001-FL
NPA2002-FL
NPA2003-FL
NPA2030-FL

Module Products to 60W

For higher levels of power and integration, Nxbeam offers modules that combine multiple Nxbeam MMICs to achieve higher performance in an easy-to-use form factor. Custom designs available

PRODUCTS:
NPM2001-KW
NPM2002-KW
NPM2003-KW

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Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Infinite Electronics Inc., a global supplier of electronic components serving the needs of customers through a family of highly recognized and trusted brands, has announced that it signed a definitive agreement to acquire **Cable Connectivity Group (CCG)** from **Torqx Capital Partners** and **TKH Group NV**. The transaction is subject to customary regulatory approval and is expected to close in Q1 2023. CCG is a leader in the production, distribution and assembly of specialty cables and cable connectivity solutions. The company operates across Europe with offices and production and distribution facilities in the Netherlands, Belgium, Germany, Poland, Italy and China.

COLLABORATIONS

Anokiwave Inc., an innovative company providing highly integrated Si ICs for mmWave ICs, and **MilliBox**, a mmWave test setup manufacturer, announced a collaboration to facilitate development of a unique and efficient over-the-air test capability for mmWave phased array antennas that provides an accurate high volume test capability. mmWave active antennas are an integral part of the emerging mmWave 5G and satcom communications systems.

ipoque GmbH, a **Rohde & Schwarz** company, announced that its cutting-edge deep packet inspection engine, R&S®PACE 2, has been selected by **BBT.live**, an Israel-based provider of enterprise-grade software-defined connectivity solutions. The collaboration between both companies will enable real-time, advanced traffic insights for BBT.live's suite of cloud-based solutions powering service providers' SDx services such as SD-WAN. ipoque's R&S®PACE 2 will be deployed in BBT.live's BeBroadband™ Edge software, the first-of-its-kind software-defined, cloud-based solution for secure network connectivity. BeBroadband™ offers service providers a highly flexible, hardware-agnostic platform that connects customers' branch offices, data centers, campuses and headquarters.

STMicroelectronics, a global semiconductor leader serving customers across the spectrum of electronics applications, and Soitec (Euronext Paris), a leader in designing and manufacturing innovative semiconductor materials, announced the next stage of their cooperation on Silicon Carbide (SiC) substrates, with the qualification of Soitec's SiC substrate technology by ST planned over the next 18 months. The goal of this cooperation is the adoption by ST of Soitec's SmartSiC™ technology for its future 200 mm substrate manufacturing, feeding its devices and modules manufacturing business, with volume production expected in the mid-term.

NEW STARTS

Pharrowtech, a growing market leader in mmWave solutions for next-generation wireless applications, has opened its first U.K. design center in the Thames Valley area. The U.K. office will be led by Dr. Mehul (Micky) Mehta and will help bolster the company's resources and talent pool as it grows its product offering. Pharrowtech's Leuven office has moved to Philipssite to accommodate the company's growing team and operations. It boasts a new state-of-the-art mmWave laboratory with the latest equipment, including the most advanced mmWave network analyzer technology, several anechoic chambers and chip characterization and qualification setups. The opening of Pharrowtech's U.K. office and the move to a new headquarter office in Belgium quadruples the company's office and lab capabilities.

ACHIEVEMENTS

Taking note of **Dr. Ulrich L. Rohde**'s outstanding contributions to engineering and also his dynamic leadership in the engineering domain that have contributed for the faster development of India, the **Indian National Academy of Engineering (INAE) Council** elected Dr. Rohde as a fellow of the INAE at its recent meeting under the special provision of Rule 37(g). Dr. Rohde is only the third foreign fellow elected by the INAE, Professor David Jeffery Wineland and Philip Knight were the only others. The INAE was established in 1987 and is a "peer" body of distinguished engineers and technologists.

MegaPhase has achieved AS9100 certification, the gold standard in aerospace industry suppliers. Based on ISO 9001 standards for implementing a quality management system, the AS9100 standard goes further and includes additional requirements and regulatory measures to ensure suppliers produce traceable, high-quality components for their customers' most critical applications.

Qorvo® has received the 2022 award for Most Respected Public Semiconductor Company in its category by the Global Semiconductor Alliance (GSA). GSA recognizes semiconductor companies that demonstrate excellence through their success, vision, strategy and future opportunities in the industry. The GSA Award is recognized globally as one of the most respected and prestigious awards a semiconductor company can receive.

Quantic Wenzel, an industry leader in crystal oscillators, frequency sources and integrated microwave assemblies, announced the successful renewal of its International Organization for Standardization (ISO) 9001:2015 certification. The extensive review process took place throughout October and was performed by the Performance Review Institute Registrar, an accredited certification body. ISO 9001:2015 is a globally rec-

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ognized quality management standard developed and published by the ISO. The standard is based upon various quality management principles including a strong commitment to customer service, high functioning organizational management, a processed approach and a commitment continual improvement.

RADX® Technologies Inc., a U.S.-based small business supplier of COTS high performance computing products and technologies for advanced test and measurement and electronic warfare (EW) applications, announced that **Pinaka Aerospace Solutions Pvt.**, a leading India-based aerospace and defense services and solutions provider for avionics, EW and communications applications, headquartered in Bangalore, India, has selected RADX Trifecta-SSD® COTS SSD RAID modules for Pinaka Aerospace advanced, modular, PXIe-based, wideband, multi-channel RF and microwave record and playback systems.

PEOPLE

Fortify, a full stack materials science and additive manufacturing company, announced that **Lawrence Ganti** will succeed **Josh Martin** as CEO. Josh Martin, co-founder and CEO will take on a new role as chief product officer. Lawrence Ganti brings more than 25 years of experience in leading global businesses, scaling start-ups and executing the delivery of new commercial models. Most recently, Ganti was president of SiO2 Materials Science, where he led the commercialization efforts and grew the company's customer base 10x and manufacturing footprint 4x. As part of the U.S. Government's Operation Warp Speed COVID-19 response, Ganti secured more than $250 million in grant funding for onshore advanced manufacturing.

▲ *Lawrence Ganti*

Indium Corp. announced the promotion of **Claire Hotvedt** to the role of senior product development specialist. As the senior product development specialist, Hotvedt plays a highly visible and critical role in the future of Indium's solder paste business. This role exists in a cross-functional team environment in which she facilitates team initiatives to execute the new product development process and deliver fully scaled, launched, marketable product solutions for PCB assembly solder pastes. Additionally, she provides training to the sales and tech teams about new products and is responsible for introducing these products to industry-leading customers.

▲ *Claire Hotvedt*

Filtronic plc announced that it has recently employed several additional engineers to extend the capabilities of both its design team and its process engineering team. At the same time Filtronic has announced the opening of a new design center in Manchester, U.K., focused on developing mmWave technology for satcom applications. Following on from the appointment in October last year of Tudor Williams as director of technology, Filtronic has further strengthened its technical team with the addition of new principal RF and filter design engineers. The engineering team has been further expanded with the appointment of additional personnel, including MMIC and PCB engineers and two graduate engineers. Two process engineers have also been recruited, one of whom is a system-in-package specialist.

▲ *Filtronic Management Team*

mmTron Inc., a fabless designer of mmWave broadband products for the satcom, 5G/6G, aerospace and defense markets, announced the appointment of **B. J. Stookey** as sales manager, reporting to Dave Horton, vice president of sales and business development. A customer-facing business development leader, Stookey brings more than two decades of sales expertise in the RF/microwave industry working for companies such as Teledyne Microwave Solutions, Loral Microwave Group and Avnet Electronics. Stookey previously served as director of high reliability value added services for Teledyne Microwave Solutions, a supplier of integrated microwave assemblies optimized for the most demanding environments.

▲ *B. J. Stookey*

Intelliconnect (Europe) Ltd, a U.K.-based specialist manufacturer of RF, waterproof and cryogenic connectors, have unveiled a new senior management team following their recent acquisition by Trexon Global. **Gareth Phillips** is now managing director and **Steve Groves** takes the role of sales and marketing director. Gareth and Steve were already in place as part of the planned retirement of **Roy Phillips**, founder and CEO, to ensure continued smooth running of the company in line with Roy's belief that people are the most important resource of any organization. He will be staying on in an advisory role for a period to make his wealth of experience available to the new team.

▲ *Intelliconnect (Europe) Ltd Management Team*

CAES, a provider of mission critical electronics for aerospace and defense, announced that the Aerospace Industries Association (AIA) has elected CAES President and CEO **Mike Kahn** to its Board of Governors Executive Committee. AIA represents more than 320 manufacturers and

▲ *Mike Kahn*

suppliers across every sector and tier of the aerospace and defense industry. AIA is led by an executive committee that meets frequently to direct its policy guidance through the involvement of CEO-level officers of the country's major aerospace companies. The government frequently seeks advice from AIA on issues, and AIA provides a forum for government and industry representatives to exchange views and resolve problems on non-competitive matters related to the aerospace and defense industry.

▲ *Lisa Wilhelm*

Quantic™ Electronics, a portfolio company of Arcline Investment Management, announced that **Lisa Wilhelm** has been promoted to general manager of the company's resistor portfolio, composed of its Quantic Ohmega and Quantic Ticer businesses. Wilhelm will replace Bruce Mahler, who will retire after 39 years in the industry. Prior to her time at Quantic, Wilhelm served as a global account manager at both TTM Technologies and Viasystems. Before then, she worked as a chemical process engineer at Zycon Corporation. Wilhelm holds a B.S. in Chemical Engineering from Lehigh University. Quantic Ohmega and Quantic Ticer are leaders in the design and production of high performance, thin film embedded resistor foils for modern, mission critical applications.

REP APPOINTMENTS

HYPERLABS of Louisville, Colo., announced the addition of **ProTEQ Solutions** as their latest addition of U.S. sales representatives covering both New England and the Mid-Atlantic states. HYPERLABS is an industry-leading provider of high performance components and test equipment with a focus on high speed data and time domain applications. HYPERLABS develops ultra-broadband baluns, pickoff tees, bias tees samplers, amplifiers (and more) to 110 GHz. Focusing heavily on cutting-edge yet budget-conscious designs, HYPERLABS also offers a range of benchtop pulse/impulse generators, TDR, TDT and signal path analyzers.

Mouser Electronics Inc., the New Product Introduction (NPI) leader™ empowering innovation, announced a new distribution agreement with **Menlo Micro**, a manufacturer responsible for creating a new category of electronic switches for RF, microwave, mmWave, AC/DC power solutions and more. Through the agreement, Mouser is now stocking Menlo Micro Ideal Switch® products. The Menlo Micro Ideal Switch delivers the benefits of both an electromechanical relay and a semiconductor switch with no compromises. The tiny, fast and reliable MEMS-based switching devices withstand extreme temperatures, boast ultra-low losses and can handle thousands of watts. Plus, they can be manufactured at scale with conventional semiconductor equipment.

DAICO Industries

Insight & Innovation Design Release 2023

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- 50-2000 MHz Broadband/33 dBm P_{1dB}
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- 10-15 VDC and 1.5"x2.5"x0.75" Small Profile

CTX09660-1: Innovative Long Pulse HPA
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- 1.2-1.4 GHz/4kW 2mSec Pulse Power
- 40W/in^3 Ultra-High Power Density

C-Band/50W HPA: DAMH9320
- GaAs and GaN Technology
- 5.1-5.9 GHz/50W Power Amplifier
- +28 VDC Nominal

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CTX09664: L-Band Scalable 30kW (7+1) CHPA
- Patented (m+n)ART CHPA Architecture
- Flexible and Scalable up to C-Band and MW
- Liquid Cool 19" Rack Mount Common Platform

Notable DAICO Legacy Designs

DAICO Industries

DAICO provides the continued support for Legacy Designs and we Redesign for Form, Fit & Function with new Technology as requested

ANTENNA SELECTORS

100D1313-1
Antenna Selector

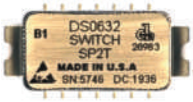
- DC-400 MHz Freq. Range
- 5-Port Antenna Selector
- 0.3 dB Insertion Loss
- 90 dB Switch Isolation

CSA09109
C/D Band Switch

- 500-2000 MHz Freq. Range
- 5-Channel Matched SPST
- 0.68 dB Insertion Loss
- 82 dB Switch Isolation

SWITCHES

DS0632
Switch, SP2T



- GaAs, Absorptive
- 5-2000 MHz Freq. Range
- 10 nSec Switch Speed
- SMT, 14 PIN

CSW25050-1
Switch, SP2T

- GaAs, Absorptive
- 50-1100 MHz Freq. Range
- 80 nSec Switch Speed
- SMT, 10 PIN

CSW45150/B2
Switch, SP4T

- GaAs, Absorptive
- 5-300 MHz Freq. Range
- 0.88 dB Insertion Loss
- SMT, 24 PIN Dihedral

CSW48067-1
Switch, SP4T

- GaAs, Absorptive
- 50-100 MHz Freq. Range
- 0.65 dB Insertion Loss
- SMT, 16 PIN Flat Pack

CSW29161
Switch, SP2T

- PIN Diode, T/R Switch
- 570-2500 MHz Freq. Range
- 0.58 dB Tx Insertion Loss
- 80 dB Tx/Rx Isolation

CSW89178
Switch, SP8T

- PIN Diode, Absorptive
- 250-500 MHz Freq. Range
- 0.5 dB Tx Insertion Loss
- 67 dB Switch Isolation

CONTROL COMPONENTS

CDA0970/B1
Attenuator, 3 Bit

- 1215-1400 MHz Freq. Range
- STEP: 6dB/12dB/24dB
- 250 nSec Switch Speed
- 1.11:1 VSWR

CPS49092
Phase Shifter, 4 Bit

- 1215-1400 MHz Freq. Range
- STEP: 22.5°
- 660 nSec Switch Speed
- 1.25:1 VSWR

CTD02064
Threshold Detector

- 10-500 MHz Freq. Range
- 0.8 dB Hysteresis
- 7.8 mSec Response
- TO-8, 5 PIN

POWER AMPLIFIERS

CAMH9167 & CAMH9165
Broadband Linear Amplifier Assembly

- 50-3000 MHz Freq. Range
- 35 dB Gain
- 33 dBm P_{1dB}
- 1.7:1 VSWR

CAMH9224
HPA/Driver Pulse Amplifier

- 1200-1400 MHz Freq. Range
- 62 dBm Tx Power
- 320 μS Pulse Width
- 10% Duty Factor

MFAs

CSA09247
T/R SW LNA

- 1215-1400 MHz Freq. Range
- 66 dBm Tx Power
- 26.8 dB LNA Gain
- 50 dB T/R Isolation

CMF09490
T/R Module

- 20-1000 MHz Freq. Range
- 53 dBm Tx Power
- 0.8 dB Insertion Loss
- 60 dB T/R Isolation

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January 2023

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Architecture achieves hundreds of kW power.
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INVITED PAPER

How Additive Manufactured Dielectrics May Solve the Challenges of "Air-Like" Dielectrics

Colby Hobart
Fortify, Boston, Mass.

Air is essentially the second most useful dielectric after a vacuum from an electrical performance standpoint as it applies to high frequency circuits. Unfortunately, air is a challenging substance with which to fabricate precision structures. The next best option to a pure air dielectric is to build structures using as much air as possible within a dielectric structural medium. This is where high performance dielectric foams come into play. These foams are nearly completely air with a minimal amount of structural polymer, ceramic or glass for physically connecting high frequency structures while minimally impacting electrical performance.

These types of foams are used in high performance advanced antenna system (AAS) panels, radomes, RF windows and many other RF structures where air would be preferred, but structure is needed. Though the effective dielectric constants (Dk) and loss tangents (Df) of these foams is typically good, almost that of air, they present a variety of design and fabrication challenges. Mainly, they are weak to compressive forces, tend to crush during lamination and have no clear and reliable pathway to support high frequency plated-through-holes.

