Vol. 62 • No. 3
March 2019

# Microwave Journal

# 5G OTA

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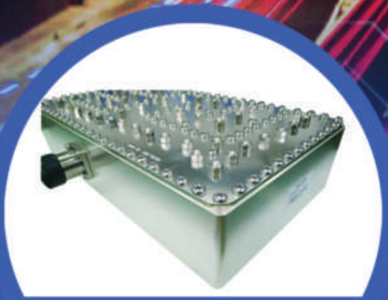
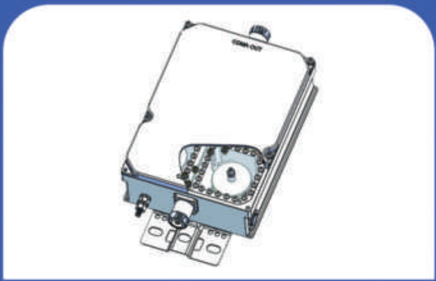
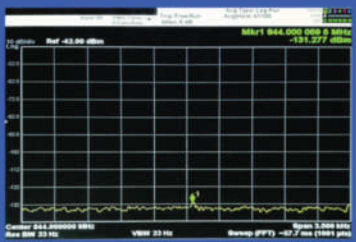


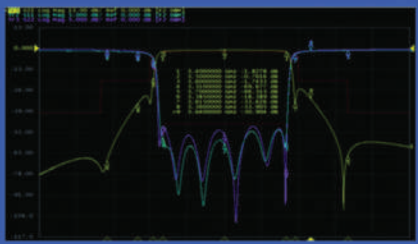
Low PIM Product



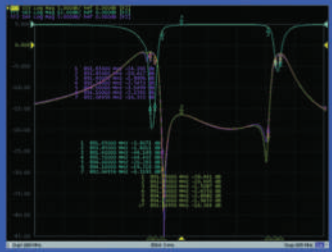
Sharp Notch Product



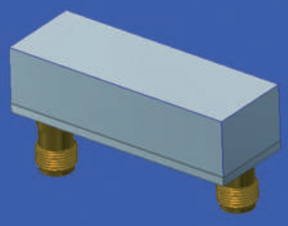
Low PIM Test Curve



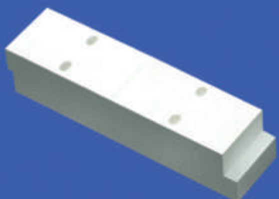
Dielectric Waveguide Test Curve



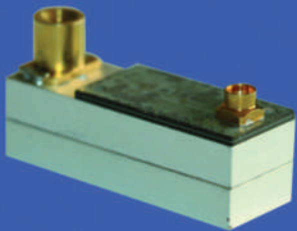
Sharp Notch Test Curve



Metallic Filter



Dielectric Waveguide Filter



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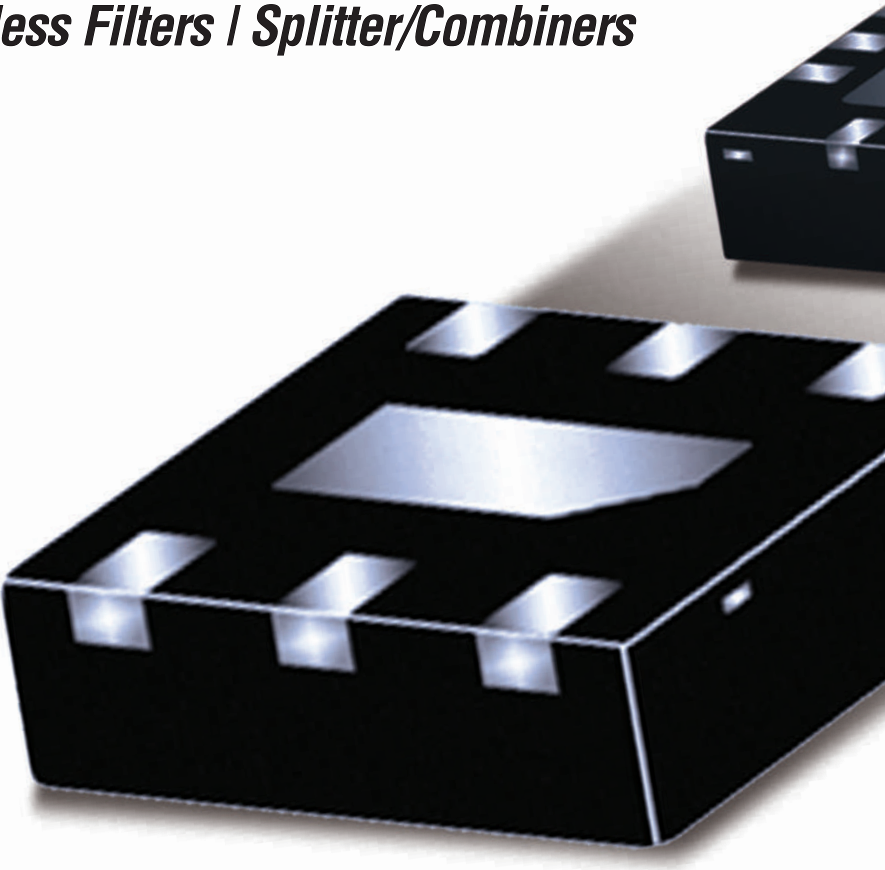

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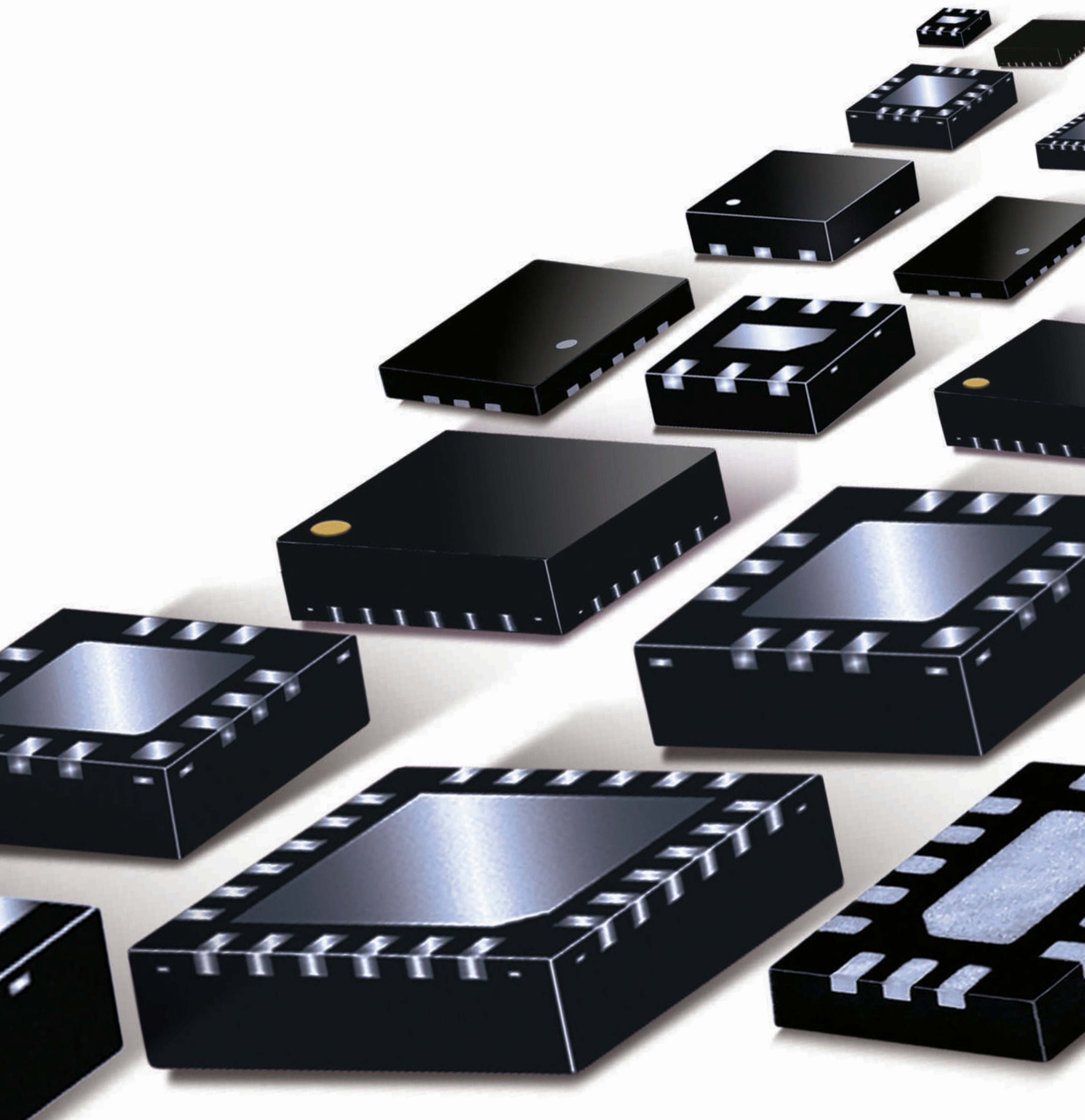