An emerging option, additively manufactured (AM) dielectric foam, is fabricated using advanced 3D printing techniques and new low Dk

TABLE 1
PROPERTIES OF SEVERAL DIELECTRICS

	Dielectric Constant Relative to Vacuum, ε_r	*Dielectric Loss (Loss Tangent)*
Vacuum	1	0
Air @ Standard Atmosphere	1.00058986	~0
PTFE	2.0 – 2.1	0.00028 @ 3 GHz
Rogers RT/Duroid 5880 LZ	2.00	0.0021 @ 10 GHz
Polyethylene LDPE/HDPE	2.26	0.00031 @ 3 GHz
ABS Molded Plastic	2.0 –3.5	0.005–0.019
Rogers Radix™ (3D Printable Resin)	2.8	0.0043 @ 10 GHz
Fused Quartz (Fused Silica)	3.8	0.0001 @ 10 GHz
FR4	~4.4	0.008 @ 3 GHz
Glass (Corning 7059)	5.75	0.0036 @ 10 GHz
Beryllium Oxide	6.7	0.006 @ 10 GHz
High Purity Alumina	~9.5	0.0003 @ 10 GHz


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and low loss dielectric composites. This new method generates dielectric lattice structures that mimic the effect of air-filled foams while providing structure where needed to support selective metallization and mechanical support.

This article aims to educate readers on the state of dielectric foam technology, the challenges it presents to designers and AAS fabricators and how new AM dielectric foam, leveraging 3D printed technology, may provide a pathway to address these challenges.

WHY & WHERE AIR IS BETTER

For low loss and low dielectric constant (Dk) applications, a vacuum is the ideal dielectric. However, in atmospheric applications, maintaining a vacuum is rarely feasible. In atmospheric cases, air is the most ideal realizable dielectric material, with a relative permittivity of approximately 1.00059 at standard temperature, pressure and humidity (see ***Table 1***). This compares to the relative permittivity of perfect vacuum (free space) at precisely 1, by definition. The dielectric loss, or loss tangent, of a vacuum is zero, where air is close enough to zero that it is largely considered negligible.

It is also important to note that the characteristics of air as a dielectric are stable over frequency, even into terahertz frequency ranges. This is particularly attractive, as many other common dielectrics are not stable over frequency, though some are stable over large frequency ranges. This is why air is used to create high Q-factor capacitive coupling structures such as those used in the latest AASs.

The dielectric strength of air at standard atmospheric conditions is roughly 30 to 70 V/mil or 118 to 276 MV/m. This is relatively low compared to other dielectrics, which means care must be taken when using air or air-like dielectrics in high-power applications where peak voltages could reach the breakdown point.

DRAWBACKS OF DIELECTRIC FOAMS

To overcome the challenge of structurally supporting electrical and mechanical components of RF systems with air, some type of solid dielectric structure is needed. This is where dielectric foams have carved a niche.[1] These foams are typically made from polymers or other dielectric materials that can be reliably fabricated with large pores or gaps (voids) in their structure while still allowing for mechanical shaping and coating/layering. The combination of air and dielectric structure in these foams effectively reduces the overall dielectric constant and loss tangent as a function of the air-to-dielectric volume ratio (void fraction or void ratio). The higher the volume ratio of air, the closer the complex dielectric properties are to air. This is why some dielectric foams can be made with dielectric constants of approximately 1.1 to 1.2 with comparably low loss tangents, as they are mostly air by volume.

It is important to note that the

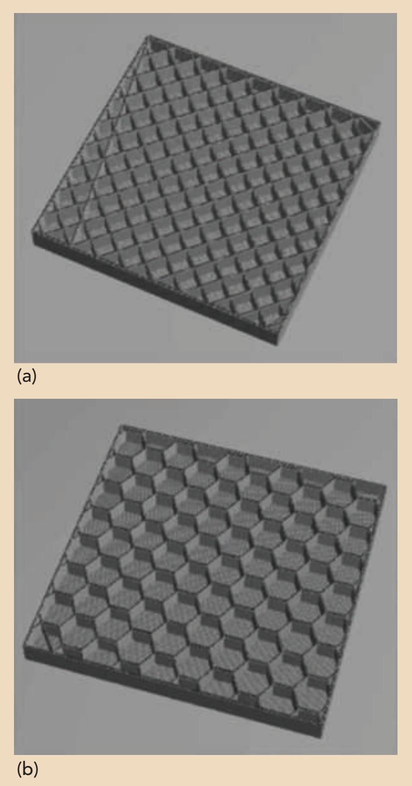

Fig. 1 **CAD sketches of 3D dielectric substrates with waffle (a) and honeycomb (b) internal structures. Lids not shown.**

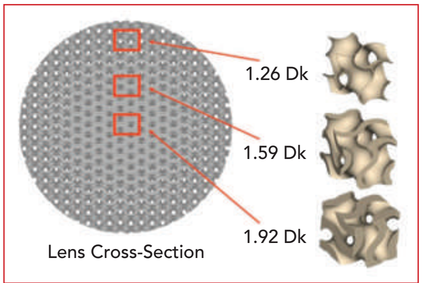

Fig. 2 **Luneburg-style GRIN lens constructed of gyroid unit cells using varying wall thicknesses to control the air-fraction and effective permittivity of the "shells" within the spherical lens.**

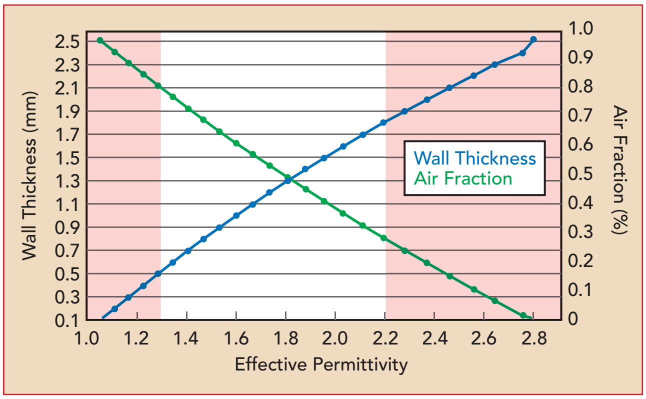

Fig. 3 **Gyroid effective permittivity and air fraction vs. wall thickness.**

TABLE 2
ε_r AND AIR FRACTION VS. WALL THICKNESS, 5 MM GYRO

ε_r	Air Fraction	Wall Thickness
1.055	0.9615	0.1
1.111	0.9229	0.2
1.168	0.8842	0.3
1.226	0.8452	0.4
1.285	0.8066	0.5
1.346	0.7678	0.6
1.408	0.7284	0.7
1.470	0.6896	0.8
1.534	0.6504	0.9
1.601	0.6106	1.0
1.668	0.5713	1.1
1.737	0.5313	1.2
1.809	0.4907	1.3
1.881	0.4504	1.4
1.956	0.4097	1.5
2.033	0.3684	1.6
2.113	0.3265	1.7
2.196	0.2843	1.8
2.281	0.2417	1.9
2.370	0.1979	2.0
2.462	0.1535	2.1
2.560	0.1079	2.2
2.645	0.069	2.3
2.759	0.0179	2.4
2.800	0.0	2.5

actual effective complex dielectric properties are a ratio of the volume fraction of the material that the electric fields pass through. This makes precise control and conformity of the foam extremely critical, as any inconsistencies in the effective dielectric properties could lead to degradation in the performance of the desired function of the foam, be it for example, an RF window, radome, lens or part of a laminated stack.

A growing use for dielectric foams has been as part of a laminated stack between circuit components and between coupled antenna elements in upper microwave and mmWave AASs. A critical design consideration for these AAS stacks is to minimize the dielectric constant and loss tangent between the coupled antenna elements while still providing structure that allows for precision alignment and fixturing.

Dielectric foams, being mostly air, typically do not have any substantial compressive strength, especially when fabricated as relatively thin sheets needed for AASs. This becomes a substantial fabrication challenge, as compression is needed to laminate sheets into stacks of substrates and electronics. Lamination is also commonly used to add metallic conductive layers to dielectric substrates. In either case, the susceptibility of dielectric foams to compression typically leads to crushing during lamination, where some thickness of the dielectric foam is lost close to where the laminating force is applied, and at fixture/support points as well.

HOW AM MAKES BETTER STRUCTURES

The degrees of freedom and material selection capability enable AM dielectric foam structures to be made with a wide range of dielectric and structural properties that can be designed and tuned for a specific application. In this case, AM dielectric foam can be fabricated to have foam-like/air-like dielectric properties but with superior structural properties. Moreover, an AM dielectric foam can be designed so that areas requiring foam-like electrical behavior are fabricated with the appropriate characteristics, but other areas, such as fixture areas or attachment points, are fabricated in a way that better fits the desired feature performance.

AM dielectric foam can be made to be foam-like in the same way that dielectric foams are designed to be air-like. The concept involves designing the structures to have the volume ratio of air-to-dielectric as high as possible while maintaining the designed structure. Where foams are formed of a multitude of small roughly spherical shells, AM dielectric foam is fabricated using a hollow lattice structure. Traditional AM dielectric foam geometries such

as honeycombs or grids are simple examples (see ***Figure 1***).[2]

More modern and sophisticated AM dielectric foam is fabricated using more complex lattices based on a unit cell design, such as a gyroid for a gradient-index of refraction (GRIN) lens (see ***Figure 2***). This approach enables the unit cell to be designed with a given air-to-dielectric volume fraction (see ***Figure 3*** and ***Table 2***), and for larger structures to be developed from a 3D matrix of unit cells. Hence, very precise control of the volume fraction can be achieved and the design of a 3D object larger than a unit cell is a relatively simple matter of filling a volume with unit cells and potentially even partial unit cells that still meet the volume fraction criteria.

Combining unit cells and varying the unit cell volume fraction can be

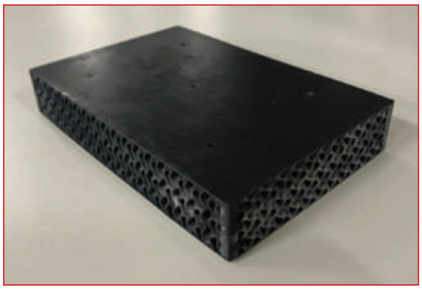

Fig. 4 3D printed foam material.

used to realize variable dielectric performance, effectively realizing metamaterial dielectric structures. With proper design, this technique can be used to design and fabricate 3D RF lenses, such as GRIN Luneburg-style RF lenses.[3-5] There are a variety of other uses for metamaterial dielectric structures made from AM materials, however, to achieve air-like or dielectric foam-like performance, the volume fraction of the lattice structure must be as conformal throughout the volume as possible.

Unlike dielectric foams, air-like AM dielectric foam can be designed so that the external surfaces that undergo stress are solid or incorporate additional structures that are more wear resistant, have higher compressive strengths (up to 400 PSI currently), or can be designed to better support attachments or fixturing. In fact, an AM dielectric foam can be designed in such a way that all mechanical and structural features are fabricated along with the air-like volume sections (see ***Figure 4***). With this capability, indexing structures and mechanical attachment points can be manufactured in a single step, as opposed to various steps with the potential for tolerance and yield issues.

Using an AAS as an example, an air-like AM dielectric foam can be designed such that the coupled antenna structures are precision indexed from the top and bottom sections of a laminated stack with the air-like volume sections in between the coupled antennas and denser sections toward where the indexing, attachment and/or fixturing points are located. In this way, the surfaces to be laminated, metallized or otherwise combined with the AAS stack can be designed to reliably withstand the forces intrinsic

to lamination or other manufacturing/assembly stages.

RF lenses and/or radomes can also be fabricated using AM technologies that enhance the coupled antenna structure performance using the same technology, which may potentially limit sourcing and supply chain issues of the RF dielectrics and reduce AAS bill-of-material complexity.

Using an AM dielectric foam approach to design and fabricate AASs or similar complex RF structures fundamentally changes the design approach and can possibly simplify the design by enhancing the degrees of freedom available to designers.

One area of simplification is in the design process, through electromagnetic (EM) simulation, parametric optimization and iterative design practices. Making use of AM dielectric foam, including air-like structures, enables very rapid prototype and development cycles, especially in software. Where traditional dielectric foam and other dielectric structural materials must be mostly designed in advance and only tweaked slightly based on feedback from EM simulation and parametric optimization, an AM-EDS approach allows for much more freedom of design and simulation with proxy structures that can then later be refined and fabricated with AM dielectric foam. This includes non-planar structures and even larger structures, as indexing can be designed into AM dielectric foam parts.

POTENTIAL OF AM DIELECTRIC FOAM

One of the largest drawbacks of dielectric foams is that they are not readily metallized without lamination or some other type of adhesive attachment of metallic conductors. There also is no clear path toward metallizing dielectric foams to produce conformal and planar metallic layers suitable for RF transmission lines and circuits.

This includes creating metallic vias in the z-axis. It is possible to insert a cylindrical metallic conductor tubes or pins inside a machined hole in a dielectric foam and use some type of conductive adhesive or soldering process to form a via, though this process is somewhat error prone and not as high performing as true vias with metallic attachments, such as soldering or selective metallization. Inserting via tubes or pins may also lead to clearance issues with the top and bottom laminated sections in a stack.

This is one of the key areas where AM dielectric foam has the potential to address many of the design challenges associated with AAS and other high performance stacked RF circuits. It is already possible to perform reliable and high performance selective metallization or even complete metallization of AM-EDS materials that are well suited to very high frequency (greater than 90 GHz) applications. Using air-like AM dielectric foam with design features, such as a solid planar surface with good surface finish and solid-wall via sections, for se-

lective metallization can enable truly 3D RF circuits with air-like dielectric structures and dielectric substrates in a simplified process.

There are clearly some limitations on the thickness and diameter of vias that can be metallized with selective metallization processes, such as laser selective activation metallization, though non-selective techniques using electroless metallic plating could enable even small and high aspect ratio vias to be developed if there is a method for masking of the portions of the structure that should not be metallized. Conical vias could also be viable for selective metallization of the inner wall of the via structure, which would enable laser selective activation in even high aspect ratio vias.

With more development in metallization processes and early involvement of AAS and RF designers in the design process, it may be possible to design entire AAS and complex RF structures using (AM) dielectric foam technology, including the dielectric substrates, planar/3D circuit elements including vias, air-like (low Dk and low Df) volumes, RF lenses, radomes, RF windows and even the structural elements. It is possible to AM both low Dk and low Df polymer composite, as well as low Df ceramics for high-power and high heat applications.

CONCLUSION

Air-like AM dielectric foam can be designed to support high pressure and precision lamination; and, it provides a pathway for selective metallization and metallic vias. The different materials available and the degrees of freedom enabled by AM of dielectrics provides designers with a much greater potential to innovate and work around previous challenges in the design process of complex 3D RF systems, such as AASs. ■

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RF Performance Characterization of Direct Digital Wideband Transceivers Using Digital/ RF Cross-Domain Stimulus Response

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Keysight Technologies Inc., Santa Rosa, Calif.

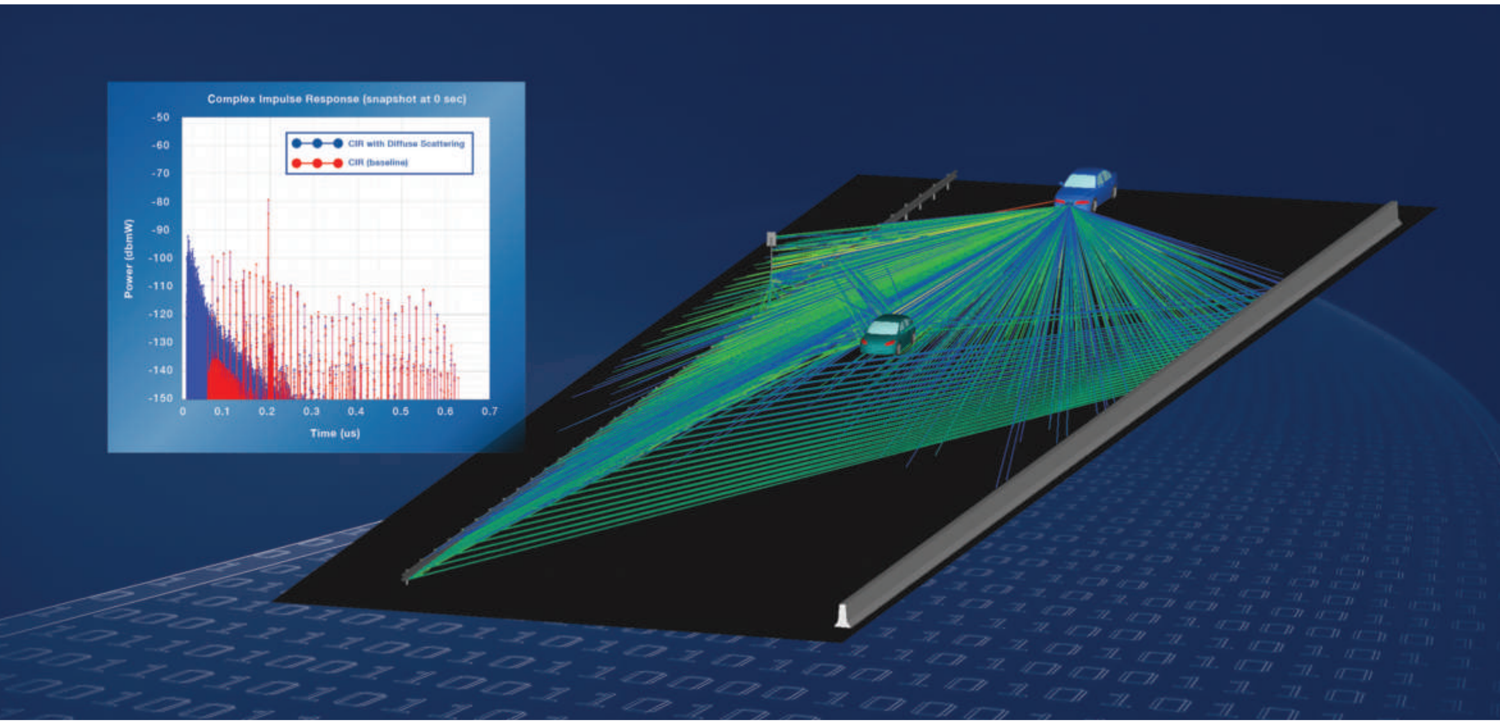
With advancements in system integration and high speed data converters, high performance phased array antenna (PAA) systems become practical in very small form factors. This expands their use cases in a variety of communication and RF sensing applications.[1,2] This article discusses the performance characterization challenges associated with highly integrated RF front-end and digital baseband devices, including the RF path in digital beamforming or software-defined radio devices, RF transceiver ICs and high speed data converters. The development of a new digital and RF cross-domain stimulus/response method is introduced using a vector network analyzer (VNA) and measurement examples are provided for a digital and RF mixed signal device.

Typical communication and RF sensing systems are configured with RF front ends, frequency up- and down-converters and digital baseband sub-modules with signal conditioning in each stage, as required. When RF systems are used on various platforms, such as unmanned aerial vehicles, airplanes (conformally mounted to the surface) or mobile equipment—size, weight and power consumption must be considered for platform compatibility. As more versatile and capable RF systems are developed for small platforms, the level of integration continues to accelerate.

Highly integrated RF systems often consist of multiple RF channels, minimized interconnects between functional blocks, the possible introduction of direct RF to digital conversion and the migration of hardware functions to software signal conditioning and analysis (see ***Figure 1***). This new RF front-end architecture becomes practical with advancements in higher frequency packaging and high speed data converters, i.e., analog-to-digital (ADC) and digital-to-analog (DAC). Such integrated RF front-end architectures bring many benefits such as improved performance, wider operating frequency ranges and greater flexibility. They also introduce many new challenges, however, especially for design verification and testing.

RF PERFORMANCE CHARACTERIZATION CHALLENGES

Engineers are well equipped with test instruments for performance characterization on RF systems under development if the device under test (DUT) is defined with



Complex Impulse Response (snapshot at 0 sec)
CIR with Diffuse Scattering
CIR (baseline)
Power (dbmW)
-50 -60 -70 -80 -90 -100 -110 -120 -130 -140 -150
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
Time (us)

ApplicationNote

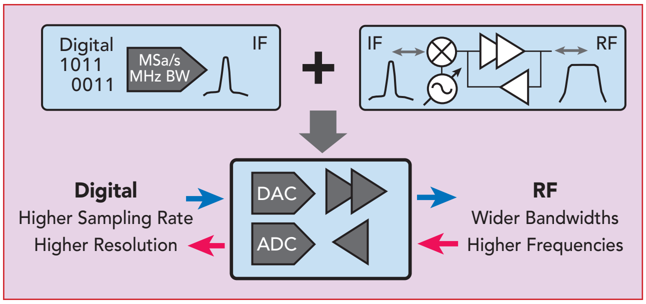


Fig. 1 New RF front-end architecture with integrated high-speed data converters.

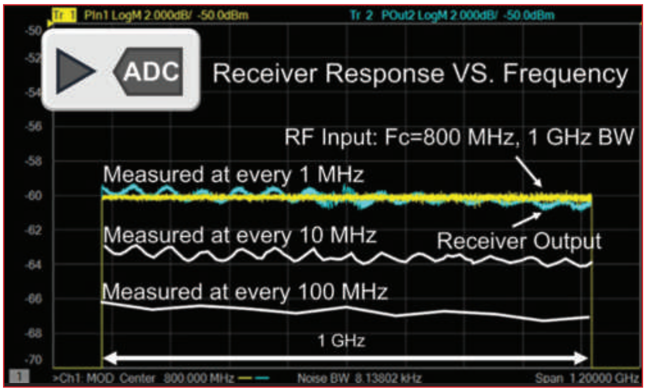


Fig. 2 Receiver frequency response vs. frequency resolution.

RF input and output ports. Unfortunately, this is no longer the case for highly integrated RF systems. The DUTs are defined with mixed RF and digital input and output ports, such as digital baseband integrated RF front ends, wideband transceiver ICs and high speed data converters.

Digital Data Analysis

Modern digital and RF integrated devices and modules contain high speed data converters, often capable of giga-samples per second sample rates. Testing the front-end RF performance of these devices requires recording and analyzing the digital output data bits. As the sampling rate increases for greater bandwidth, more digital data must be processed and analyzed. Recording digital data to analyze the entire operating RF band becomes time consuming. For systems with many RF paths such as PAA systems, this must be repeated hundreds of times, making complete characterization time consuming and costly.

Conventional Test Tool Limitations

VNAs are commonly used for precise performance characterization of RF front-end modules and components. However, the RF stimulus response measurement and calibration methodologies used in VNAs are no longer suitable for testing devices that directly convert digital and RF signals. Therefore, RF signal analyzers and generators are the only available options. The drawback is that the measurements often rely on assumptions of linearity and signal fidelity of the instrumentation used and the digital data analysis capability of the engineers. This makes current measurement options not nearly as dependable as the VNA's RF stimulus response methodology.

Performance Deviation in Higher Frequencies and Wider Bandwidths

The operating frequencies of RF systems with high speed data converters continue to increase, sometimes up to mmWave frequency ranges. The end applications use designated frequency channels in these frequencies, but the equipment needs to be tested over the entire operating bandwidth. As RF performance becomes frequency dependent at higher frequencies and wider bandwidths, it is important to test at finer frequency resolutions to obtain an accurate understanding of frequency dependencies (see ***Figure 2***). It is simple for RF devices that can be characterized with traditional VNA measurement techniques. However, it becomes more difficult and requires more effort for digital and RF mixed signal devices.

DIGITAL RF CROSS-DOMAIN STIMULUS AND RESPONSE MEASUREMENT METHOD

This new test methodology addresses the engineering challeng-

0.3~18GHz

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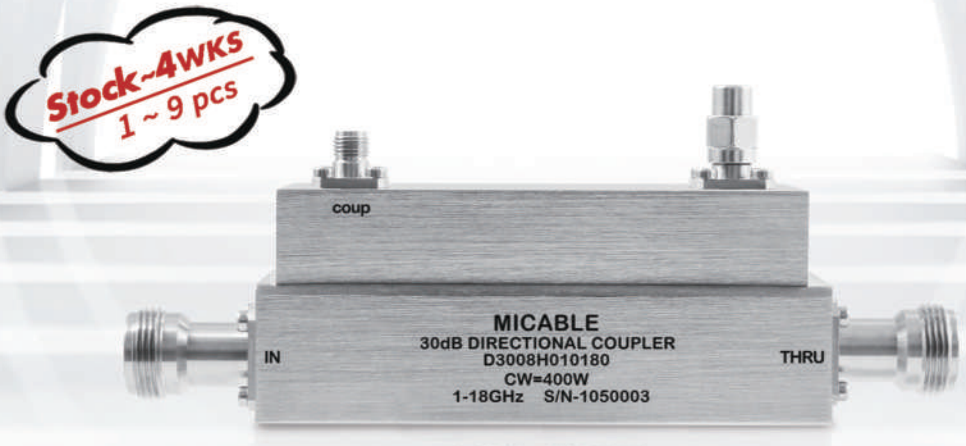
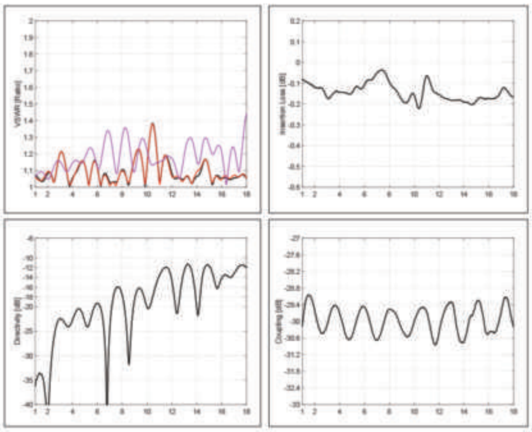
- Excellent coupling, flatness and directivity which will significantly improve the signal acquisition accuracy
- Environment conditions meet MIL-STD-202F
- Low VSWR & insertion loss
- Custom-design & narrow band is available
- Arbitrary customization of 30-40dB nominal coupling



Test Curve of D3008H010180



Freq. Range (GHz)	P/N	Coupling Max.(dB)	Main Line VSWR	Coupling VSWR	Insertion Loss*	Flatness	Directivity Min.(dB)	Power Max.(W)	Unit Price** (USD)
			Max.(:1)		Max.(dB)				
0.3-6	D3012H003060	30±0.9	1.4	1.4	0.6	±1.2	15	600	1,678
	D4012H003060	40±1.0	1.4	1.4	0.6	±1.3	15	600	1,678
0.5-6	D3012H005060	30±0.7	1.3	1.3	0.4	±1.0	15	600	1,175
	D4012H005060	40±0.8	1.3	1.3	0.4	±1.1	15	600	1,175
0.5-18	D3008H005180	30±1.2	1.5	1.6	1.0	±1.2	10	400	3,362
	D4008H005180	40±1.2	1.5	1.6	1.0	±1.4	10	400	3,362
0.7-8	D3012H007080	30±0.8	1.4	1.4	0.5	±1.0	14	600	1,265
	D4012H007080	40±0.8	1.4	1.4	0.5	±1.0	14	600	1,265
1-8	D3012H010080	30±0.8	1.4	1.4	0.4	±0.9	14	600	1,076
	D4012H010080	40±0.8	1.4	1.4	0.4	±0.9	14	600	1,076
1-18	D3008H010180	30±1.2	1.5	1.6	0.6	±1.0	10	400	2,475
	D4008H010180	40±1.2	1.5	1.6	0.6	±1.0	10	400	2,475
2-18	D3008H020180	30±1.0	1.5	1.6	0.6	±0.8	10	400	2,178
	D4008H020180	40±1.0	1.5	1.6	0.6	±0.8	10	400	2,178
6-18	D3008H060180	30±1.0	1.5	1.6	0.5	±0.7	10	400	928
	D4008H060180	40±1.0	1.5	1.6	0.5	±0.7	10	400	928

* Theoretical I.L. Included
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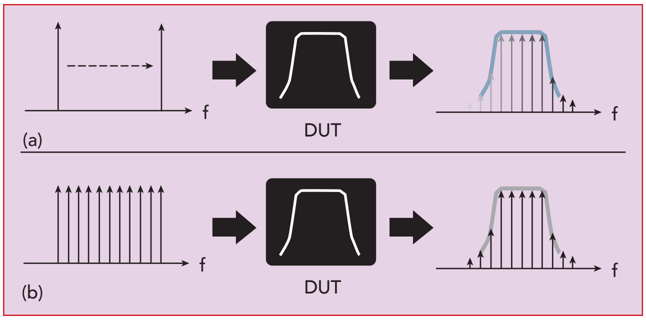

Fig. 3 Swept single tone stimulus response (a) vs. wideband multi-tone stimulus response (b) methods.

es in digital and RF mixed device performance characterization. It is based on the well-known RF stimulus response methodology used in traditional VNA measurement techniques, but is modified to accommodate digital waveforms for either stimulus or response.

An ordinary VNA's stimulus response measurement methodology uses a swept single tone stimulus with a tuned narrowband receiver for frequency response measurements. In contrast, the new approach includes a wideband multi-tone stimulus capability with a wideband analysis technique to yield the device's frequency response (see ***Figure 3***).[3] The test waveform (digital or RF) is precisely defined and repeatedly played for the response wave (digital or RF) and can be coherently correlated at each spectral component with the stimulus waveform, resulting in vector response measurements between input and output signals within the stimulus waveform bandwidth.

This new cross-domain stimulus response methodology yields RF performance characteristics of digital and RF mixed devices over frequency or power ranges in one set of measurements, while it takes days or weeks for the same measurements using the traditional approach—stimulating with a single tone at a fixed frequency and capturing the response at a single frequency point.

MEASUREMENT EXAMPLES

Measurement System Configuration

The measurement system configuration is shown in ***Figure 4***. The DUT used in the measurement examples is a commercially available wideband RF transceiver IC mounted in its manufacturer's evaluation kit with an integrated DUT controller. It includes multi-channel transmitters and receivers with 12 GSa/s DACs and 6 GSa/s ADCs, respectively. The measurements are completed with one transmitter and one receiver channel. The application software called Device Measurement Expert (DMX) with cross-domain test capability controls the N524xB PNA-X VNA and the external vector signal generator (VSG).

When testing receivers, the DMX defines the digital IQ waveform for the VSG to generate, which is measured with the PNX-X's reference receiver in addition to the receiver under test. The DMX uploads the digital IQ waveform file generated from the receiver and the VNA processes the data. When testing transmitters, the DMX sends the digital IQ waveform to the transmitter under test and the PNA-X's reference receiver. The PNA-X measures the output RF waveform from the transmitter and processes the data. This configuration enables receiver, transmitter

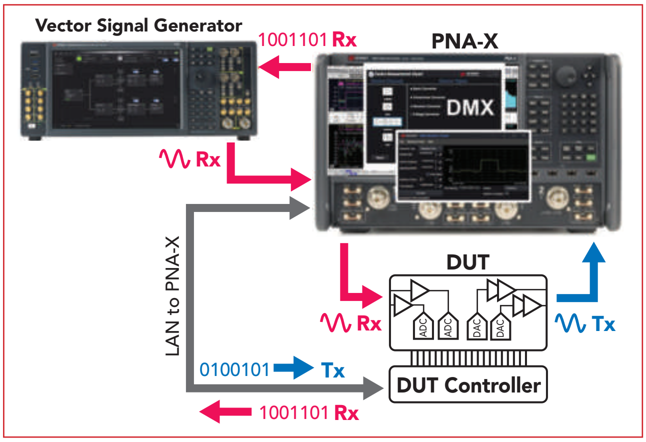

Fig. 4 Wideband transceiver IC measurement setup.