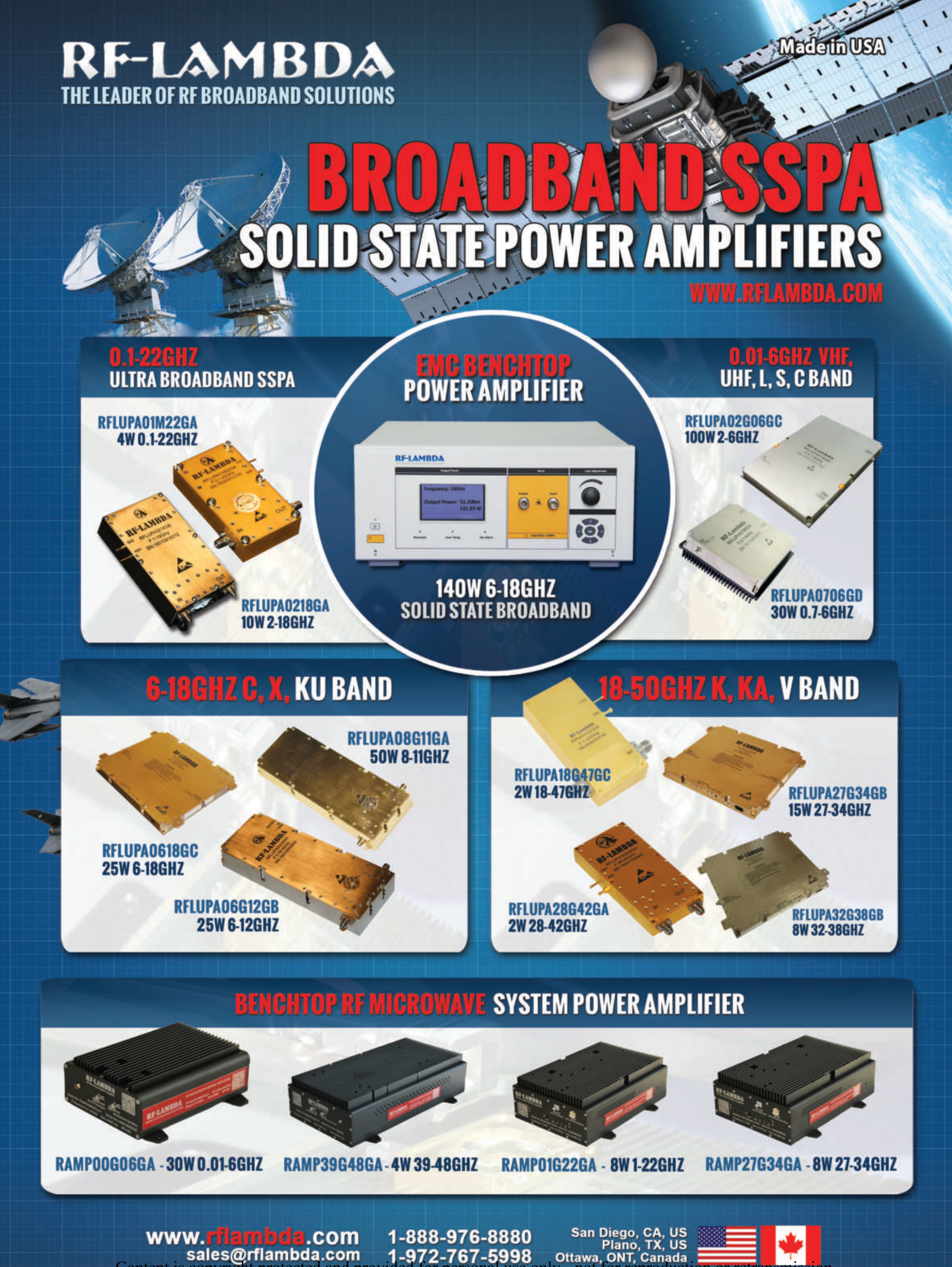
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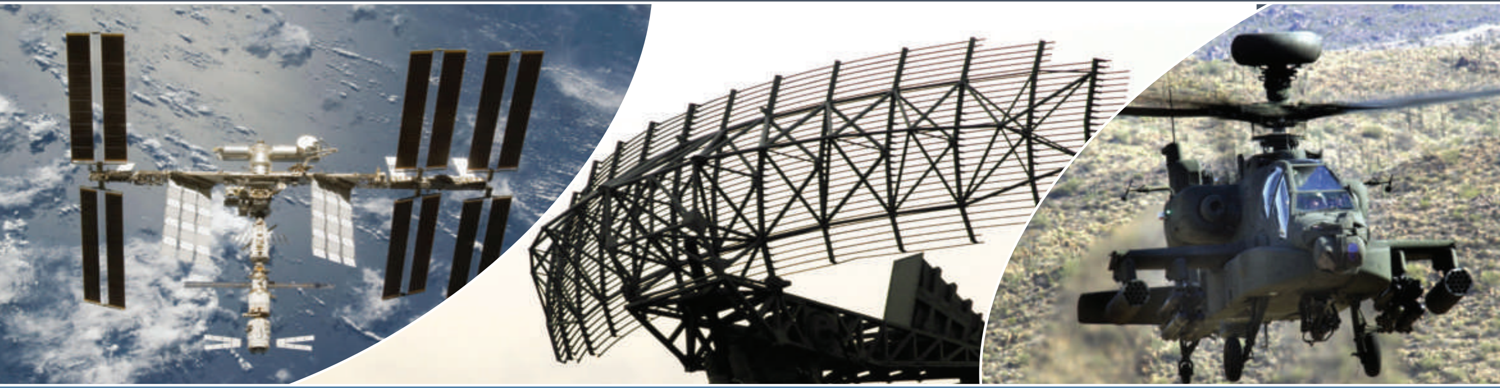

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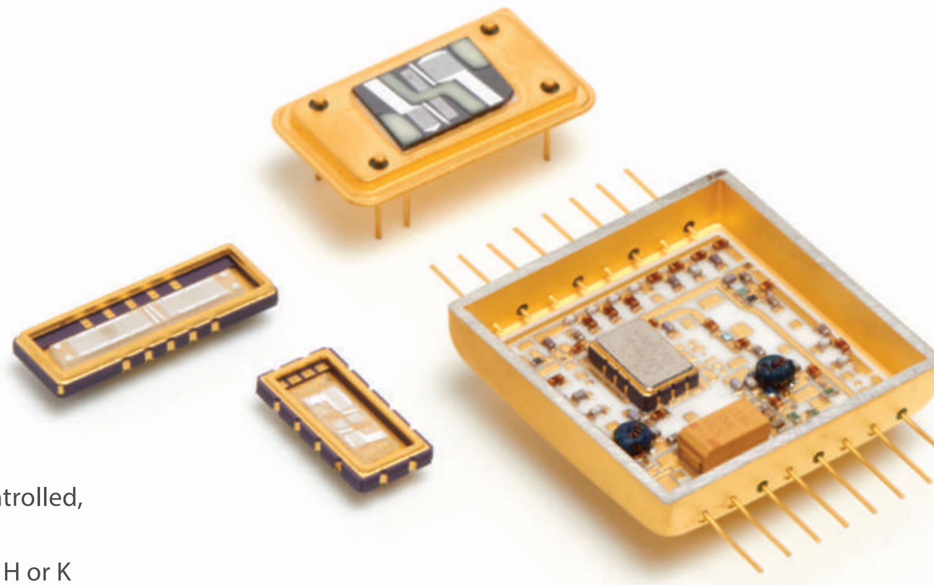

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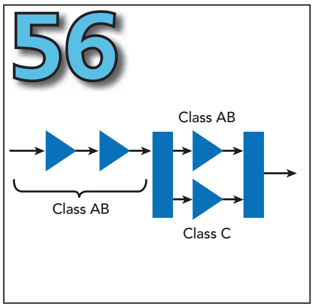


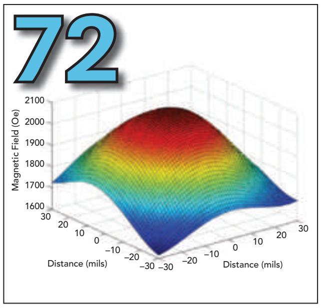


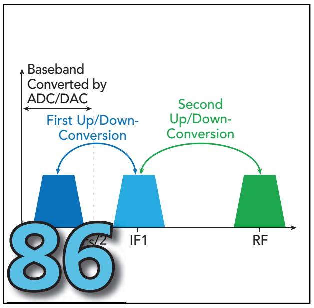


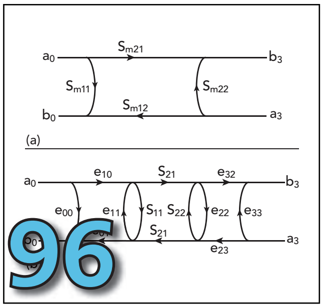


## Cover Feature



## Technical Features



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# E LEARNING CENTER

**GaN Electrothermal Modeling for 5G MMIC Power Amplifier Designs**
*Sponsored by: National Instruments* **3/6**

**GaN-Based 5G and Pulsed Signal Measurements**
*Sponsored by: Boonton* **3/26**

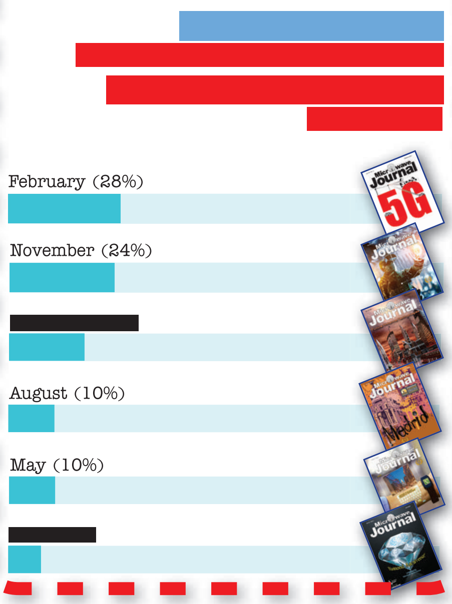
**Critical Material Properties for Millimeter-Wave Radar Applications for Autonomous Driving**
*Sponsored by: Rogers* **3/28**

## Executive Interviews

**Diane Delaney**, president of **Delta Electronics Manufacturing**, discusses the company's broad portfolio of interconnect products, the market trends driving new products and the similarities between teaching and leading a business.

**Ted Heil**, president of **Mini-Circuits**, reflects on the company's 50-year history as an innovator and how the company is building on that reputation to help enable future market opportunities.

## Survey




## WHITE PAPERS

Anokiwave — Introduction to All Silicon Millimeter-Wave 5G Arrays

Knowles — RF Filtering For 5G Millimeter Wave Applications

Rohde & Schwarz — Triggering Read and Write Cycles of DDR3 Memories

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## 1-3

EDI CON 2019 Electronic Design Innovation Conference 电子设计创新大会

Beijing, China

EDI CON China 2019 celebrates electronic design innovation, bringing together RF, microwave, EMC/EMI and high speed digital design engineers and system integrators for networking, training and learning opportunities. Attendees come to EDI CON to find solutions, products and design ideas that they can put into immediate practice.
**http://ediconchina.com/**

## 8-9

WAMICON

Cocoa Beach, Fla.

The 20th annual IEEE WAMICON 2019 central theme will focus on "Simulation Driven Design of Emerging Wireless, Microwave and mmWave Circuits and Systems." The conference features an active vendor exhibition area, an array of networking opportunities, oral and poster presentations, tutorials and special sessions.
**www.wamicon.org**

## 10

WEBINAR

**MIMO Radar: Introduction and Applications**

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## 15-17

EXPO ELECTRONICA

Moscow, Russia

The Expo Electronica 2019 exhibition will feature electronic, semiconductor, electromechanical, passive components, PCB and chips, a display, embedded systems and much more. Exhibitors are leading Russian and international manufacturers and suppliers of electronic components, modules and components.
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## 16

WEBINAR Signal Integrity Journal

**Understanding SNDR**

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## 29-5/2

CS MANTECH

Minneapolis, Minn.

The 32nd annual CS MANTECH conference has more than 80 presentations and posters delivering the latest insights into technology trends, manufacturing innovations and practices and materials and device development.
**http://csmantech.org/**

## 29-5/2

AUVSI XPONENTIAL ALL THINGS UNMANNED

Chicago, Ill.

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# ComingEvents

## CALL FOR PAPERS

2019 IEEE International Symposium on Phased Array Systems and Technology
March 15

ITC 2019
March 29

SEMICON West 2019: Smart Manufacturing
April 8

IEEE COMCAS 2019
April 18

AMTA 2019
April 26

SEMICON West 2019: Test Vision 2020
May 4

BCICTS 2019
May 10

Asia Pacific Microwave Conference 2019
June 30

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## MARCH

**EMV 2019**
March 19–21 • Stuttgart, Germany
https://emv.mesago.com/events/en.html

**RF & Microwave 2019**
March 20–21 • Paris, France
www.microwave-rf.com

**GOMACTech 2019**
March 25–28 • Albuquerque, N.M.
www.gomactech.net/2019/index.html

**2019 IEEE Texas Symposium on Wireless and Microwave Circuits and Systems**
March 28–29 • Waco, Texas
https://texassymposium.org/

## APRIL

**EDI CON China 2019**
April 1–3 • Beijing, China
http://ediconchina.com/

**WAMICON 2019**
April 8–9 • Cocoa Beach, Fla.
www.wamicon.org/

**Expo Electronica 2019**
April 15–17 • Moscow, Russia
www.expoelectronica.ru/en-GB

**CS Mantech 2019**
April 29–May 2 • Minneapolis, Minn.
http://csmantech.org/

**AUVSI Xponential 2019**
April 29–May 2 • Chicago, Ill.
www.xponential.org/

## MAY

**SATELLITE 2019**
May 6–9 • Washington, D.C.
https://2019.satshow.com/

**EuMCE 2019**
May 13–15 • Prague, Czech Republic
www.eumce.com/

**Space Tech Expo 2019**
May 21–22 • Pasadena, Calif.
www.spacetechexpo.com/

## JUNE

**IEEE MTT-S IMS 2019**
June 2–7 • Boston, Mass.
https://ims-ieee.org/

**MILSATCOM USA West Coast 2019**
June 11–12 • Los Angeles, Calif.
www.smi-online.co.uk/defence/northamerica/conference/Milsatcom-USA-West-Coast

**MILSATCOM USA East Coast 2019**
June 26–27 • Arlington, Va.
www.smi-online.co.uk/defence/northamerica/MilSatCom-USA

## JULY

**SEMICON West 2019**
July 9–11 • San Francisco, Calif.
www.semiconwest.org/

**IEEE EMC+SIPI 2019**
July 22–26 • New Orleans, La.
www.emc2019.emcss.org/

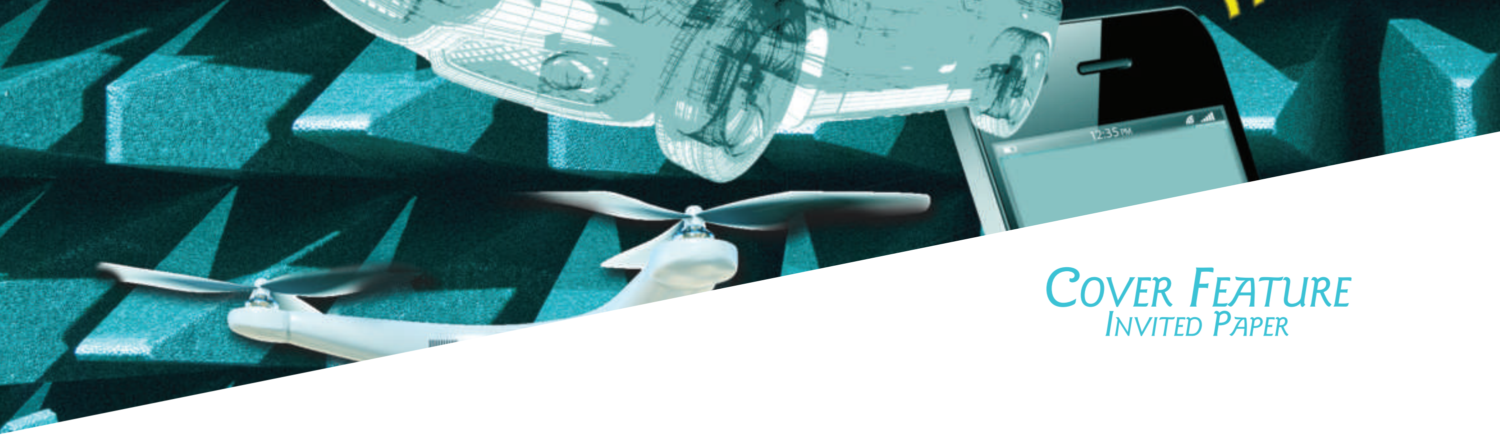
## AUGUST

**ESC Silicon Valley 2019**
August 27–29 • Santa Clara, Calif.
http://escsiliconvalley.com/

## SEPTEMBER

**PCB West 2019**
September 9–11 • Santa Clara, Calif.
www.pcbwest.com/

**EuMW 2019**
September 29–Oct. 4 • Paris, France
www.eumweek.com/



COVER FEATURE
INVITED PAPER

# Test & Measurement Industry Tackles 5G Over-the-Air Testing

Pat Hindle
Microwave Journal *Editor*

*With the full approval of Release 15 by the 3GPP in June 2018, 5G commercial networks were quickly launched in the U.S. (Verizon and AT&T) and South Korea (KT, LG UPlus and SK Telecom) by the end of the year. In 2019, the industry will see increased activity with many 5G launches and a major shift in emphasis from LTE to 5G networks. Since 5G testing standards are still not completely defined, base station and handset manufacturers, wireless carriers and regulators have to come together quickly around the world and agree on how to install, verify and maintain commercial 5G networks. At this critical point in time,* Microwave Journal *reached out to nine leading test & measurement companies in the industry and compiled their information about the challenges and solutions currently available in the area of 5G over-the-air (OTA) testing. The companies included Anritsu, EMITE, ETS-Lindgren, Keysight, MVG, National Instruments (NI), NSI-MI, Rohde & Schwarz (R&S) and Boonton, Noisecom.*

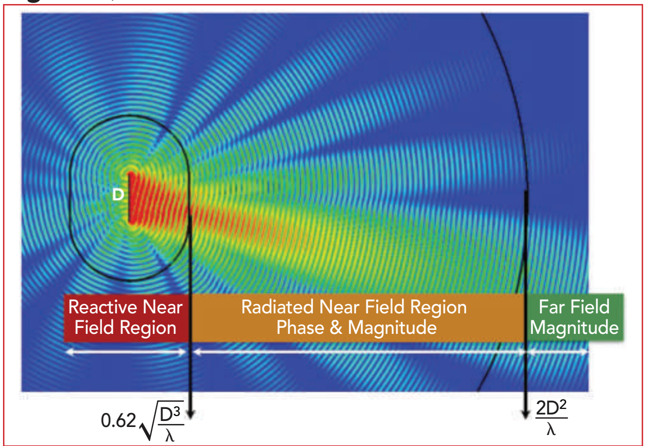
## 5G TEST CHALLENGES

Anritsu outlined the primary challenge due to the fundamental differences in the technology used in 5G testing—like mmWave frequencies, massive arrays of antennas, beamforming and dynamic physical layer attributes—so trying to apply LTE test methods to 5G networks will not work. Countries in different regions of the world are using different frequency bands for 5G deployments, and in addition to showing compliance with the 3GPP 5G New Radio (NR) standard, many countries require compliance with local government regulations.