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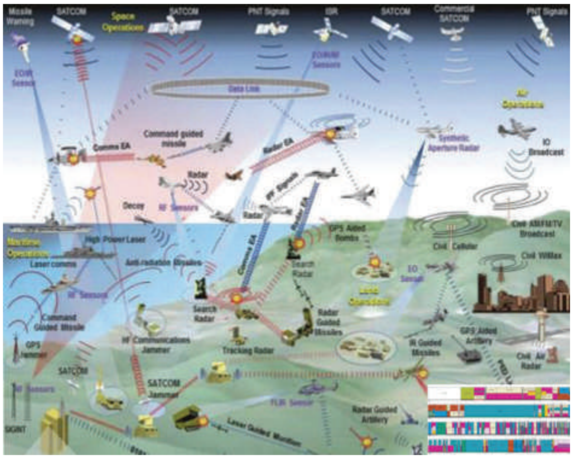

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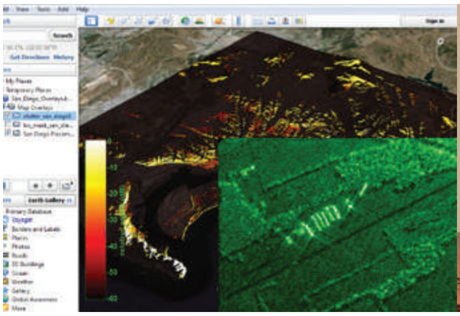
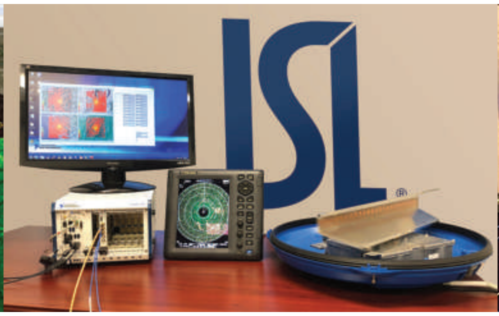
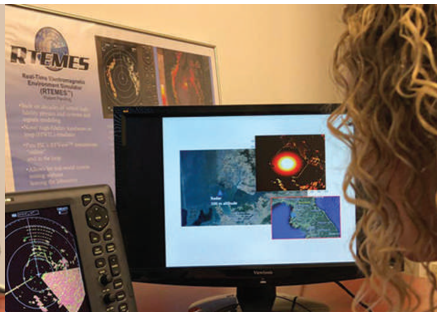






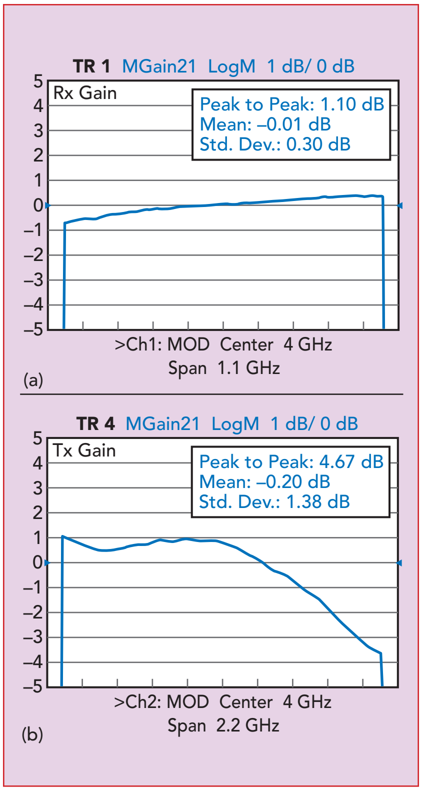


Fig. 5 Measured gain flatness: 1.1 dB for the receiver (a) and 4.67 dB for the transmitter (b).

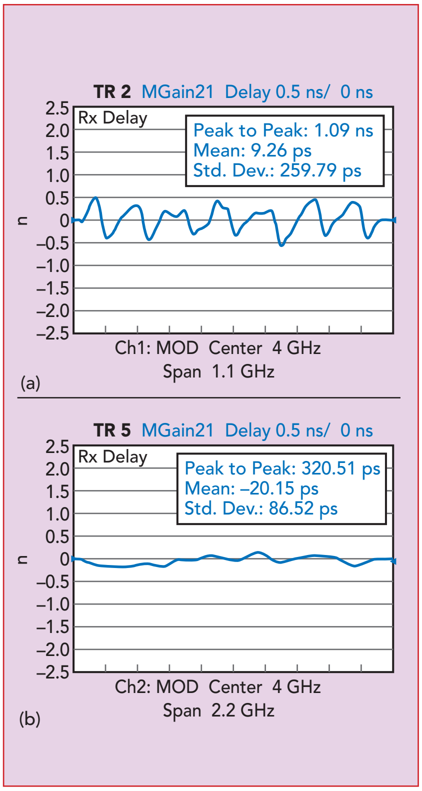


Fig. 6 Measured deviation from average delay: 1.09 ns for the receiver (a) and 320.5 ps for the transmitter (b).

and transceiver measurements with a single set of connections.

Calibration

Measurement system calibration on the VNA is available on this setup, limited to the RF test ports. When measuring transmitters, the stimulus is digital and treated as an ideal waveform and the RF response waveform is measured with the calibrated test receiver of the VNA. When measuring receivers, the stimulus is an RF waveform that is distortion-corrected and measured using the VNA's calibrated reference receiver. The digital response waveform is then measured by the receiver under test. In the RF stimulus waveform correction process, the waveform is pre-distorted to account for the source distortion errors in addition to linear errors. This results in an RF stimulus that is a nearly ideal waveform at the receiver input. The effect of source distortion correction is reviewed in the following section.

Frequency Response Measurements

The measurement example in ***Figure 5*** demonstrate fast receiver and transmitter gain flatness versus frequency measurements. It includes nearly one thousand frequency response points on each measurement, with 1.1 MHz resolution in a 1 GHz bandwidth at 4 GHz center frequency in the receiver measurements (see Figure 5a), and with 2.2 MHz frequency resolution in a 2 GHz bandwidth at 4 GHz center frequency in the transmitter measurements (see Figure 5b).

The measurements were completed in only a few minutes including time for device initialization using the new measurement methodology described previously. This is a remarkably short time compared to the traditional method of point-by-point measurements obtained from single tone measurements using a signal generator and a signal analyzer.

The same measurement setup yields deviation of average delay measurements across the entire operating bandwidth with no additional effort (see ***Figure 6***). With the repetitive multi-tone stimulus response method, phase responses are effectively stitched between

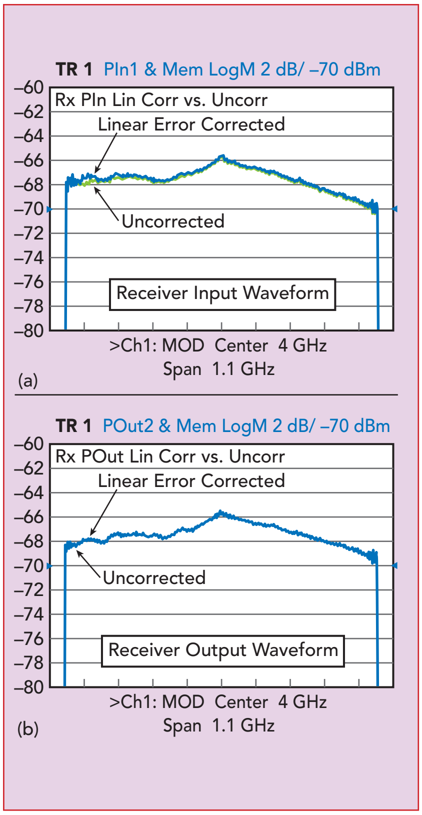


Fig. 7 Effect of linear error correction: receiver input (a) and output (b) waveforms.

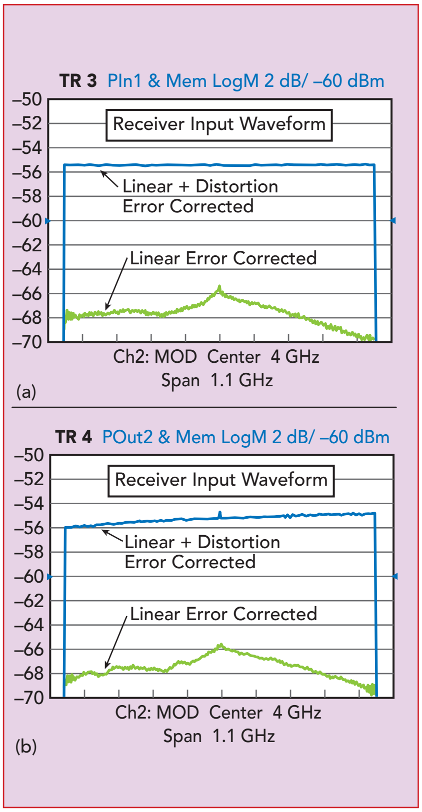


Fig. 8 Source distortion may significantly affect receiver response measurements: receiver input waveform (a) and output waveform (b).

repeated measurements, resulting in virtually unlimited analysis bandwidth.

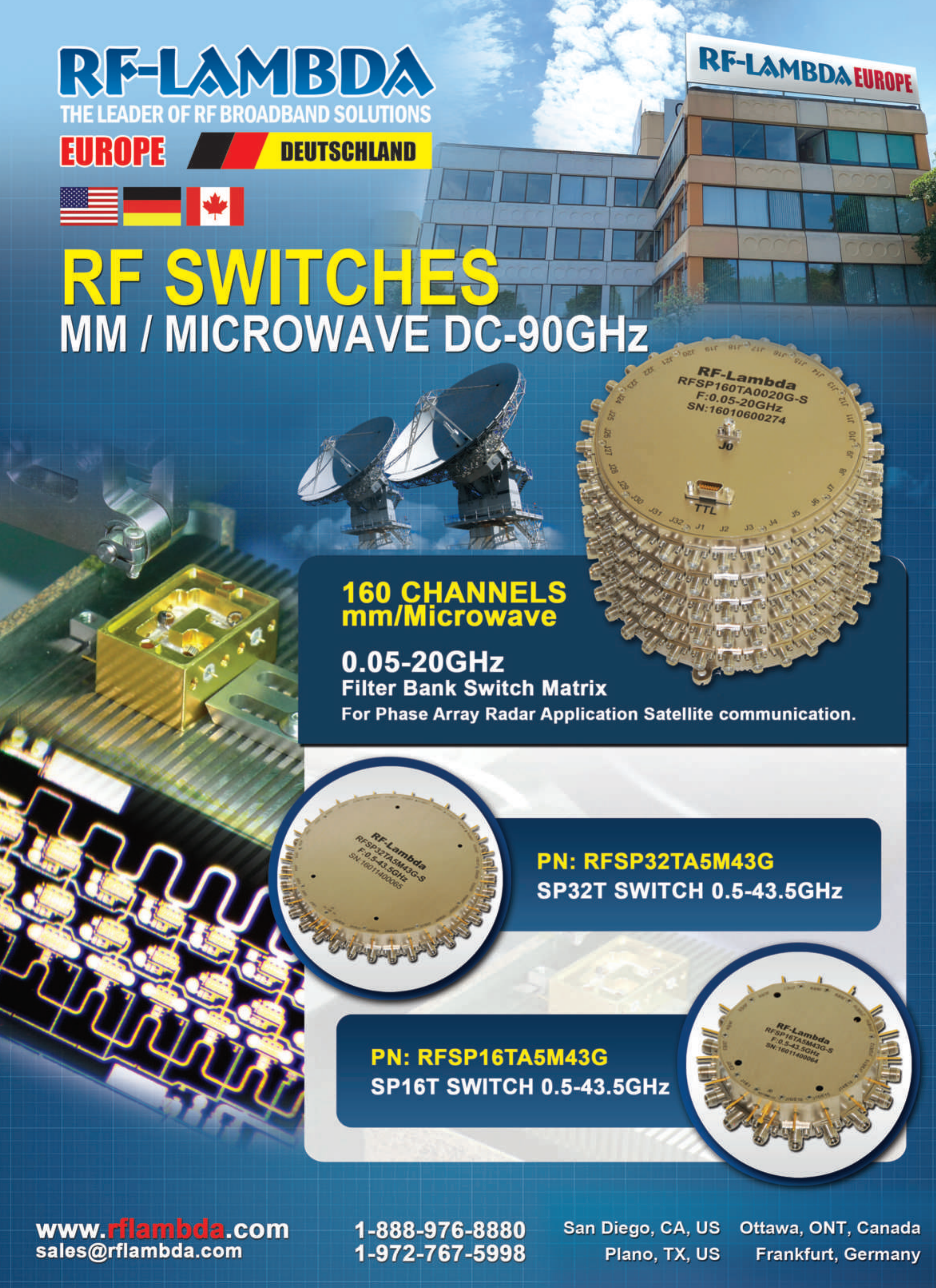
Corrected Versus Uncorrected Measurements

These receiver measurements highlight the impacts with available error correction options (see ***Figure 7***). The first compares uncorrected and linear error corrected measurements with an input waveform (see Figure 7a) and measured with the VNA's reference receiver (see Figure 7b). The output waveform is measured with the receiver under test. The effect appears as a slight adjustment. If there were more test accessories in the path between the test instruments and the receiver's input port, such as longer test port cables and switch matrices, the linear errors would be more noticeable.

The next series of measurements only compares measurements between linear error correction, and linear and source distortion error corrections (see ***Figure 8***). The RF receiver input waveform level is adjusted by nearly 6 dB to nearly an ideal flat-level input stimulus across a 1 GHz frequency bandwidth, which is expected to influence the receiver response. The corresponding output waveform exhibits the receiver's frequency dependency clearer than results with source distortion uncorrected stimulus.

Error Vector Magnitude (EVM) Measurements

The new measurement methodology also allows distortion measurements of digital RF mixed devices.[4] The examples shown in ***Figure 9*** include corrected and uncorrected receiver and transmitter EVM measurements. Error correction in receiver measurements includes both linear error and source distortion corrections. There is noticeable EVM improvement in receiver measurements and the source-generated distortion is minimized for accurate receiver performance characterization. Linear error corrections are only applied in the transmitter test because the RF source is the DUT. The signal distor-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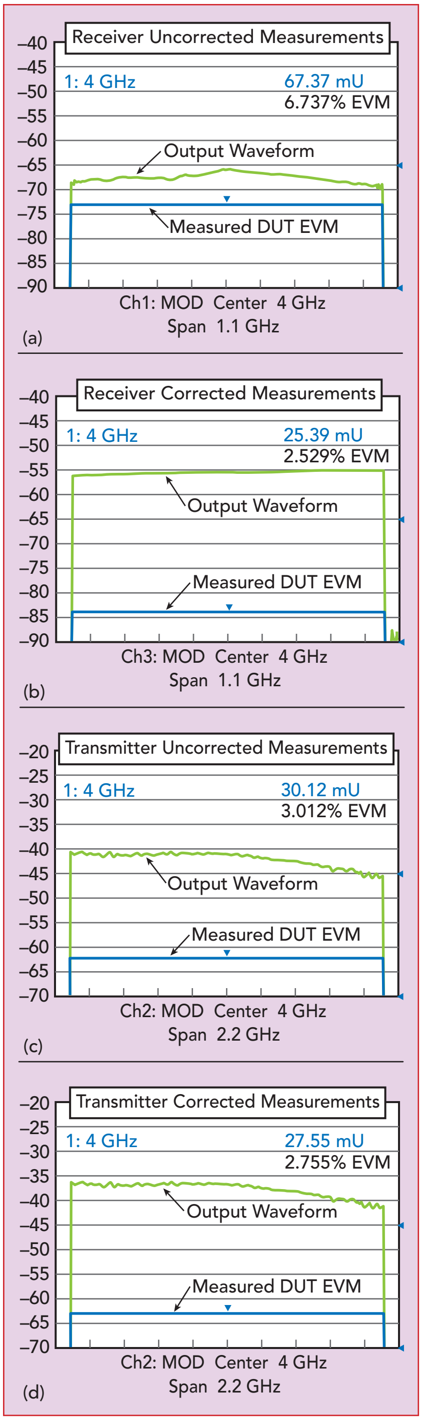

Fig. 9 EVM measurements: receiver uncorrected (a) and corrected (b); transmitter uncorrected (c) and corrected (d).

tion introduced by the RF source in the transmitter is what is of interest to be characterized.