R&S wrote in a recent *Microwave Journal* article that 5G deployment will rely on the performance of highly integrated solutions combining the modem, RF front-end and antenna. The challenge is to define new methods and setups for performance evaluation, as RF test ports tend to disappear and beam steering technologies require system-level testing. In this context, both antenna and transceiver performance criteria must be measured OTA: effective isotropic radiated power (EIRP), total radiated power (TRP), effective isotropic sensitivity (EIS), total isotropic sensitivity (TIS), error vector magnitude (EVM), adjacent channel leakage ratio (ACLR) and spectrum emission mask (SEM) are some of the critical measurements needed.

R&S continued with the point that assessing these OTA raises the critical question of the required measurement distance. Antenna characteristics are usually measured in the far field (see ***Figure 1***). Using direct far-field probing and applying the Fraunhofer distance criterion ($R = 2D^2/\lambda$), a 75 cm massive MIMO device under test (DUT) radiating at 2.4 GHz should be evaluated in a chamber with at least 9 m range length. Even a 15 cm smartphone transmitting at 43.5 GHz needs a 6.5 m testing distance. This distance is required to create a region encompassing the DUT, where the impinging field is as uniform as possible and approaches a plane wave with phase deviation below 22.5 degrees, known as the quiet zone.

One way to overcome the space constraint of a big chamber is by using a reflector that projects the incoming spherical wave front to a plane wave due to the reflector's parabolic shape. Using such a reflector is a well-known method for




▲ **Fig. 1 R&S provided antenna radiation pattern in the near-field, far-field, and Fraunhofer distances.**

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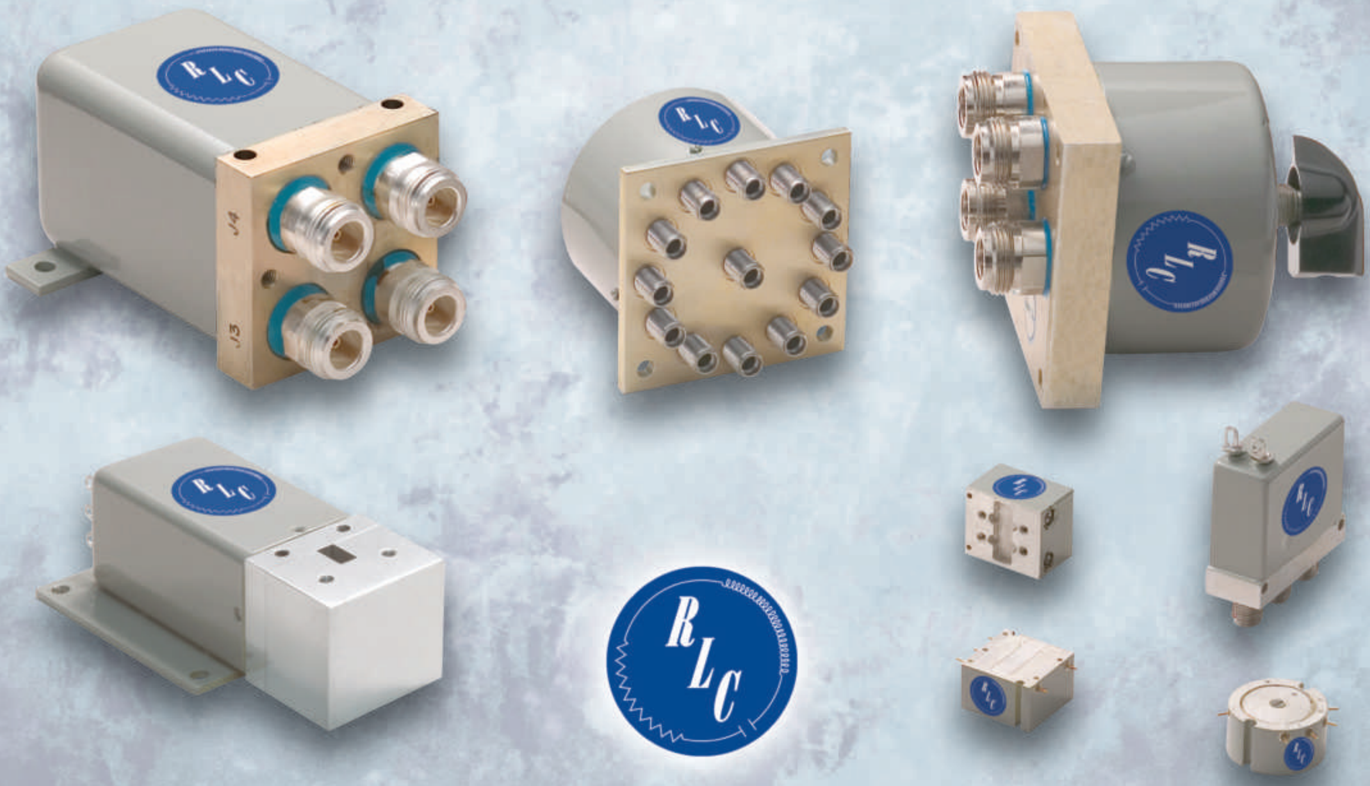

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mmWave OTA setups and is called a compact antenna test range (CATR). The principal is shown in ***Figure 2***.

Anritsu said a key companion to EIRP is gated sweep. With a gated sweep, the user can define which portion of the 5G transmission to measure. This is important because 5G NR signals can be configured through the slot configuration parameter in 55 different TDD Tx/Rx ratios in a 10 ms frame. By gating only the subframe or symbol of interest, the user can ensure that only the RF of the downlink is measured. This will give a more true representation of the RF energy being radiated into the atmosphere.

ETS-Lindgren and Anritsu both noted that significant changes are needed for meaningful EMC tests on 5G devices. TRP is a common measurement required by regulatory standards to ensure radios are not transmitting too much power. Because the signal is transmitted from one isotropic transmitter that is radiating energy evenly across an entire sector in LTE, it is easy to make a measurement on the total power at the radio and determine if the atmospheric energy is within safe limits. ETS-Lindgren stressed the challenge with beamforming as shown in ***Figure 3***; there is no easy way to measure the energy at any single point and know how much power is being transmitted into space since it is directional. With side lobes and back lobes, the only way to measure the TRP is to integrate the power in a 360 degree sphere around the entire antenna. While this can be done, it can be expensive and time consuming.

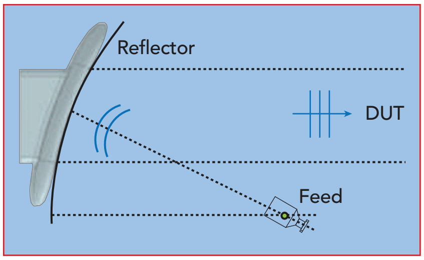


**Fig. 2** Diagram of how a compact antenna test range operates.

Anritsu commented that as the industry starts to converge on installation and maintenance best practices, the next challenge will be defining procedures and finding equipment that will make the test as accurate, efficient and affordable as possible. This will require test vendors to react quickly to test needs and be ready with new generation hardware that can meet the challenge.

## OTA TEST METHODS

Keysight explained the test methods well, stating that when defining an OTA test strategy, it is important to have a good understanding of what will be tested, how it should be tested and what are the appropriate test methods for the different test cases. In the consumer market, testing will be done on modems, antennas, subsystems and fully assembled end-user devices. Base stations will follow a similar testing workflow. A typical testing cycle starts from R&D through conformance and device acceptance testing.

Typically, tests can be categorized into conformance and performance tests. Conformance tests are mandatory tests that need to be completed to release a device. Conformance tests are a key requirement and involve connecting a device to a wireless test system and

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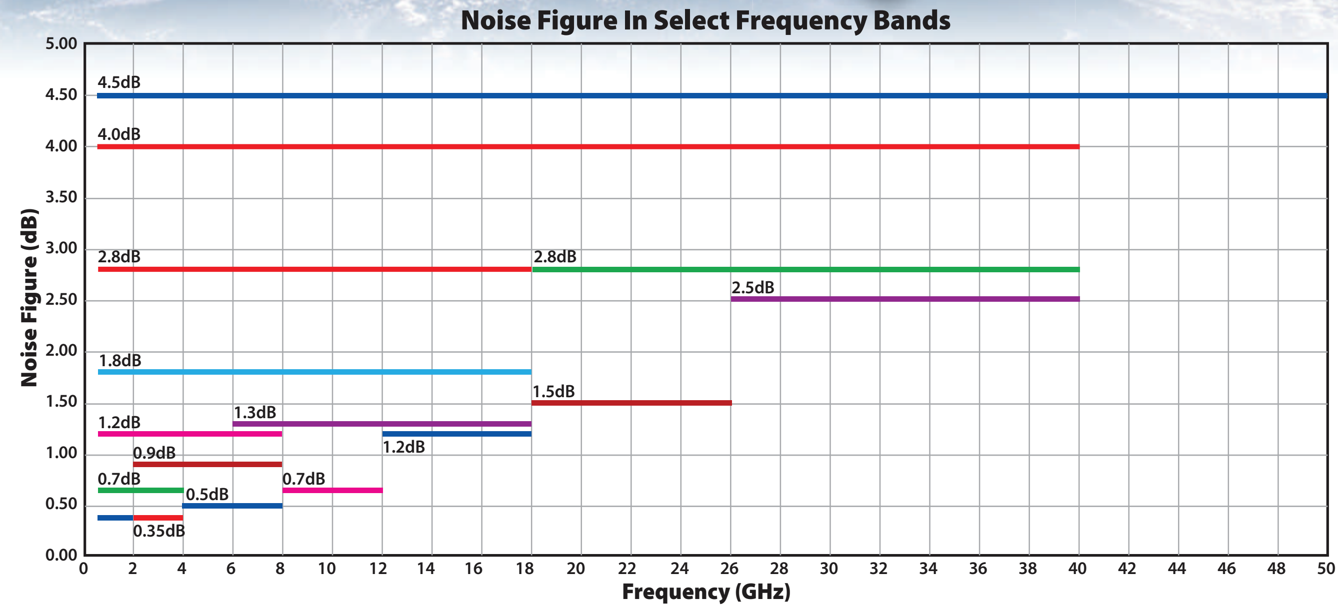


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performing the required 3GPP tests:

- RF transmission and reception performance—minimum level of signal quality.
- Demodulation—data throughput performance.
- Radio resource management (RRM)—initial access, handover and mobility.
- Signaling—upper layer signaling procedures.

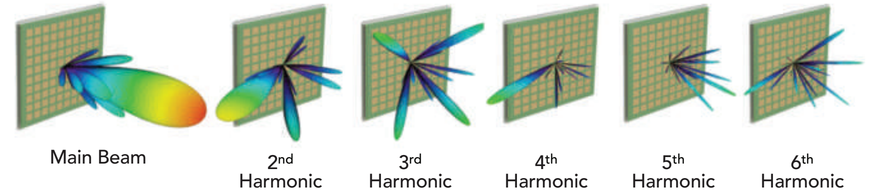


**Fig. 3** ETS-Lindgren provided radiation pattern for a 28 GHz phased array showing the main beam to the left and the first through sixth harmonic radiation patterns going left to right.

Keysight stated that modem chipsets, antennas, base stations and integrated devices will require a mix of conducted and OTA tests. Most frequency range 1 (FR1: 450 MHz to 7.125 GHz) tests will be done using conducted measurements, while 3GPP has defined all frequency range 2 (FR2: 24.25 to 52.6 GHz) conformance tests to be done using OTA test methods.

To date, there are three OTA test methods approved by 3GPP, according to Keysight:

- **Direct Far Field (DFF):** The measurement antenna is placed in the far field. The far-field or Fraunhofer distance begins at $2D^2/\lambda$, where D is the maximum diameter of the radiating elements and $\lambda$ is the wavelength. This is where the angular field distribution stops evolving. The direct far-field method can perform the most comprehensive tests, measuring multiple signals, but can also result in a longer test range at mmWave frequencies.
- **Indirect Far Field (IFF):** A far-field environment is created using a physical transformation, typically involving a parabolic reflector to collimate the signals transmitted by the probe antenna. This method is limited to measuring a single signal angle of arrival/departure but provides a much shorter distance with less path loss. This test method is accomplished using a CATR.
- **Near Field to Far Field Transformation (NFTF):** Phase and amplitude of the electrical field are sampled in the radiated near-field region, and the far-field pattern is computed. This method is also limited to a single line-of-sight transceiver measurement.

According to R&S, as of early January 2019, 3GPP specified a number of transmitter and receiver tests in the 3GPP TS38.521-3, which is the NR User Equipment (UE) conformance specification for radio transmission and reception where "−3" refers to part 3 and means FR1 and FR2 interworking operation with LTE, basically Non-Standalone (NSA) sub-6 GHz as well as NSA mmWave.

For mmWave, testing becomes

**TABLE 1**

**HIGH LEVEL SUMMARY OF FIDELITY AND APPLICABILITY OF 5G TEST ENVIRONMENTS (CREDIT: NSI-MI)**

| | AUT Size | FF | DFF | IFF | NFTF |
|---|---|---|---|---|---|
| RF Testing | Small UEs | (yellow) | (green) | (green) | Tx only (green) |
| | Large UEs | (red) | (yellow) | (green) | Tx only (green) |
| | gNodeBs | (red) | (red) | (green) | Tx only (green) |
| Demod Testing | Small UEs | (yellow) | (green) | (green) | (red) |
| | Large UEs | (red) | (yellow) | (green) | (red) |
| | gNodeBs | (red) | (red) | (green) | (red) |
| RRM Testing | Small UEs | (yellow) | (green) | (yellow) | (red) |
| | Large UEs | (red) | (yellow) | (yellow) | (red) |
| | gNodeBs | (red) | (red) | (yellow) | (red) |

more difficult since everything will need to be tested OTA and a black box approach has to be assumed. This means that achievable measurement uncertainties (MU) and test tolerances (TT) will need to be much wider than in sub-6 GHz FR1 conducted testing. It is an ongoing discussion in 3GPP which MUs are acceptable and what TT to use for FR2. Until this is fixed by 3GPP, spec compliant RF conformance tests for FR2 are not practical.

For Standalone (SA) deployment scenarios, the matching 38.521 parts 1 (sub-6 GHz) and 2 (mmWave) are more advanced, even though the first 5G NR deployments early this year will be NSA. On top of this, the specifications for performance tests (38.521-4) and RRM test requirements (38.533) are not yet ready for NSA.

***Table 1***, created by NSI-MI, summarizes the applicability of the test environments to different types of testing and different antenna sizes. Colors indicate quality of the solution in terms of SNR, utility, cost, etc.

EMITE said there is no single OTA test method capable of providing the answers to all of the problems and challenges we have today. Therefore, industry will need to adopt a variety of methods. Some companies have shown that there are benefits to rich isotropic systems for obtaining some key performance parameters, while directionality is needed to address the evaluation of other 5G features. Simultaneously testing at both near- and far-field distances, low and high frequencies, large and small form factors may also be needed.

ETS-Lindgren added that engineers often ask if a single do-it-all chamber for 5G OTA, EMC and cable replacement tests could be designed. They find there are too many compromises each method would impose on the others to make this a cost effective approach. Measurement uncertainty requirements drive optimization in different directions for each type of test. Consider the additional absorber and measurement antennas that would need to be moved in and out of a traditional 3 m EMC chamber quiet zone to transition between EMC and far-field OTA requirements. The transition time and costs associated with a do-it-all test chamber will mostly outweigh the benefits.

## OTA PRODUCT OFFERINGS

Here are some of the OTA solutions being offered by these leading test & measurement suppliers:

### Anritsu's New Solution

With the launch of the Field Master™ Pro MS2090A at MWC Barcelona 2019 in February, Anritsu introduces the first field portable instrument with continuous frequency coverage for sub-3 GHz, sub-6 GHz and mmWave 5GNR measurements (see ***Figure 4***). The Field Master Pro MS2090A has been developed in close cooperation with all leading 5G base station manufacturers, as well as being used to install the first commercial 5GNR networks. This should have a significant impact on the testing market to have this capability in a handheld unit.

The key features of the Field Master Pro MS2090A are:

- Continuous frequency coverage from 9 kHz to 9, 14, 20, 32, 44 or 54 GHz.
- 100 MHz analysis bandwidth for current 5G deployments.
- 5G NR demodulation capabilities.
- RTSA for interference hunting.
- Built-in EIRP and gated sweep for transmission testing.
- 10.1 in. multi-touch screen user interface.

### EMITE Solutions

For a small company in this space, EMITE offers a broad range of solutions. The EMITE PT-Series is a small reverberation chamber

**Fig. 4** Anritsu's Field Master™ Pro MS2090A handheld solution.

**Fig. 5** EMITE's F-Series 200 MHz to 110 GHz hybrid Anechoic-reverberation chambers.

which serves as a simple go, no-go mmWave SISO OTA test and some non-signaling production OTA tests for up to eight simultaneous DUTs of up to 15 cm.

Their E-Series is a medium-size reverberation chamber capable of providing fully-automated 5G OTA testing of some isotropic key performance indicators, as well as latency and throughput. The E-Series chambers can easily accommodate many carriers with 4G and 5G technologies, with up to 8×8 MIMO, and can make use of channel emulators for 5G channel modeling. A unique solution from EMITE, these can also be cascaded to test massive MIMO and E2E OTA tests, representing a first step into 5G OTA signaling testing.

Their F-Series is a hybrid reverberation-anechoic chamber capable of providing a blend of both worlds (see ***Figure 5***). The RC mode provides easy, fully-automated overnight testing of 4G and 5G OTA while the AC mode incorporates all 3GPP-permitted OTA test methods (IFF, NFTF and DFF) for DUTs of up to 1.5 m.