CONCLUSION

The new digital RF cross-domain stimulus response methodology demonstrates fast and precise digital and RF mixed signal device characterization. This approach leverages commonly used RF test instruments like VNAs and VSGs for testing new types of digital RF mixed devices, which are expected to be common building blocks of RF front-end architectures in the foreseeable future. Existing error corrections are helpful for improved measurement accuracy, although some residual errors still need mitigation techniques such as undesired-signal isolation. EVM measurements, in addition to frequency response measurements, are useful as these RF systems become integrated into communication applications.

Future RF systems with mixed digital and RF architectures will continue to grow with broad applications. More measurement capabilities are expected to become available to meet the diverse end-application requirements. This includes not only linear response, but also noise and distortion performance characteristics.

ACKNOWLEDGMENT

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INVITED PAPER

Optimized Air Flow and Thermally Efficient Test System Enables 3D OTA Measurements Over Temperature

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5G communications have supported the deployment of mmWave antenna array beam steering technologies at an unprecedented commercial scale. As per 3GPP[1] and CTIA[2] test specifications, 5G mmWave capable mobile phones must undergo a large number of tests to guarantee adequate performance. The defined measurement methodology relies on far-field over-the-air (OTA) assessments in compact antenna test ranges (CATR). As temperature influences the active electronics in the wireless devices and, hence, the beamforming characteristics, OTA measurements are also required in temperature conditions ranging from -10°C to +55°C, per 3GPP test specifications. For such tests, an innovative realization of a CATR with an embedded thermal compartment meeting conformance and compliance testing needs is required.

3GPP requirements for RF conformance testing of mobile devices or user equipment (UE) are essentially designed to avoid problems that would impair the functioning and performance of wireless networks. Up until 4G and 5G FR1 (i.e., frequencies below 7.125 GHz), all 3GPP conformance evaluations were based on conducted measurements, typically achieved by connecting RF cables at the antenna ports of the device under test (DUT). A major change occurred in 5G, with the added FR2 frequency range in the mmWave spectrum (i.e., FR2-1: 24.25 to 52.6 GHz and FR2-2: 52.6 to 71 GHz). As UE FR2 antennas are dynamic beam steering arrays, the conducted approach became irrelevant because the overall performance of a DUT is intrinsically linked to the antenna. In addition, the high level of integration of arrays and RF front-ends enabling the operation of such technologies makes it practically impossible to reliably connect cables at adequate points.

OTA assessment appeared as the correct and most straightforward approach for testing, and far-field (FF) spherical measurements in anechoic chambers became the basis for all sorts of tests of FR2 UE. Because the UE can be large (e.g., a mobile phone, tablet or laptop) and manufacturers are not constrained to communicate the exact location of the antenna elements, the so called black-box approach was adopted, with the whole DUT placed within the quiet zone (QZ) of the FF measurement setup. The CATR was adopted by 3GPP as the reference test environment because of its capability to provide a large QZ within a confined space.

Since UEs are used in diverse environmental conditions, and temperature will influence the active electronics in the DUT

and affect the beamforming performance,[3] spherical OTA measurements at extreme temperature conditions (ETC) ranging from -10°C to +55°C became part of the 3GPP UE RF conformance test specifications.

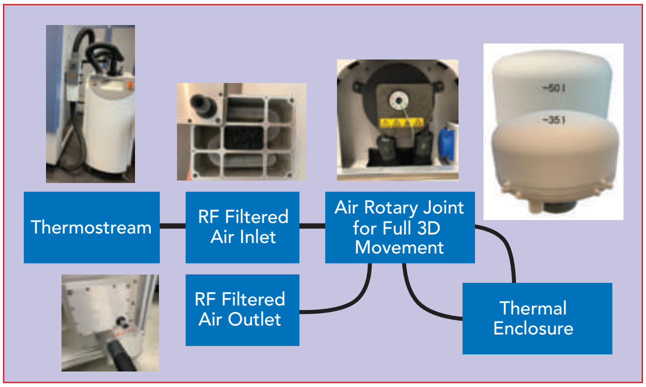

Fig. 1 Air flow of the ETC test system.

ETC REQUIREMENTS

Designing a CATR that enables dual-axis rotation of the DUT, to perform accurate FF 3D measurements under ETC, sounds simple but is a complex engineering problem. The complexity increases when considering the need for fast testing—hence fast temperature ramps—while protecting the anechoic chamber and positioning system from damage due to the high or low temperatures and maintaining the shielding effectiveness of the chamber. Combining the requirements from 3GPP and typical customer needs yields the following constraints on the design of the CATR environment for ETC testing:

- Positioning system azimuth range from 0 to 360 degrees and an elevation range from 0 to 120 degrees, not reduced by the air pipes or other ETC requirements on the positioner
- Spherical measurements with the device temperature from -10°C to +55°C (as defined by 3GPP) and an extended temperature range of -40°C to +85°C (for customer stress tests)
- Minimum DUT dimension of 40 cm diameter with the ETC solution in place
- 30 cm diameter QZ during ETC testing, with an uncertainty better than 0.9 dB
- Chamber shielding > 70 dB, not degraded by air injection pipes
- Time for DUT heating and cooling as brief as possible.

Innovation was necessary to design a system complying with this set of criteria, leading to many sophisticated details to solve the challenges, resulting in several patents for multiple components of the final ETC OTA solution.[4]

Exposure to a temperature range from -40°C to +85°C can damage the absorbers in an anechoic chamber, as well as the motors and drives in a 3D positioner. To protect from this, the DUT is enclosed in a thermal compartment within the OTA chamber, which contains the cold or hot air as hermetically as possible. The rest of the chamber is ventilated to maintain close to the ambient temperature. One upside from limiting the volume exposed to the temperature swings is reduced energy and air volume that must be provided to stabilize the DUT at the ETC condition. This also reduces the time necessary to reach the target temperature.

While this approach offers the benefits noted, it is not without major difficulties. First, the thermal enclosure must be sufficiently RF transparent to minimize any impact on QZ uniformity and DUT radiation. Yet the enclosure must be stable and withstand the increase in inner air pressure from the temperature air flow while isolating the hot and cold air flow from the surrounding environment. All mechanical parts of the thermal enclosure, as well as the air pipes which connect to it, must support full 3D movement of the dual-axis positioner—hence the DUT—while being airtight. The air hoses must run in and out of the chamber through RF shielded walls without compromising the shielding effectiveness.

CHAMBER DESIGN

All these considerations led to a system concept with the air flow chain shown in ***Figure 1***. Com-

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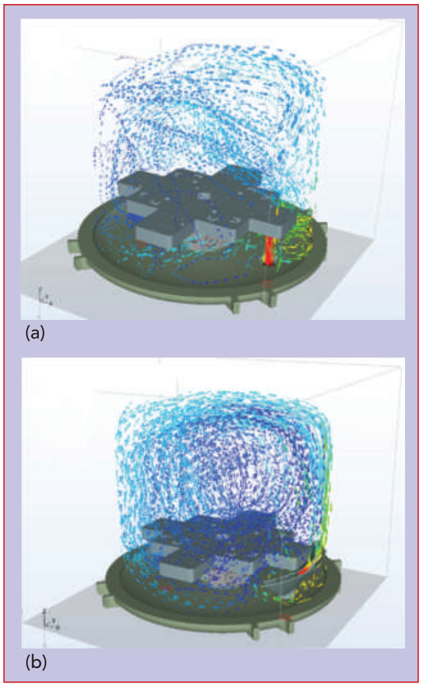

▲ Fig. 2 Temperature and air flow simulations of the 50 l thermal enclosure with direct pipe entry (a) and added diffusor (b).

pressed dry air at the desired temperature is provided by an external climate machine called a Thermostream. Connected to power and the central compressed air supply, it provides the required air volume between the minimum and maximum air temperatures to the air inlet of the anechoic chamber. Running the air pipes through the shielded chamber walls requires RF filtered air feedthroughs, which comprise multiple metal pouches filled with absorber, guiding the air through winding pipes to the inside of the chamber.

Once inside the shielded chamber, the hoses connect to an air rotary joint. It separately supports airflow in both directions (supply and exhaust) through the elevation axis of the combined azimuth-over-elevation positioner, while not limiting its angular movement capabilities. By using well selected seals, it keeps the leakage of air through the moving parts of the air rotary joint to a minimum over the entire air temperature range. The supply and exhaust tubes run along the elevation swing and connect to the lower shell of the thermal enclosure, which is made of robust plastic material and fixed on the elevation swing of the 3D positioner. The azimuth rotation stage of the positioner is guided in an isolated manner through this lower shell into the thermal compartment, enabling full rotation of the DUT in the second axis and achieving full 3D assessment of the DUT across the extreme temperature range.

▲ Fig. 3 ETC OTA test system (R&S©ATS1800C) with a commercial Thermostream.

To close the thermal compartment, the upper dome—made of RF transparent Rohacell® material—interlocks to the lower shell via an air-sealed locking ring. The dome material enables high-quality RF measurements with the dome in place since its permittivity is close to air to minimize any impact on the RF radiation. The shape of the dome, the thickness of its wall and the processing of the material were optimized to close the foam cells as much as possible to increase the air-tightness and robustness of the dome to withstand increases in internal air pressure, while minimizing RF perturbations. Different sizes of the dome provide smaller and bigger volumes, either for a larger DUT or to support faster temperature cycles. The larger dome is compliant with 3GPP and CTIA DUT alignment, as well as the quality of the QZ assessment mandated by the 3GPP RF conformance testing specifications.

Once inside the thermal enclosure, the air is guided using a patented diffusor. By designing mechanical pieces to guide the air flow at the output of the air supply pipe toward the exhaust pipe, the homogeneity of the temperature within the enclosure was increased significantly. This ensures a fast and equalized temperature distribution and eliminates hot or cold spots, increasing performance and accelerating the time for stable temperature convergence. Ideally, the sensor-controlled air flow volume provided by the Thermostream is maximized, however, the supply air temperature range must be adopted to the other materials used in the air flow chain. These parameters also influence the air cycle times, so they had to be chosen carefully.

After the temperature energy of the air is provided into the thermal compartment, the air exhausts through pipes in the same, yet separate, way through the air rotary joint and the exhaust air feedthrough out of the chamber. To reduce noise, the hose ends at a specially designed noise canceller. Since the diameters of the exhaust path affect the pressure increase inside the thermal enclosure, they were selected to keep the internal pressure low enough, with headroom, to avoid damage from excessive pressure.

ETC OTA PERFORMANCE

Multiple optimization rounds were necessary to develop a solution meeting both major test specifications requirements and user needs for high speed testing. These involved electromagnetic, air flow and thermal simulations used to optimize the air distribution within the thermal enclosure (see ***Figure 2***). Many prototypes were required, accompanied by hundreds of hours of testing to validate the numerical findings and optimize the design. The multiple versions of the ETC OTA leading to the final solution yielded a very compact and easy to handle test environment where various size devices can be tested in full 3D and across a wide temperature range (see ***Figures 3*** and ***4***).

With this setup, temperature changes well beyond the 3GPP required limits can be achieved in a short time using an air flow rate up to 700 l/min. At that flow rate, a tem-

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perature change between +85°C to -40°C is possible in 10 to 14 minutes within a 50 liter ETC compartment. Even without a need for the 125°C wide temperature window, having it is an advantage because the additional temperature range enables fast temperature ramps when testing across the 3GPP specified temperature range. A temperature change between -10°C and +55°C can be achieved in less than 3 minutes in the same thermal enclosure size. Cooling takes longer than heating, as expected; over the full 3GPP temperature window, cooling takes about 40 seconds longer (see ***Figure 5***). Using this ETC OTA setup supports all 3GPP conformance testing and additional stress testing while keeping test time reasonable. ■

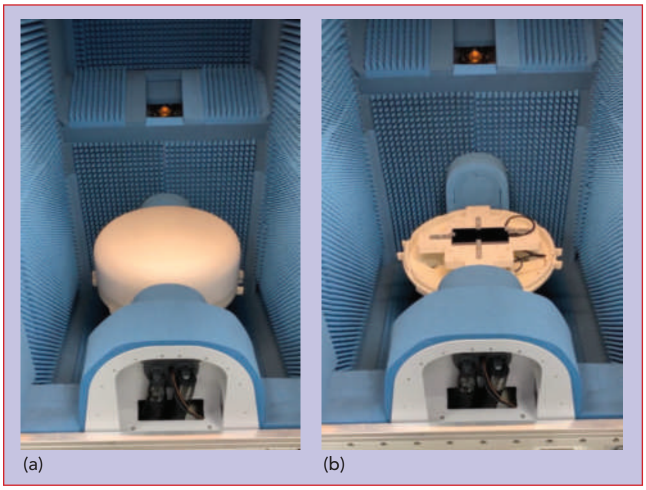

Fig. 4 **Inside of the ETC OTA test system with 35 l Rohacell thermal enclosure closed (a) and open showing a DUT (b).**

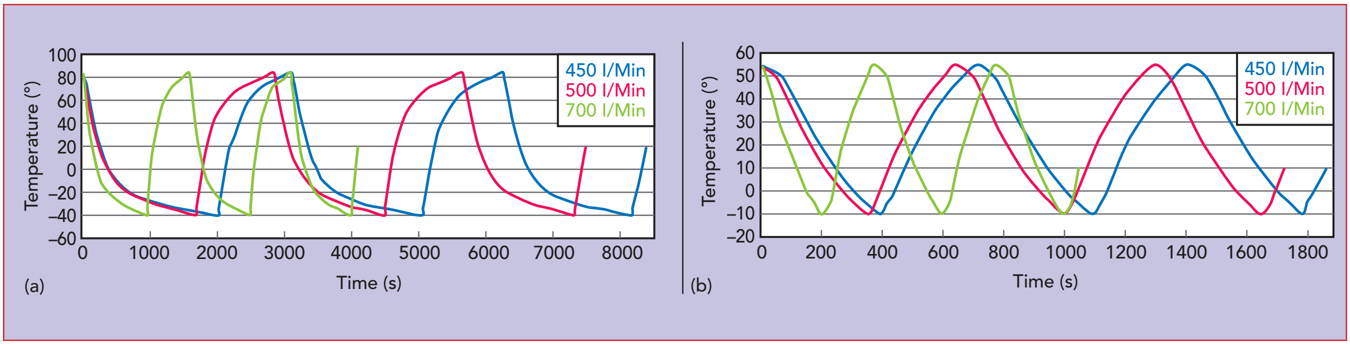

Fig. 5 **DUT temperature cycling times in 50 l enclosure at 450, 500 and 700 l/min air flow rates: –40°C to +85°C (a) and 3GPP range from –10°C to +55°C (b). Supply air temperature range from –60°C to +125°C.**

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The Trinity of Inaccuracy: Phase Noise, Jitter and Short-Term Stability –

What Everyone Should Know About Their Measurement and Interrelationships

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In electrical components and circuits, noise effects with different physical causes occur everywhere. In crystal oscillators there are three primary noise generating mechanisms: A ubiquitous background noise due to the thermal motion of the atoms and molecules of all components creates an insurmountable noise floor, which mainly affects noise far from the carrier (white noise). Noise caused by semiconductor components is called shot noise which has a 1/f dependence on the frequency. The dominant noise source close to the carrier is called flicker noise, which largely depends on the quality of the crystal. A high Q-factor of the crystal suppresses noise near the carrier. Depending on the application, noise is described differently; phase noise, jitter and short-term stability are different ways of looking at the same physical phenomena. This article provides an overview of the interrelationships.