The H-Series is a small anechoic chamber intended to simultaneously test FR1 and FR2 frequency combinations using a combined CATR, spherical near-field (SNF) and DFF test system with the only climatic foam enclosure in the market for testing wireless OTA under both temperature and humidity conditions

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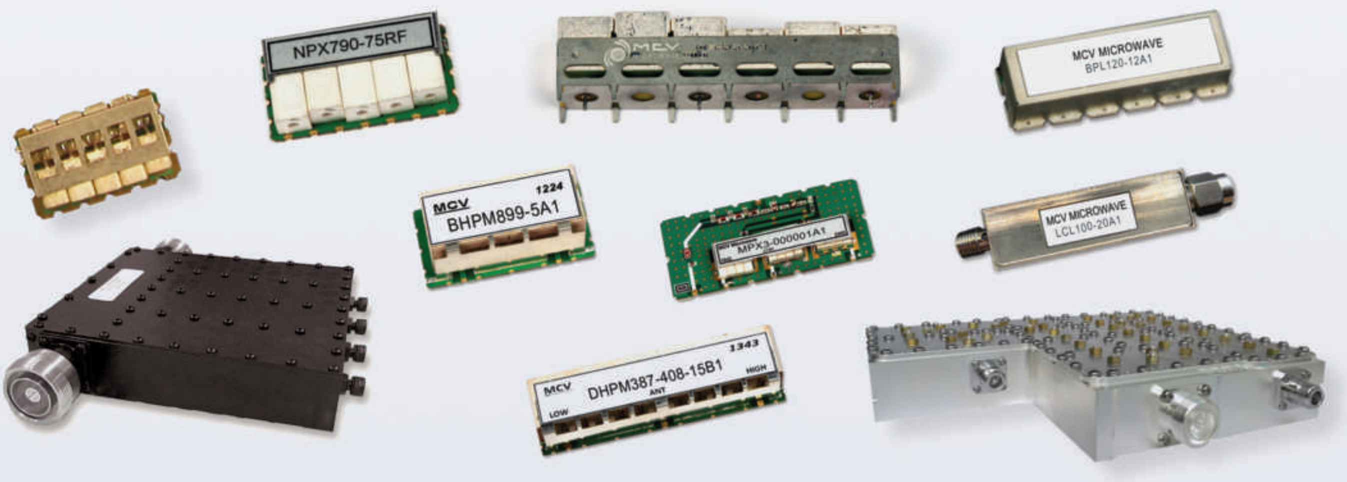


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**Fig. 6** EMITE H-Series 600 MHz to 110 GHz small anechoic chamber including climatic enclosure.

(see ***Figure 6***). Temperature range from –40°C to 90°C with fluctuation of about ±0.5°C and heating and cooling change rates of 2°C to 4.5°C per minute, and humidity range from 10 to 98 percent relative humidity with fluctuations of ±0.5 to ±3 percent relative humidity are available.

### ETS-Lindgren Solutions

Labs with current ETS-Lindgren OTA systems or those manufactured by others will be pleased to know that an upgrade package for 5G testing in the sub-6 GHz, FR1 band is available. This upgrade is economical and backward compatible, providing a three generation OTA system covering 5G, 4G and

**Fig. 7** ETS-Lindgren's table top AMS-5700 OTA test chamber.

3G, if so equipped.

For 5G FR2 mmWave OTA, ETS-Lindgren offers the AMS-5700 series of OTA test chambers (see ***Figure 7***). The AMS-5700 series is highly flexible, offering one system serving multiple projects and use cases. The 5700 series offers direct and indirect far-field configurations covering any array size up to 60 cm. The AMS-5703 is designed with a large quiet zone and unique positioning system to accommodate future CTIA phantom test requirements.

ETS-Lindgren also offers custom solutions: one recent ETS-Lindgren project enabled end-to-end data throughput, MIMO and beam steering performance to be measured on gNBs linked to moving UEs. Another complex automotive project provided vehicle to everything (V2X) measurement and optimization results from dozens of antennas and sensors integrated in an autonomous vehicle.

### Keysight Solutions

Keysight offers a portfolio of OTA solutions based on the workflow from R&D to device acceptance. A typical solution consists of measurement software, a network emulator to emulate a 5G gNB and a channel emulator to emulate the radio conditions. For FR2, these solutions include OTA measurement systems, typically adding RF enclosures, probe and link antennas, different DUT positioners and associated control software. Keysight's offerings address the different test approaches and the varying needs for modems, antennas, integrated devices and base stations. OTA tests are required from R&D through design validation, protocol and RF/RMM conformance testing and device acceptance testing. Keysight supports the wide range of solutions shown in ***Table 2***.

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- Advanced Digital Features
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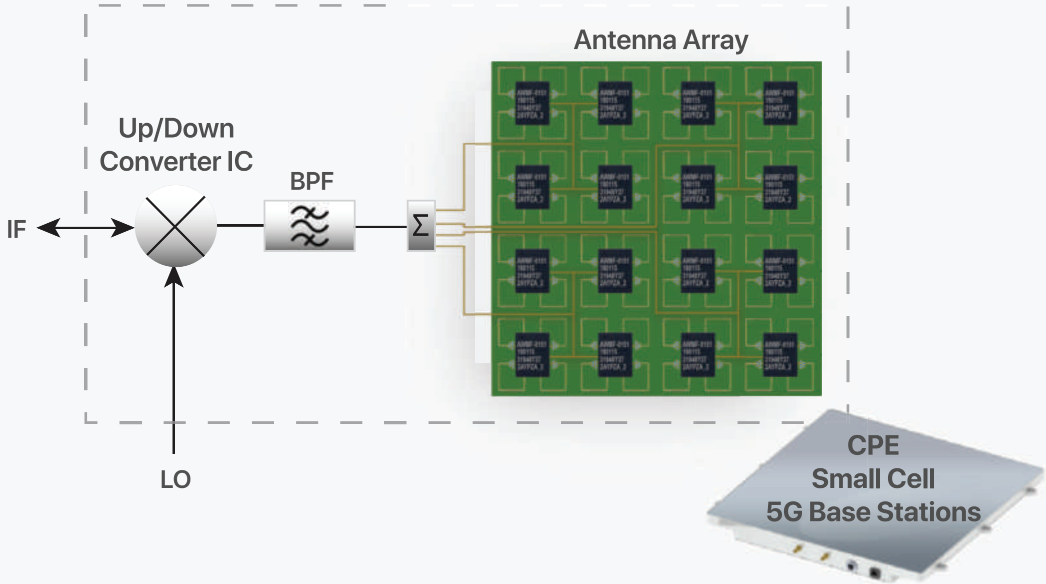
Reference design for complete RF signal chain

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Keysight has CATR solutions that offer IFF measurements for RF, RF parametric testing and antenna pattern measurements, well suited for testing antennas, phones, phablets, tablets, laptops and small 5G gNBs. To test devices under real world operating conditions, a solution needs to emulate different directions of arrival of the 5G signal, i.e., emulating the spatial characteristics of the environment. For this, Keysight models signal from the base station (gNB) to the device. Their multi-probe anechoic chamber solutions are good for understanding how a device operates in the spatial environment with multiple simultaneous radiated beam angles (see ***Figure 8***). This solution utilizes the Keysight UXM 5G Wireless Testset, PROPSIM F64 channel emulator and performance network analyzers for testing the device under real world conditions for different key performance indicators like throughput, handover, etc.

**TABLE 2**

**KEYSIGHT'S RANGE OTA TESTING SOLUTIONS**

| | UE RF Tx | UE RF Rx | DEMOD | RMM | Protocol Signaling |
|---|---|---|---|---|---|
| Direct Far-Field (DFF) | ✔ | ✔ | ✔ | ✔ | ✔ |
| Simplified DFF | ✔ | ✔ | ✔ | ✔ | ✔ |
| Indirect Far-Field (IFF) | ✔ | ✔ | ✔ | ✔ | ✔ |
| Near-Field with Transformation (NFTF) | | | | | |
| Near-Field Without Transformation (NFWOT) | | | ✔ | | |

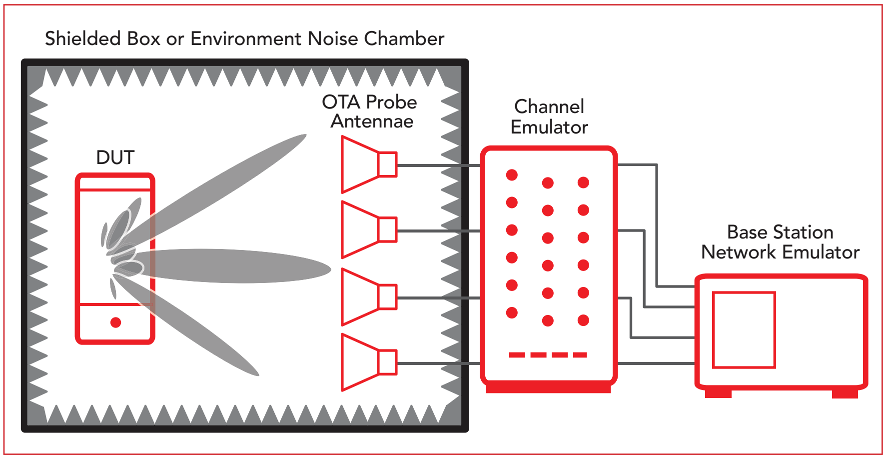



Fig. 8 **Keysight's multiprobe anechoic chambers (MPAC) solution.**

## MVG Solutions

MVG offers multi-probe systems based on rapid sampling, using probe arrays of the radiated near field in amplitude and phase on a closed surface around the device. The far-field performance of the device is determined from near-field to far-field transformation. The exact knowledge of the amplitude and phase of the radiating device gives access to important investigative features on the device behavior through post processing.

As the electrical size of devices and systems at 5G frequencies increase, the sampling required for exhaustive testing of the devices becomes a burden to the users, as the testing time increases. The multi-probe systems from MVG enable much faster testing than traditional single probe systems allowing users to fully characterize their devices within much more reasonable times, enabling in-the-loop research and development activities (see ***Figure 9***).

When integrating antennas on larger electrical devices, as is the case for the small arrays integrated on handheld 5G devices, the coupling phenomenon between antennas can significantly alter device performance. Testing including representative and standardized phantoms (hand, head, torso, etc.) are needed to understand the final device performance. New measurement post processing features allow users to examine results and better understand the radiation properties of the device in these scenarios, enabling research and development engineers to develop better products.

Historically, CATRs have been the preferred solution for testing high gain antennas such as base stations. The features of MVG systems are the high performance feeds, which are designed specifically to maintain high plane wave purity of the quiet zone over very wide bandwidths. Another feature of the MVG systems is the positioner, designed for minimum interference with the device, making it usable also for testing of smaller handheld devices.

The plane wave synthesizer (PWS) array or plane wave generator (PWG) array is an array of elements with suitably optimized complex coefficients, generating a plane wave in close proximity to the array. The PWG can achieve far-field testing conditions in a quiet zone located in a region close to the array, similar to what is achieved in a CATR but at shorter distance making the system more compact and easier to use. The main features of the PWG systems from MVG are the ability to cover the entire bandwidth for 5G testing in a single system. MVG offers large systems that can accommodate entire base stations, even vehicles (see ***Figure 10***).

Fig. 9 **MVG's multi-probe system testing a drone.**

### National Instruments Solutions

Whenever engineers discuss OTA test solutions, RF chambers almost automatically appear as necessary components of the solution. For design characterization, validation, compliance and conformance tests, a proper RF chamber (anechoic, CATR or reverberation types) provides a quiet RF environment that ensures the design meets all performance and regulatory requirements with sufficient margin and repeatability. However, for volume production, traditional RF chambers can take much of the production floor space, disrupt material handling flows and multiply capital expenses.

▲ **Fig. 10** MVG's SG3000F automotive test system.

To tackle these problems, OTA-capable IC sockets—small RF enclosures with an integrated antenna—are becoming commercially available, enabling semiconductor OTA test functionality in a reduced form factor. Although the measurement antenna is a couple of centimeters away from the DUT IC, that is enough distance for far-field measurements for each individual antenna element. The relatively small size of the socket also facilitates multi-site, parallel tests to multiply test throughput, while minimizing signal power losses. On the other hand, the small socket prevents making beamformed measurements for the whole antenna array, which typically has a far-field distance of 10 cm or longer.

At 28 GHz, a 10 cm distance translates to over 20 dB of free space path loss, as opposed to just 1 dB on an equal length coax cable. Considering a receiver IP3 measurement, OTA methods would require the test instrument to produce 20 dB higher output power at the transmit antenna in order to achieve the same level of received power at the DUT. This can be a challenge for RF chamber-based OTA configurations; however, for OTA socket-based solutions, at 1.5 cm away, it only requires 5 dB higher transmitted power.

With the inclusion of active beamformer electronics, newer generation of 5G active antenna array devices now have many non-linear RF components, such as digitally controlled PAs, LNAs, phase shifters and mixers. New designs incorporate multi-channel configurations in a single package. NI's software-designed test platform keeps pace with the latest 5G NR PHY layer requirements and includes the measurement science and instantaneous bandwidth necessary to test wide NR component carriers or carrier-aggregated signals. NI's high bandwidth instrumentation also allows for linearization of the DUTs using digital predistortion techniques. The NI platform provides for phase-coherent and time-aligned expansion into multi-channel measurement systems for comprehensive test coverage of the latest NR semiconductor devices.



Fig. 11 NSI-MI's SNF-FIX-1.0 SNF System.

### NSI-MI Solutions

NSI-MI Technologies products for 5G testing include near-field and CATR systems. For near-field testing, NSI-MI recommends pattern testing only with CW tones when possible. The SNF-FIX-1.0 is a spherical near-field system that rotates a probe to any position on a sphere up to $\theta \leq 150°$ around a stationary DUT. It does this with a dual rotary stage articulating arm. The advantage of this system is its ability to sample near-field patterns without the need for any type of rotation of the DUT. ***Figure 11*** shows the SNF test system. If DUT stationarity is not required, the SNF-RAZ-0.7 roll-over-azimuth system may also be used for SNF pattern testing.

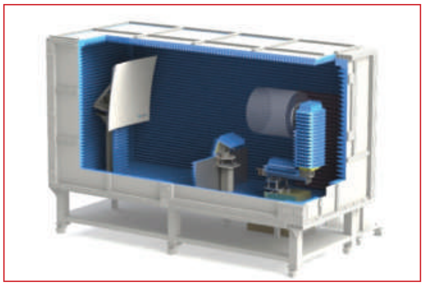


Fig. 12 CAD drawing of NSI-MI's portable CATR system with 80 cm quiet zone.

For more general 5G testing, NSI-MI recommends a CATR. The chambers designed by NSI-MI can handle mmWave frequencies up to 110 GHz. The CATRs designed for 5G testing are intended for mmWave testing, as those frequencies are the primary driver for OTA testing in 5G. But they can be modified for FR1 OTA testing. They are designed for 30, 50, 80 and 100 cm quiet zones (see ***Figure 12***).

Fig. 13 R&S ATS800R compact test chamber.

### Rohde & Schwarz Solutions

It is difficult to heat up or cool down an entire OTA chamber, more so since the absorber material used in these chambers cannot withstand very high or low temperatures. Neither can the motors in high accuracy positioners. The solution is the use of a relatively small enclosure around

Fig. 14 R&S ATS1000 test chamber.

the DUT inside the chamber, changing the temperature only inside this enclosure rather than in the entire chamber. Of course, the enclosure itself must have only minimal influence on the radiation parameters or the beam emitted by the DUT.

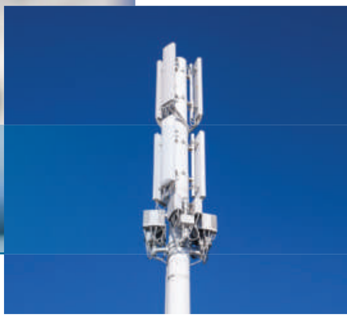
A typical CATR setup is mounted inside a shielded chamber for RF conformance testing, typically together with a positioner. However, a chamber takes up space in a space limited R&D environment. R&S created a product where a CATR setup can be put on an engineer's work bench or even inside a 19 in. rack taking up minimal floor space inside the lab, while providing a big and accurate quiet zone for RF and protocol R&D and regression testing (see ***Figure 13***).

For testing antenna array systems, typically a chamber with 3D positioner is required to measure the 3D radiation pattern of the array under test. R&S offers the ATS1000 with a high precision conical cut positioner to fulfill these tasks in a very compact size (see ***Figure 14***). As an additional option, the ATS1000 can be equipped with a "temperature bubble" in which extreme temperature conditions between −40°C and +85°C can be achieved using an external thermal stream. The bubble creates a relatively small closed environment around the DUT so the temperature changes can be achieved quickly. Since the bubble is made out of RF transparent material, the influence on the overall test results can be neglected.

### Boonton, Noisecom Solution

The equipment and testing techniques used for engineering and quality assurance will be expensive and time consuming compared to what will be needed on the production line for 5G. Boonton, Noisecom has an interesting approach for OTA testing using a Noisecom calibrated noise source outside the chamber, connected to a transmit antenna inside the chamber. Receive antennas inside the chamber are connected to test equipment outside the chamber. The noise source can have one or two known excess noise ratio (ENR) values with calibration data for the bandwidth of interest. The benefit of having two ENR levels is the ability to determine Y factor noise figure of the DUT for radiated measurements.

An advantage of the noise source is the calibration points can normalize the equipment for power and frequency response. Once the equipment is normalized, the noise source is used to determine and

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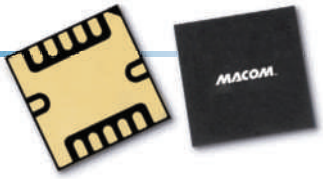


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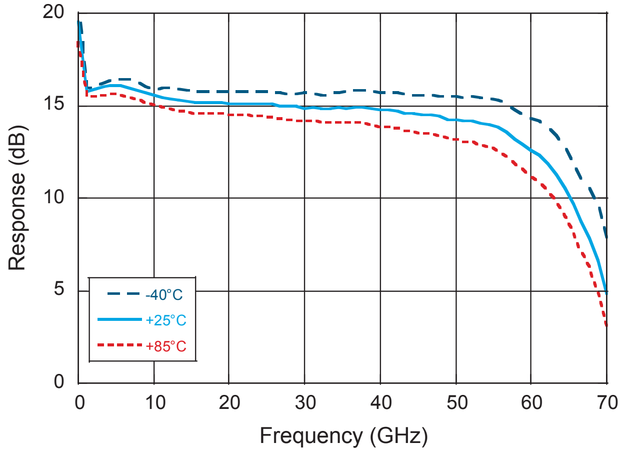


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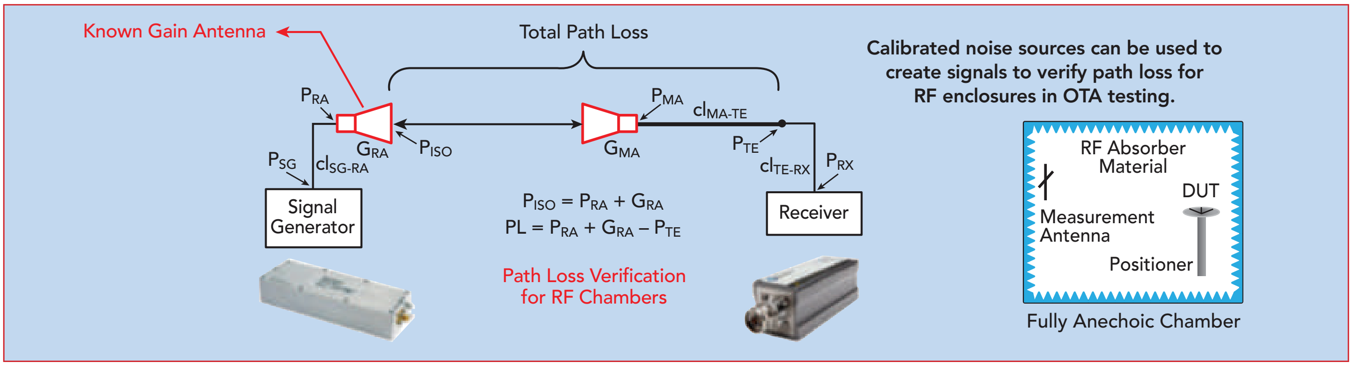


Fig. 15 Boonton, Noisecom's OTA path loss measurement using noise.



verify the path loss of the interconnects in the system. Since the noise source is generating wide bandwidth OFDM-like signals, with crest factors (CF) similar to those to and from the DUT, it is straightforward to verify the system response to see if anything has changed between tests, perhaps caused by connector wear or operator error.