Ideal oscillators produce a time-dependent, sinusoidal output voltage of the form:

$$u(t) = A_0 \sin(2\pi f_0 t) \quad (1)$$

with amplitude A_0 and frequency f_0. This sine wave has a perfect period, and the Fourier transform of u(t) is a spectrally pure delta function $\delta(f-f_0)$. A non-ideal, noisy signal u'(t) can be described in general terms by introducing a term for the amplitude noise $\in(t)$ and a term for the phase noise $\Delta\varphi$ (t) of the signal in the time domain given by:

$$u'(t) = (A_0 + \in(t)) \cdot \sin(2\pi f_0 t + \Delta\varphi(t)) \quad (2)$$

Here A_0 is the amplitude of the pure sinusoidal signal and f_0 its nominal fundamental frequency, which can be interpreted as a statistical mean value. In this case, the frequency spectrum is no longer spectrally pure, but a function of frequency, or more precisely, the Fourier transform of the time-dependent voltage signal.

Figure 1 shows the short-term frequency instabilities caused by the phase noise term. They show up in the time domain as a deviation of the zero crossings (phase angle) of the actual signal waveform compared to the ideal sinusoid. A modulation of the amplitude is not shown in this figure.

In the following discussion, only the temporal change of the phase angle is considered, which is caused by random, and thus Gaussian

distributed processes. In the following, the three most important forms of description, namely phase noise $L(f)$, jitter $\Delta T(\Delta f)$ and short-time stability $\sqrt{\sigma_y^2(\tau)}$ are described.

PHASE NOISE

Considering the phase instability of a signal source as phase noise is one of the possible representations to be considered in this article. The amplitude of the phase noise signal $L(f)$, more precisely the noise power spectral density of the phase noise, increases with increasing proximity to the carrier. An empirical description of the single-sideband phase noise is given by the so-called Leeson formula. It describes the amplitude of the phase noise as a function of carrier frequency f_0 of the oscillator, its quality factor Q_l, cutoff frequency f_c, noise factor of the amplifier F, Boltzmann constant k_B, absolute temperature T and output power P_s:

$$L(f) = 10\log\left[\frac{1}{2}\left(\left(\frac{f_0}{2Q_l f}\right)^2 + 1\right)\left(\frac{f_c}{f}+1\right)\left(\frac{Fk_BT}{P_S}\right)\right] \quad (3)$$

Without having to analyze this equation in detail, it is easy to estimate the behavior of phase noise for small and large frequencies f. For small frequency distances from the carrier, the two factors $\frac{f_0}{2Q_l f}$ and $\frac{f_c}{f}$ grow. Due to the monotonic property of the logarithm, $L(f)$ also grows. Far away from the carrier, for $f \rightarrow \infty$, these two terms vanish and the phase noise tends toward the value $10\log\left[\frac{1}{2}\left(\frac{Fk_BT}{P_S}\right)\right]$.[1]

Therefore, it is very important that a requirement for maximum phase noise includes the exact distance from the carrier at which a specific value of the phase noise is specified. The fraction close to the carrier is largely determined by the Q of the crystal, where the phase noise fraction for frequencies above 1 kHz is determined by the noise of the semiconductor devices used.

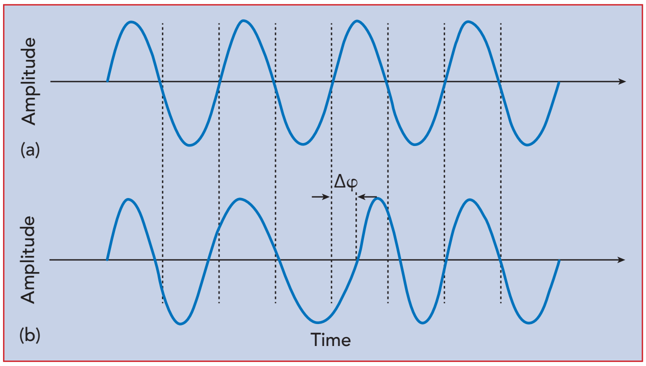


Fig. 1 Pure sinusoidal waveform (a) and effect of a random, time-dependent phase deviation = Δφ.

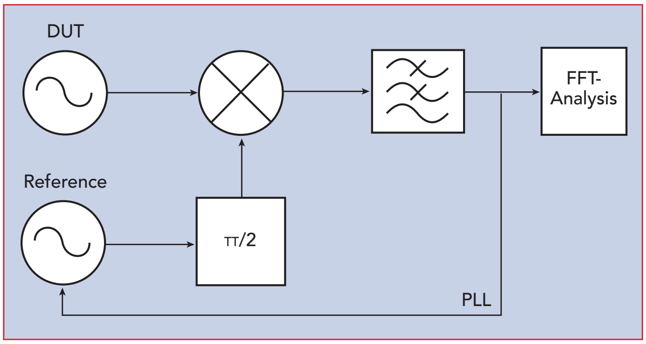


Fig. 2 PLL measurement for determining the phase noise of an oscillator (DUT).

In principle, the phase noise of an oscillator can always be measured (approximately) directly by means of a spectrum analyzer if the local oscillator of the measuring device has a significantly better phase noise performance than the device under test (DUT) and the sampling rate is far above the Nyquist frequency of the signal. Spectral analysis using a fast Fourier transform (FFT) can be used to determine the spectral distribution of the noise far away from the carrier frequency. Here, however, the measurement is limited by the noise characteristics and the limited sampling rate of the spectrum analyzer.

In the following, a much more precise measurement method is presented, which also enables the mea-

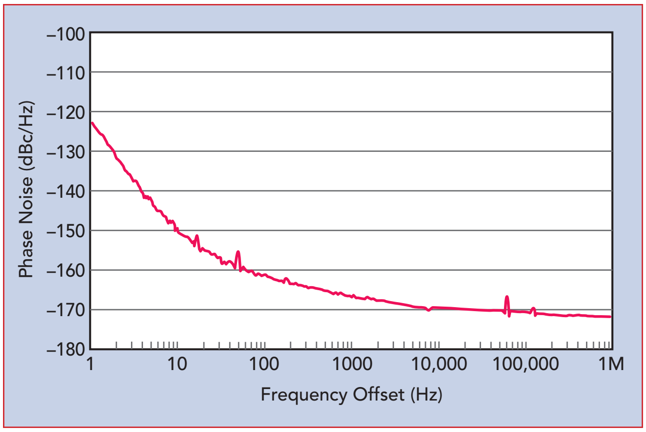


Fig. 3 **Phase noise measurement of an ultra-low phase noise oscillator with a carrier frequency of 10 MHz.**

surement of DUTs with extremely low phase noise. This method is generally valid and suitable for oscillators with high phase noise as well. To determine phase noise, the so-called phase detector method with phase locked loop (PLL) synchronization of the reference phase is used.

As shown in ***Figure 2***, this method uses a quadrature mixer as a phase detector. Here, the reference oscillator and the mixer form a PLL. By manipulating the control voltage of the reference oscillator, a condition is sought in which the signal of the test oscillator (DUT) and the signal of the reference oscillator have a phase shift of $\Delta\Phi=\frac{\pi}{2}$ with respect to each other at the same frequency. Both signals are mixed in a mixer element. In general, for given input signals f_a and f_b, the output signal of a mixer can be described as a superposition of the high frequency sum signal (f_a+f_b) and the low frequency difference signal $|f_a - f_b|$.

The unwanted sum signal at the output of the mixer is removed by means of a lowpass filter, so that only the difference signal remains. The low frequency signal component filtered in this way generates a time-dependent voltage v(t) whose maximum amplitude is determined by the scaling factor of the phase detector constant K_D. In general, K_D is device-dependent and has no influence on the calculation of the phase noise *L*(f).

$$v(t) = K_D \cdot \cos\left(\phi_{Ref} - \phi_{DUT}\right) = K_D \cdot \cos\left(\Delta\phi(t) - \Delta\phi\right) \qquad (4)$$

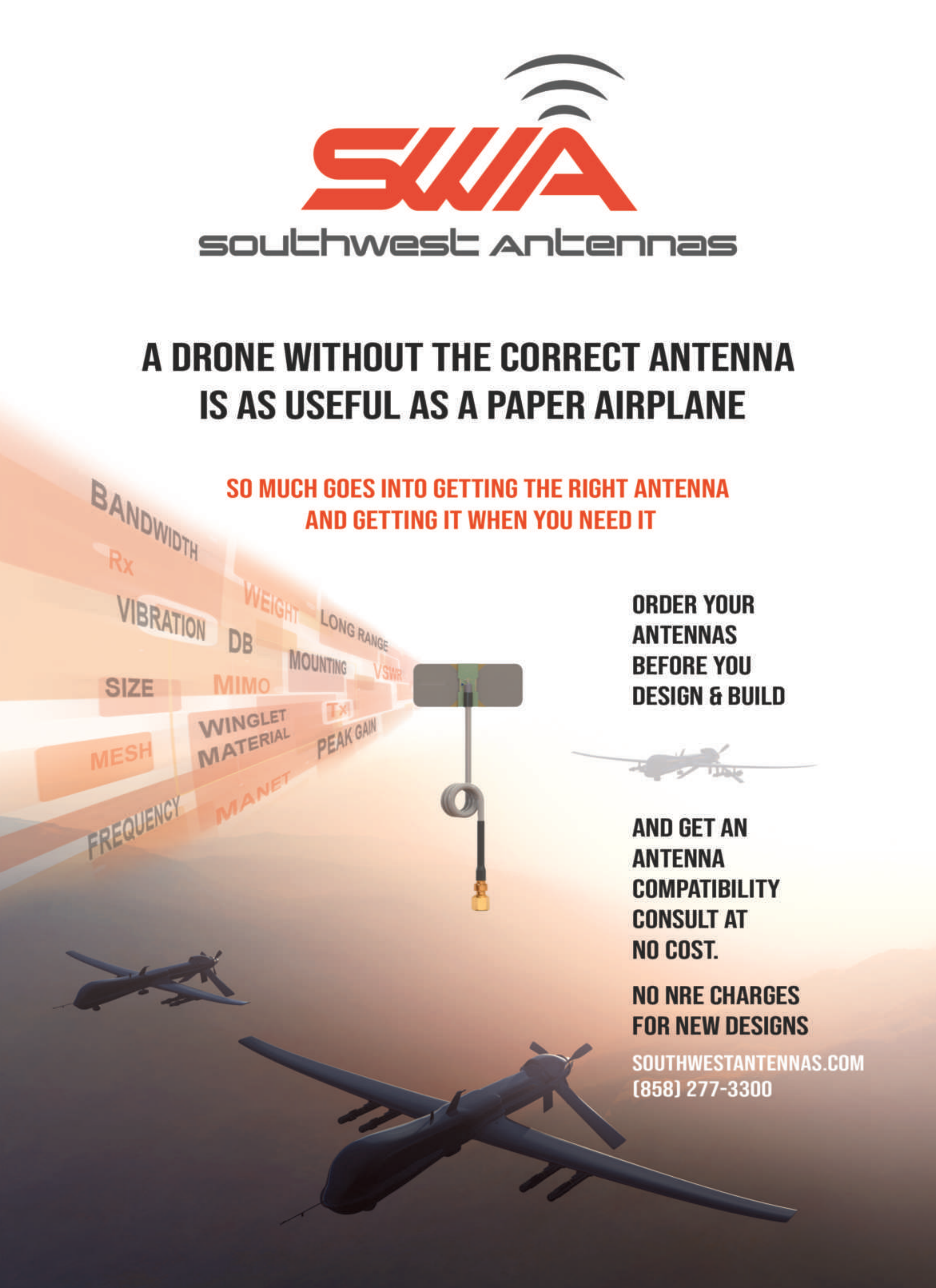
Considering the small-angle approximation cos(α)≈α for α<<1, Equation (4) can be simplified, assuming a mean phase difference of $\Delta\Phi=\frac{\pi}{2}$.

$$v(t) = K_D \cdot \cos\left(\Delta\phi(t) - \frac{\pi}{2}\right) = K_D \cdot \cos\left(\Delta\phi(t)\right) \approx K_D \cdot \Delta\phi(t) \qquad (5)$$

The output voltage v(t) of the phase comparator is evaluated as a measure of the phase changes in the time domain. The calculation of the single sideband phase noise *L*(f) is performed by means of an FFT in the frequency domain. If the reference oscillator has the same phase noise characteristics as the test oscillator, the measurement result must be corrected by -3 dB (factor of 0.5), since the uncorrelated noise powers of both oscillators add up. If the reference oscillator has a better phase noise by at least one decade, no correction is necessary.

Figure 3 is an example of a phase noise measurement of an ultra-low phase noise oscillator from KVG Quartz Crystal Technology with a carrier frequency of 10 MHz. The measurement was performed with a Holzworth phase noise analyzer with a measurement time of 1 hour. Both the near-carrier phase noise with a value of -122.5 dBc/Hz at 1 Hz offset and the phase noise of -169 dBc/Hz at 10 kHz show the limits of what is physically feasible.

A standard oven-controlled crystal oscillator (OXCO) at the same frequency has about 20 dBc/Hz worse phase noise at 1 Hz carrier offset than an ultra-low phase noise oscillator. Phase noise measurements are strongly sensitive with respect to mechanical or electromagnetic disturbances originating from the environment of the measurement setup. In Figure 3, small disturbances of the phase noise measurement can be observed, for example, at 50 Hz (mains frequency household current)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and 16.7 Hz (mains frequency of the German railway), which can be further minimized by suitable mains filters of the measurement equipment and the control voltage of the oscillator.

JITTER

In addition to phase noise, jitter is another representation of the deviation of the phase angle of a periodic signal. It can be graphically interpreted as the time deviation of a signal from its ideal position over a series of signal periods. With an ideal measuring device (infinite time resolution and no inherent noise), one could look at individual clock edges and derive a jitter value via an absolute time measurement. This is not possible, however, even with the best measuring devices available.

In practice, the jitter measurement is often derived from the phase noise measurement, previously described, and will be explained in more detail later. For a direct jitter measurement, a measurement by means of a so-called "eye diagram" is used, in which the measurement is performed relative to a reference edge.

The eye diagram consists of a superposition of many sections from the signal curve to be measured. An exemplary measurement setup is shown in ***Figure 4***. The signal from the DUT is split by a splitter with one signal path fed through a delay line whose delay is greater than the period of the signal. The non-delayed signal serves as a trigger and the delayed signal is applied to the input of the oscilloscope. This results in the phase shift always being measured relative to one of the preceding signal edges. By superimposing a large number of these measurements, a quantitative value of the jitter magnitude can be determined from the "opening of the eye diagram" by means of statistical analysis.

Figure 5 is an example of an eye diagram. Due to the intrinsic signal trigger, the signal edges are mapped on top of each other according to their phase shifts. From the superposition of several oscillation periods, quantities such as the average period duration and jitter can be determined. From the width of the signal distribution at zero crossing, a quantitative value for the jitter can be calculated on a statistical basis. In this example, the peak-to-peak value of the jitter is shown as the maximum expansion of the signal curve.

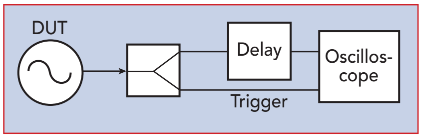

Fig. 4 Jitter measurement using a delayed signal.

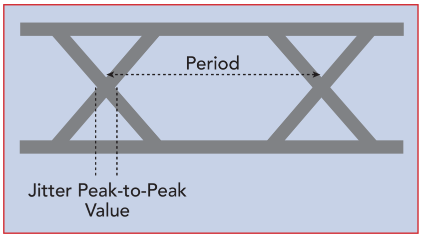

Fig. 5 Deriving jitter from the eye diagram.

This measurement method is limited by the noise of the oscilloscope below the frequency range $f = 1/(2 \pi \tau_d)$, where τ_d is the length of the delay line. Below this cutoff frequency, the sensitivity drops by about 20 dB per decade. Thus, this method is well suited for jitter measurements at frequencies far from the carrier, for example the sidebands.

The noise in oscillators is basically a superposition of stochastic processes. The peak value is therefore usually specified on a purely statistical basis using a Gaussian distribution as the distribution function. This results in a crest factor (ratio of peak value to RMS value) of 3 between the peak and RMS value, or factor of 6 between the peak-to-peak and RMS value. The maximum jitter amplitude is with a probability of 99.7 percent (deviation in the interval $\pm 3\sigma$) within the statistical limits of the specified peak-to-peak value. When measuring and specifying jitter, it is important to note whether the specification is expressed as the effective value (RMS), peak value (peak) or peak-to-peak value (peak-to-peak).

SHORT-TERM STABILITY

Along with phase noise and jitter, short-term stability can be used to describe phase deviations of a sig-

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KBK-HP-1100	10 - 1000	10	0.5	1.2 / 1.4	17 / 15	5
KDK-HP-255	20 - 550	20	0.4	0.25 / 0.35	23 / 18	27.5
SDCHP-255	20 - 550	20	0.4	0.25 / 0.35	23 / 20	27.5
SDCHP-335	30 - 350	20.1	0.85	0.24 / 0.32	24 / 20	75
SDCHP-484	40 - 840	19.2	0.9	0.3 / 0.4	24 / 20	30
SCCHP-560	50 - 560	14.6	0.7	0.48 / 0.65	23 / 20	75
SCCHP-990	90 - 900	15.2	0.6	0.52 / 0.64	20 / 17	38.3
SBCHP-2080	200 - 800	12.3	0.7	0.64 / 0.80	24 / 18	48.3
SBCHP-2082	200 - 820	11.0	0.5	0.74 / 0.9	22 / 19	22.5
KDS-30-30-3	27 - 512	27.5	0.75	0.3 / 0.4	23 / 15	50
KDS-30-30	30 - 512	27.5	0.75	0.3 / 0.4	23 / 15	50
KBK-10-225	225 - 400	11	0.5	0.6 / 0.7	25 / 18	50
KBS-10-225	225 - 400	10.5	0.5	0.6 / 0.7	25 / 18	50
KDK-20-225	225 - 400	20	0.5	0.2 / 0.4	25 / 18	50
KDS-20-225	225 - 400	20	0.5	0.2 / 0.4	25 / 18	50
KEK-706H	500 - 2500	31.5	2.5	0.28 / 0.4	18 / 12	100
SCS-8012D	800 - 1200	20	0.6	0.22 / 0.25	22 / 18	100
KEK-704DH-2	850 - 1250	30	0.25	0.20 / 0.30	28 / 25	500
KEK-704H	850 - 960	30 5	0.25	0.08 / 0.20	38 / 30	500
SCS100800-10	1000 - 8000	10.5	2	1.2 / 1.8	8 / 5	25
SCS100800-16	1000 - 7800	16.8	2.8	0.7 / 1	14 / 5	25
SCS100800-20	1000 - 7800	20.5	2	0.4 / 0.75	12 / 5	25
SCS-1522B	1500 - 2200	10	--	0.65 / 0.75	23 / 18	100
SCS-1522D	1500 - 2200	20	--	0.32 / 0.38	23 / 20	100
SCS1701650-16	1500 - 15500	17	2.5	1 / 1.4	16 / 5	25
SCS1701650-20	1700 - 15000	21	2.5	0.9 / 1.3	10 / 7	25
SDC360440-10	3600 - 4400	8.6	0.25	0.7 / 1.4	18 / 10	10
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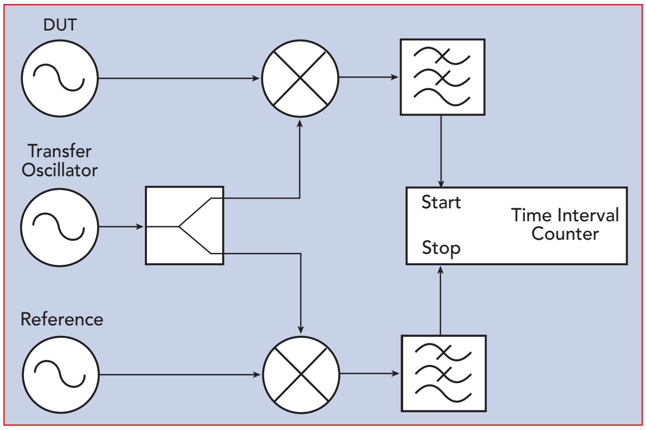

Fig. 6 Determining the short-term stability using a dual mixed signal.

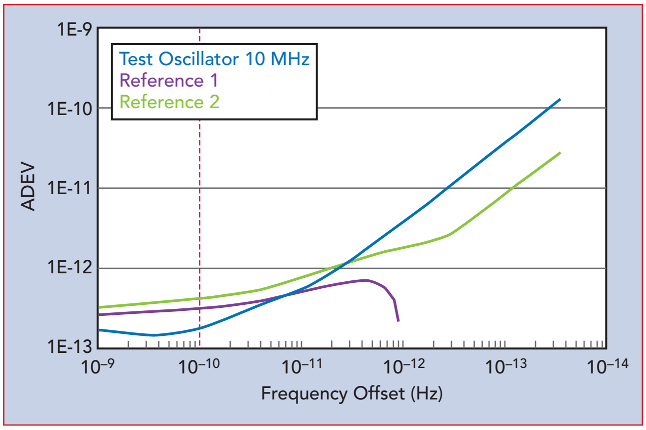

Fig. 7 ADEV measurement of a 10 MHz ultra-low phase noise oscillator.

nal. The Allan deviation, named after the physicist D.W. Allan, is used as a common measure of short-term stability. The Allan deviation (ADEV) is defined as the square root of the Allan variance $\sigma^2(\tau)$:

$$\mathrm{ADEV}(\tau) = \sqrt{\sigma^2(\tau)} \qquad (6)$$

Here, the Allan variance itself is defined as half of the expected value of the difference squares of two consecutive measured values (denoted here as y_n and y_{n+1}) of the normalized frequency deviation in the time interval τ. It should be noted that the ADEV is a function of the averaging time τ, which defines the period in which the average of the expected value is calculated.

$$\sigma^2(\tau) = \frac{1}{2}\left\langle (y_{n+1} - y_n)^2 \right\rangle \text{mit } y_n = \left\langle \frac{\delta f}{f} \right\rangle_n \qquad (7)$$

Compared to the classical variance, where the deviation from the mean is measured in each case, the Allan variance only considers the deviation of two successive measured values. This leads to a convergence for all kinds of noise even with long averaging times with a mean value drift (e.g., random walk processes).

The measurement of short-term stability in the form of the ADEV can be carried out in different ways. For low frequency signals and low short-term stability, the frequency deviation between two successive oscillation periods can be determined directly by an absolute time measurement. In the following, one of many possible measurement methods is presented, which is also suitable for the measurement of high precision signals.

As shown in ***Figure 6***, the dual mixer time difference method requires a reference oscillator and a so-called transfer oscillator in addition to the DUT. In this simple example, the reference oscillator must have better short-term stability than the DUT. During the measurement the transfer oscillator is slightly detuned against the other two signal sources. Here, a detuning of a few Hz up to a few kHz gives the best results, depending on the application.

By mixing this signal with the two signals of the DUT and the reference and subsequent lowpass filtering, two low frequency signals are produced. These signals are used as start and stop triggers for a time interval counter. With the interval counter the time difference between the zero crossings of both signals is measured. Depending on the desired averaging time τ, an

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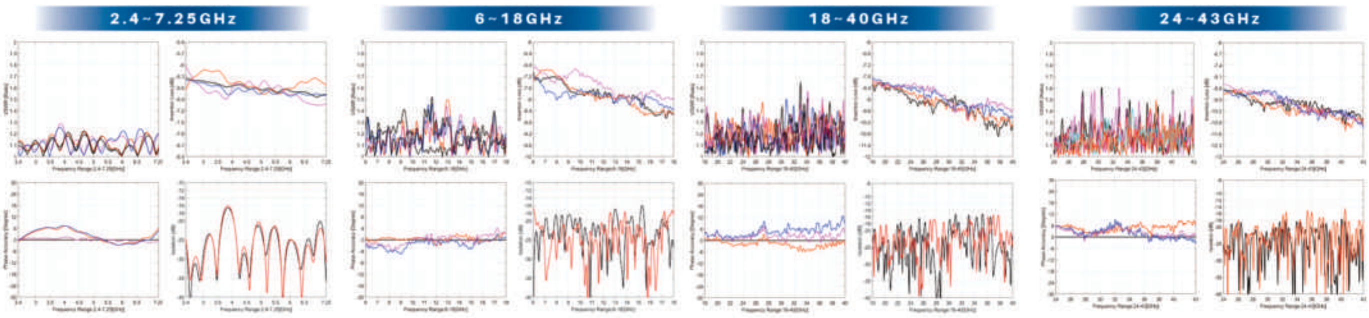
SA-07-4B020080	2.4~2.5	1.4	7.3	±0.5	±0.3	±4	14	100	±5
	5.18~5.83	1.5	7.7	±0.6	±0.4	±5	13		
	5.9~7.25	1.5	7.8	±0.7	±0.5	±6	13		
SA-07-4B060180	6~18	1.8	9.5	±1.1	±1.4	±12	12	100	±8
SA-07-4B180400	18~40	2.0	12.0	±1.2	±2.0	±15	10	200	±8
								400	±10
SA-07-4B240430	24~43	2.0	12.4	±1.2	±2.0	±15	10	200	±8
								400	±10

*Theoretical 6dB Included

— Typical Test Curve** —



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Tel: +86-591-87382856 Email: sales@micable.cn Website: www.micable.cn adequate frequency offset of the transfer oscillator must be set.

If the short-term stability of the reference oscillator is not significantly better than that of the DUT, this can no longer be neglected. This effect can be mathematically corrected by using another reference oscillator. For this purpose, we refer to the so-called "three-cornered hat method."[2]

Figure 7 is an example of an ADEV measurement of an ultra-low phase noise oscillator from KVG Quartz Crystal Technology with a carrier frequency of 10 MHz. Because the DUT has very good short-term stability, the measurement was performed using the three-cornered-hat method. Two oscillators with 10 MHz each were used as references. The total measurement duration was 4 hours, the sample interval was 0.1 s. The test oscillator achieved an ADEV of 1.8×10^{-13} at a time interval of $\tau=1$ s.

RELATIONSHIP OF THE DIFFERENT REPRESENTATION TYPES

Phase Noise and Jitter

As previously described, phase noise and jitter are two different ways of describing the same physical signal property; therefore, it is obvious to look for possibilities to relate them. Jitter within a defined frequency range can be calculated from the measured values of phase noise by integrating *L*(f) over the frequency. The jitter power P in the frequency interval f_1 to f_2 is defined for a given single-sideband phase noise *L*(f) as:

$$P(f_1, f_2) = \int_{f_1}^{f_2} \frac{L(f)}{2\pi f_0} df \qquad (8)$$

It should be noted that the phase noise is normalized by a factor of $2\pi f_0$, where f_0 represents the carrier frequency. This also ensures the correct conversion of units.

The RMS value of jitter $\Delta T(\Delta f)$ in the specified frequency range can be calculated as the square root of the jitter power P:

$$\Delta T(\Delta f) = \sqrt{P} \qquad (9)$$

As previously mentioned, this conversion provides another indirect way of measuring jitter. Often in practice, phase noise is determined for a typical offset range from 1 Hz to about 10 MHz. From this, the resulting jitter value can then be flexibly calculated by integration over different frequency ranges (see ***Figure 8***).

A reverse calculation of phase noise from measured values of jitter over certain bandwidths is mathematically not possible, since for this the jitter would have to be known for all possible bandwidths/frequency intervals.

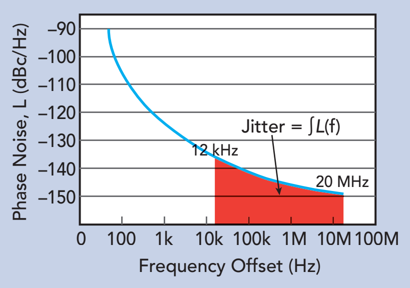

Fig. 8 Jitter can be calculated by integrating the phase noise over a frequency interval.[3,4]

Phase Noise and Short-Term Stability

Short-term stability can also be determined mathematically from the values of *L*(f). The transition from phase noise, which is a function of frequency, to ADEV, which is a function of time, can be described by means of a Fourier transform. The derivation of this transform is far beyond the scope of this article, so reference is made to Barnes et al.[5]

As a result, the Allan variance $\sigma_y^2(\tau)$ can be written as an integral over the entire frequency range with carrier frequency f_0, averaging time τ and frequency offset f as integration variables.

$$\sigma_y^2(\tau) = 2\int_0^{\infty} S_y(f)\cdot\frac{\sin^4(\pi f\tau)}{(\pi f\tau)^2}\,df$$

such that

$$S_y(f) = 2\frac{f^2}{f_0^2}L(f) \qquad (10)$$

The property from Equation (10) imposes certain conditions on the spectral distribution of the phase noise, for example, that the magnitude of the phase noise becomes very small for large distances from the carrier. These constraints also go very deep mathematically, so no further consideration is given.

SUMMARY

The need for high precision frequency sources, such as quartz oscillators, with extremely low noise characteristics is undisputed for modern technology of the 21st century. Whether it be measurement technology, data transmission or navigation—in all areas there are applications that place the highest demands on signal sources.

Depending on the field of application, a different one of the described measurement quantities is proven to be practical. In telecommunications, the specification of a maximum jitter value is usually resorted to, since it can be used to derive how high the bit error rate is during the transmission of discrete information. In metrology, on the other hand, the oscillator is often characterized by a phase noise curve, in which the phase noise values are specified at different distances from the carrier signal depending on whether phase noise close to or far from the carrier is relevant for the specific application.

Since all approaches are based on the same physical phenomenon, a conversion from one form of representation to the other can be performed if the data basis is sufficiently complete. ■

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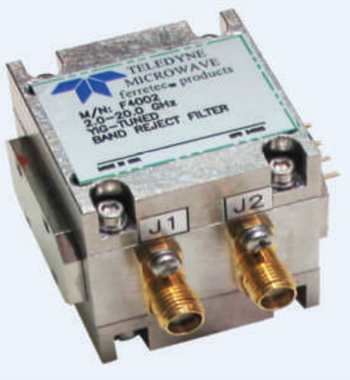
2. F. Vernotte, M. Addouche, M. Delporte and M. Brunet, "The Three Cornered Hat Method: An Attempt to Identify Some Clock Correlations," *Proceedings of the IEEE International Frequency Control Symposium and Exposition*, August 2004.
3. "Understanding Jitter Units," *Renesas Electronics Corporation*, Application Note AN-815, Rev. A, March 2014, Web: https://www.renesas.com/eu/en/document/apn/815-understanding-jitter-units?language=en.
4. D. Herres, "Measuring Oscillator Jitter," *EE World*, August 2017, Web: https://www.testandmeasurementtips.com/measuring-oscillator-jitter/.
5. J. A. Barnes, A. R. Chi, L. S. Cutler, D. J. Healey, D. B. Leeson, T. E. McGunigal, J. A. Mullen, W. L. Smith, R. L. Sydnor, R. F. C. Vessot and G. M. R. Winkler, "Characterization of Frequency Stability," *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-20, No. 2, May 1971, pp. 105–120.

500 MHz to 20 GHz, YIG-Based Notch Filters for EW



Developed for electronic warfare (EW) systems, Teledyne RF & Microwave offers a family of three tunable notch filters that use its patented shunt yttrium iron garnet (YIG) technology. Because YIG spheres have such high Q, Teledyne's YIG filters achieve "super notch" performance: greater rejection over a narrower bandwidth than other notch filters, including competing YIG filters.

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The frequency of the filter's notch is tuned with a current source, which has a typical tuning sensitivity of 10, 20 and 20 MHz/mA for the three models. The YIGs use a built-in heater, which is biased with 28 V and draws a steady state current of approximately 150 mA. Over the 0°C to +70°C temperature range, the temperature drift is 10 MHz for the F3874 and F3875 models and 20 MHz for the F4002.

Teledyne RF & Microwave also offers oscillators and bandpass filters that use its YIG technology, as well as a complete line of RF/microwave components for aerospace and defense: e.g., amplifiers, switches, power dividers, mixers and circulators.

Teledyne RF & Microwave
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Small Power Sensors with USB C Interface

LadyBug Technologies is developing a new series of small form factor, USB C power sensors, designated SF. Combining small size with the capability to measure multiple signal types—from single tone and multi-tone CW to wideband, complex digital waveforms—the SF series will provide an attractive combination of performance, size and cost.

The SF line will have both diode sensors with > 95 dB dynamic range and thermally-based CW sensors with frequency coverage to 110 GHz. LadyBug will release lower frequency models in early 2023, with the thermally-based sensors by the end of the year. The thermal sensors, fabricated with a new foundry process, will extend frequency coverage to V-, E- and W-Band. All transducer technologies have sub-millisecond rise times, and all sensor models use LadyBug's patented NoZero NoCal functionality, which is stable over temperature and traceable to NIST (first-tier).

This SF series of power sensors is the first to adopt the type C USB interface. USB enables PC connectivity with triggering and embedded system control to be achieved with a single, standard connector. USB communication will continue using the USB 2.0 protocol to support the widest range of computers, operating systems and interface standards, including SPI, I2C, Ethernet and SCPI.

SF power sensors will work well from the lab to ATE systems on the manufacturing floor, particularly where small size is important. For example, 16 sensors can be placed side by side in a 1U rack, eliminating the need for a 16-way switch feeding a single power sensor in an ATE system.

VENDORVIEW

LadyBug Technologies LLC
Boise, Idaho
www.ladybug-tech.com

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KRYTAR Inc. announced the continued expansion of its line of ultra-broadband directional couplers with the addition of a new model offering 16 dB of nominal coupling over the frequency range of 1 to 65 GHz (S- through V-Bands), in a compact and lightweight package. KRYTAR's latest addition, model 101065016, enhances the selection of multi-purpose, stripline designs that exhibit excellent coupling. This coupler offers the ultimate solution for emerging designs and test and measurement applications including mmWave and 5G.

KRYTAR Inc.
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MMIC Frequency Tripler

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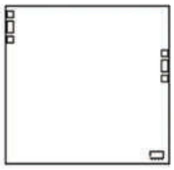

Mini-Circuits' model CY3-453-DG+ MMIC frequency tripler delivers output signals from 20 to 45 GHz. It accepts inputs from 6.66 to 15.00 GHz at typical power levels of +12 to +17 dBm and provides output signals with conversion loss of typically 19.0 to 20.3 dB and fundamental and harmonic suppression of -25 dBc or better. Based on GaAs HBT technology, the 50 Ω tripler die measures 2500 × 2400 µm and is a good fit for back-haul radio, satcom and test applications.

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PS RF Cable Assemblies

VENDOR**VIEW**

FastEdge™ PS RF cable assemblies feature enhanced phase and amplitude stability with flexure without sacrificing flexibility. The PS series distinguishes itself by guaranteeing a maximum phase and insertion loss stability specification. They are optimized for laboratory and production test environments that require precise and repeatable measurements. The flexibility of FastEdge™ PS cables reduces mechanical stresses on the device under test as compared to phase stable assemblies from other manufacturers.

Swift Bridge Technologies
www.swiftbridgetechnologies.com

AMPLIFIERS

Solid-State X-Band Pulse Amplifier

VENDOR**VIEW**

Exodus Advanced Communications' AMP4022DBP-4KW Pulse Amplifier is designed for pulse/HIRF, EMC/EMI MIL-STD-461/464 and radar applications. Providing superb pulse fidelity and up to 100 usec pulse widths. Duty cycles to 6 percent with a minimum 66 dB gain. Available monitoring parameters for forward/reflected power in watts, dBm, VSWR, voltage, current and temperature sensing for outstanding reliability and ruggedness for compact integrations.

Exodus Advanced Communications
www.exoduscomm.com

Temperature-Compensated Amplifiers

VENDOR**VIEW**

Fairview Microwave Inc. has released a series of temperature-compensated amplifiers to address precision performance and test and measurement applications. Fairview's new series of coaxial packaged, temperature-compensated amplifiers covers broadband and ultra-broadband frequencies ranging from 0.5 to 40 GHz. Designs incorporate pin diode attenuation circuitry that senses and adjusts broadband gain levels and maintains a minimum gain level of 35 dB over the full operational temperature range of -67°F to +185°F.

Fairview Microwave Inc
www.fairviewmicrowave.com

New**Products**

Low Noise Amplifier

VENDOR**VIEW**

Quantic PMI model PE2-20-1G40G-5R5-15-12-292FF is a low noise amplifier that operates over the frequency range of 1 to 40 GHz and provides +20 dB minimum gain with gain flatness of ±2.75 dB maximum; noise figure of 4.0 dB typical; VSWR in/out 2.5:1; OP1dB 15 dBm minimum and input power of +17 dBm maximum. This amplifier is supplied with 2.92 mm connectors in a housing that can be used as a surface-mount or connectorized component.

Quantic PMI
www.pmi-rf.com

SOURCES

OCXOs

Raltron is enabling communications networks around the globe with its OX7000 Series, the smallest SMD oven controlled crystal oscillator (OCXO) available on the market. At only 9 x 7 mm, the OX7000 Series features superior temperature stability in an ultra-small package and is designed for all aspects of 5G wireless infrastructure, network interface cards, transmission and base station application requirements. The OX7000 Series covers a frequency range from 10 to 40 MHz with a power supply voltage of 3.3 V at 150 mA steady state.

Raltron
www.raltron.com

TEST & MEASUREMENT

RF Microwave Generator

RIGOL Technologies announced a new RF microwave generator, the DSG5000 Series, that can generate up to 20 GHz carriers with high signal fidelity. These new generators are available with two, four, six or eight independent RF channels packaged in a single 2U full width mainframe. The DSG5000 Series features impressive long-term phase stability between channels of ±1 degree and is designed for high frequency signals in applications like radar and quantum research.

RIGOL Technologies
www.rigolna.com

Diode Power Sensors

VENDOR**VIEW**

The new R&S NRP90S and R&S NRP90SN power sensors from Rohde & Schwarz provide unheard-of performance in power measurements. The new instruments combine an extraordinary frequency range of 50 MHz to 90 GHz with a dynamic range from -70 to 20 dBm along with high measurement speeds of 50,000 measurements per second. Compared to current thermal power sensors for measurements over 67 GHz, the diode technology increases the power measurement dynamic range by 35 dB and significantly cuts test times.

Rohde & Schwarz
www.rohde-schwarz.com

Chip War: The Fight for the World's Most Critical Technology

Chris Miller

In the 1980s, the American semiconductor industry lost ground to Japan. Japan's use of continuous quality improvement led to better quality and, after emerging from denial, U.S. industry embraced quality gurus—Joseph Juran and Phil Crosby, authors of "Quality Is Free"—and initiatives such as Six Sigma and the Malcolm Baldrige National Quality Award. Despite U.S. improvements in semiconductor quality, Japan remained a center for new wafer fabs because of the country's lower cost of capital. The interest on a billion dollar investment was, as a former colleague said, "adult money."

Over the next decades, South Korea and Taiwan built semiconductor industries, often beginning with the lowest cost devices that were hard for the U.S. and Europe to competitively produce. The inexorable capitalist pull of gravity led to China, as the country traded low cost labor in exchange for economic development, bootstrapping its entry into high tech, including, of course, semiconductors.

If the U.S. government considered the implications of this flow of technology, the DoD was the most vocal about the looming threat, concerned that China would use the latest generations of silicon and compound semiconductors to enable its weapons systems and erode U.S. technology leadership. The threat became more apparent with the authoritarian regime of Xi Jinping and the near juggernaut growth of Huawei. The pandemic and Russian invasion of Ukraine provided double exclamation points on U.S. dependence and vulnerability to China. The Trump and Biden administrations moved to restrict, then stop, exporting the latest semiconductor products and manufacturing technologies to China, and Congress passed the CHIPS and Science Act to invest in U.S. semiconductor facilities and R&D, mimicking China's policy of state and "private" company collaboration.

"Chip War, the Quest to Dominate the World's Most Critical Technology" tells a synopsis in fascinating and readable detail. It was researched and written by Chris Miller, who teaches international history at the Fletcher School at Tufts University. There's no better primer as we watch the "chips act" unfold.

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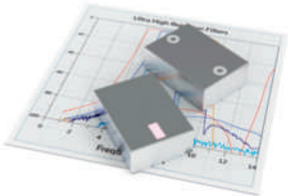

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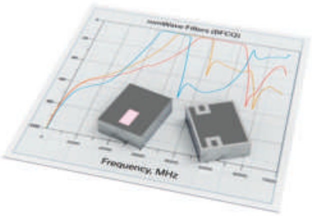

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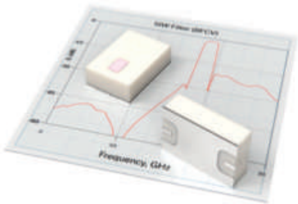

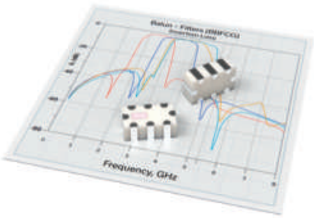

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Maury Microwave: For 65 Years, Always Part of The Solution

Maury Microwave is one of a handful of eponymous RF/microwave companies that proudly reflects the legacy and vision of its founders—in this case 65 years after Mario Sr., Mario Jr. and Marc Maury started the company in southern California. Anyone working in the microwave industry quickly learns the importance of precision. While the frontier today may be mmWave and sub-THz, low GHz measurements were the challenge when Maury Microwave was founded. Maury's mission was and is to ensure they are accurate.

After three generations of family leadership, the company was acquired by Artemis Capital Partners in 2021. But the mission is the same: ensuring confidence in RF through THz measurements and models by providing the best, proven characterization solutions, components and services. Over the decades, Maury's products expanded, from vector network analyzer (VNA) calibration kits to rugged, precision cables. The company realized that the painstaking effort to calibrate a VNA could be compromised by the cables used for measurements. The next challenge was power amplifier (PA) design. As computing power enabled designers to extend simulation beyond simple load line analysis, Maury developed systems for load-pull measurements. Load-pull characterization enables a designer to precisely map the output power, efficiency, harmonics and gain contours of a semiconductor device, then define the PA load to optimize the performance.

Today, the company organizes its activities around four product lines: device characterization, precision calibration, interconnects and instrument amplifiers. Along the way, Maury acquired Anteverta-mw in 2015 and dBm-Corp in 2021. Anteverta-mw, based in Eindhoven, had developed a novel load-pull technology for active impedance control with wideband modulated signals, enabling device characterization with real-world signals. dBm, based in Oakland, N.J., brought system-level testing of satellite payloads and wireless systems, enabling Maury to add systems solutions to the portfolio.

The heart of the company remains in Ontario, Calif., a 90,000 square-foot facility that houses R&D, manufacturing, calibration and repair services, warehousing and shipping. Almost half of the facility—40,000 square feet—is dedicated to internal manufacturing, assembly and test of its precision coaxial and waveguide components. Maury has 15 advanced CNC milling and lathe cells, wire electrical discharge machining, honing and heat treatment capabilities. To guarantee precision tolerances, Maury uses optical and touch probe coordinate measuring machines, laser micrometers and air gages, as well as other standard inspection equipment. To assess RF performance, 20 VNAs support the metrology, interconnect and tuner product lines.

The Ontario facility also has a 3000 square-foot measurement and modeling lab with capabilities that are an engineer's dream: DC and pulsed IV measurements to 250 V and 30 A, S-parameter measurements to 170 GHz for CW and 67 GHz for pulsed. Load-pull testing comprises passive load-pull to 110 GHz, active to 170 GHz and harmonic to 67 GHz. Noise parameters and noise figure can be measured to 90 GHz, and Maury has a Faraday cage to avoid interference. The lab also has capabilities to measure mixers and transmit/receive signal chains to 67 GHz. Both fixtures and automated on-wafer measurements are supported, on-wafer with 200- and 300-mm probe stations. Fixture measurements support power levels to 1 kW pulsed. Following characterization, device modeling capabilities include enhanced poly harmonic distortion (EPHD) and neural network behavioral models to 67 GHz. The Ontario quality system is certified to ISO9001 and AS9100; its testing and calibration capabilities meet ISO/IEC 17025 requirements.

Reflecting the Maury family legacy, the company remains committed to using measurement science to serve the RF/microwave industry and help its customers develop new generations of products. Design success begins with accurate simulation, which relies on measurement accuracy. That's Maury Microwave's commitment, to always be part of the solution.

www.maurymw.com

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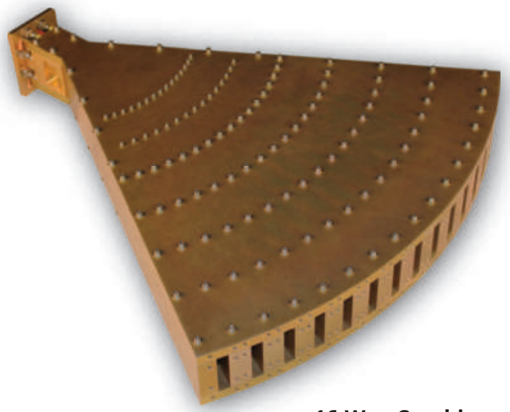

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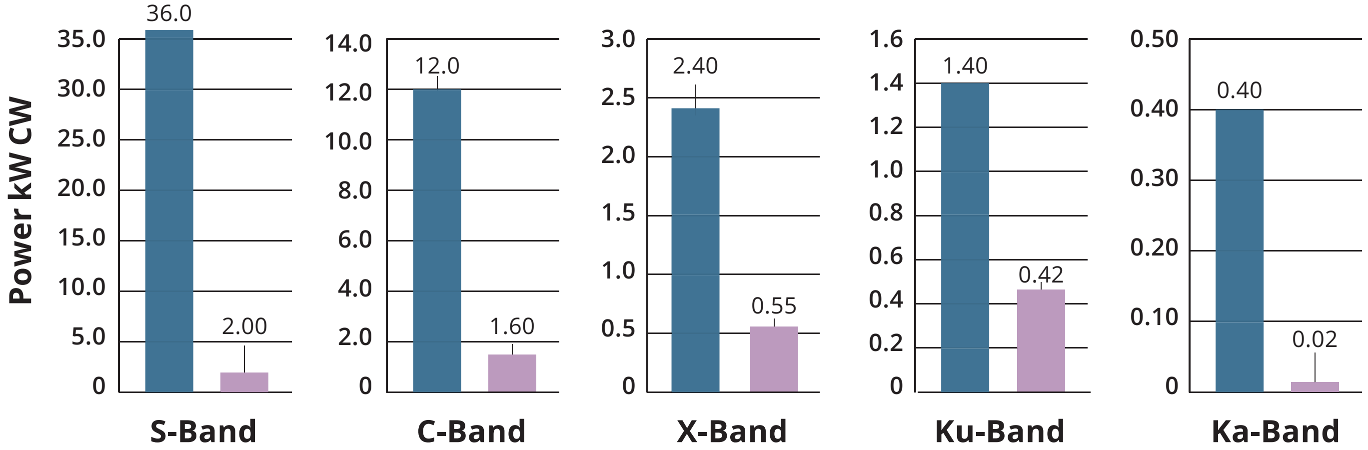
CW Power ■ E-Plane Combiner vs. ■ Radial Combiner



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