Boonton RTP5000 RF broadband RF power sensors can be connected to multiple receive antennas inside the chamber around the DUT (see ***Figure 15***). The RF peak power sensors are capable of measuring the average and peak power being transmitted from the DUT. RF sensors can be synchronized to obtain composite average and peak power and determine CF. CF measurements are a quick figure of merit in a production test environment.

Noisecom noise sources are proven OFDM-like signal generators at a fraction of the cost of expensive signal generators and can be used for verification, calibration and signal source to speed up production tests. Boonton RTP5000 series RF peak power sensors offer a simple and fast way to measure complex OFDM signals using CF as a figure of merit to develop go, no-go testing.

## SUMMARY

5G OTA testing will evolve quickly in 2019, as standards are defined and 5G products go into production. There will certainly be several methods needed to test and verify 5G components and systems, as noted in this article. The primary tradeoffs for cost, accuracy and throughput will need to be determined quickly and the test methods standardized as 5G deployments accelerate.■

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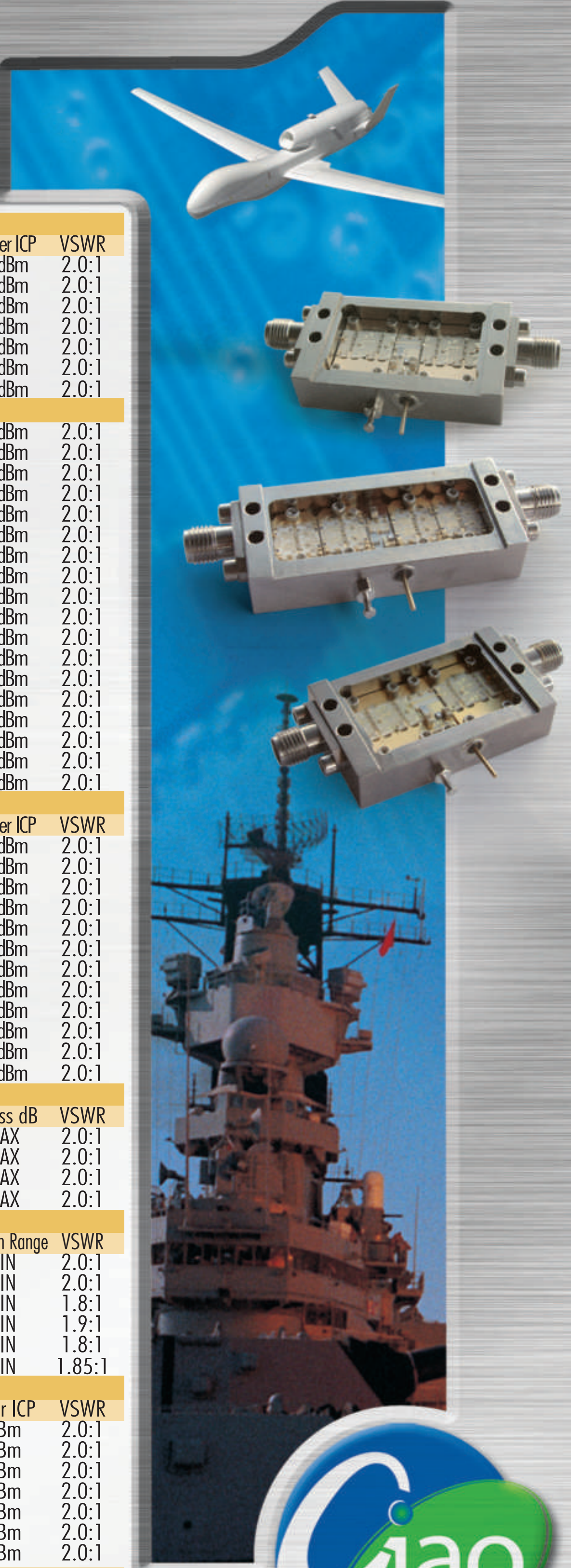

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| Model No. | Freq (GHz) | Gain (dB) MIN | Noise Figure (dB) | Power-out @ P1-dB | 3rd Order ICP | VSWR |
|---|---|---|---|---|---|---|
| CA01-2110 | 0.5-1.0 | 28 | 1.0 MAX, 0.7 TYP | +10 MIN | +20 dBm | 2.0:1 |
| CA12-2110 | 1.0-2.0 | 30 | 1.0 MAX, 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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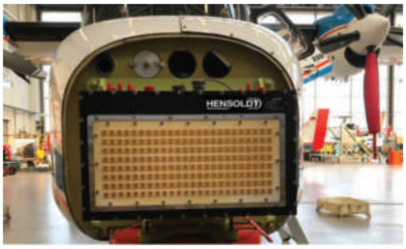
## Successful Flight Tests with HENSOLDT's Collision Warning Radar for UAVs

Sensor solutions provider HENSOLDT has successfully concluded flight tests with its collision avoidance radar system for unmanned aerial vehicles (UAV). This sensor is intended to improve safety in both military and civilian air traffic.

HENSOLDT has developed a demonstrator of a so-called detect-and-avoid radar system, which uses the latest radar technology to detect objects in the flight path of a UAV and to give early warning of any threat of collision following precise evaluation of the flight direction. At the same time, the sensor also assumes all the functions of a weather radar system.

In the flight tests, which were carried out on behalf of the German procurement authority BAAINBw and in collaboration with the German Aerospace Center (DLR) in Brunswick, the radar demonstrated its capabilities in a real setting, thus confirming the results previously achieved in ground tests. In test flights lasting several hours, the radar installed in a Dornier Do 228 belonging to the DLR reliably detected the test aircraft approaching at different altitudes and angles.



*HENSOLDT Radar (Photo Courtesy: HENSOLDT)*

The detect-and-avoid radar system uses state-of-the-art active electronically scanned array (AESA) technology, which allows several detection tasks to be carried out at the same time and enables objects to be detected extremely fast. It replaces the pilot's visual assessment of the situation. Thanks to its excellent detection capabilities, the multifunction radar is equally suitable for both military and civilian UAVs, e.g., for the delivery of cargo. A second series of flight tests is planned for the coming year.

## Building Trusted Human-Machine Partnerships

A key ingredient in effective teams—whether athletic, business or military—is trust, which is based in part on mutual understanding of team members' competence to fulfill assigned roles. When it comes to forming effective teams of humans and autonomous systems, humans need timely and accurate insights about their machine partners' skills, experience and reliability to trust them in dynamic environments. At present, autonomous systems cannot provide real-time feedback when changing conditions such as weather or lighting cause their competency to fluctuate. The machines' lack of awareness of their own competence and their inability to communicate it to their human partners reduces trust and undermines team effectiveness.

To help transform machines from simple tools to trusted partners, DARPA recently announced the Competency-Aware Machine Learning (CAML) program. CAML aims to develop machine learning systems that continuously assess their own performance in time-critical, dynamic situations and communicate that information to human team-members in an easily understood format.

"If the machine can say, 'I do well in these conditions, but I don't have a lot of experience in those conditions,' that will allow a better human-machine teaming," said Jiangying Zhou, a program manager in DARPA's Defense Sciences Office. "The partner then can make a more informed choice."

That dynamic would support a force-multiplying effect, since the human would know the capabilities of his or her machine partners at all times and could employ them efficiently and effectively.

In contrast, Zhou noted the challenge with state-of-the-art autonomous systems, which cannot assess or communicate their competence in rapidly changing situations.

"Under what conditions do you let the machine do its job? Under what conditions should you put supervision on it? Which assets, or combination of assets, are best for your task? These are the kinds of questions CAML systems would be able to answer," she said.

Using a simplified example involving autonomous car technology, Zhou described how valuable CAML technology could be to a rider trying to decide which of two self-driving vehicles would be better suited for driving at night in the rain. The first vehicle might communicate that at night in the rain it knows if it is seeing a person or an inanimate object with 90 percent accuracy, and that it has completed the task more than 1,000 times. The second vehicle might communicate that it can distinguish between a person and an inanimate object at night in the rain with 99 percent accuracy, but has performed the task less than 100 times. Equipped with this information, the rider could make an informed decision about which vehicle to use.


*Autonomous Taxi (DARPA Image)*

**For More Information** Visit mwjournal.com for more defense news.

The CAML program seeks expertise in machine learning, AI, pattern recognition, knowledge representation and reasoning, autonomous system modeling, human-machine interface and cognitive computing.

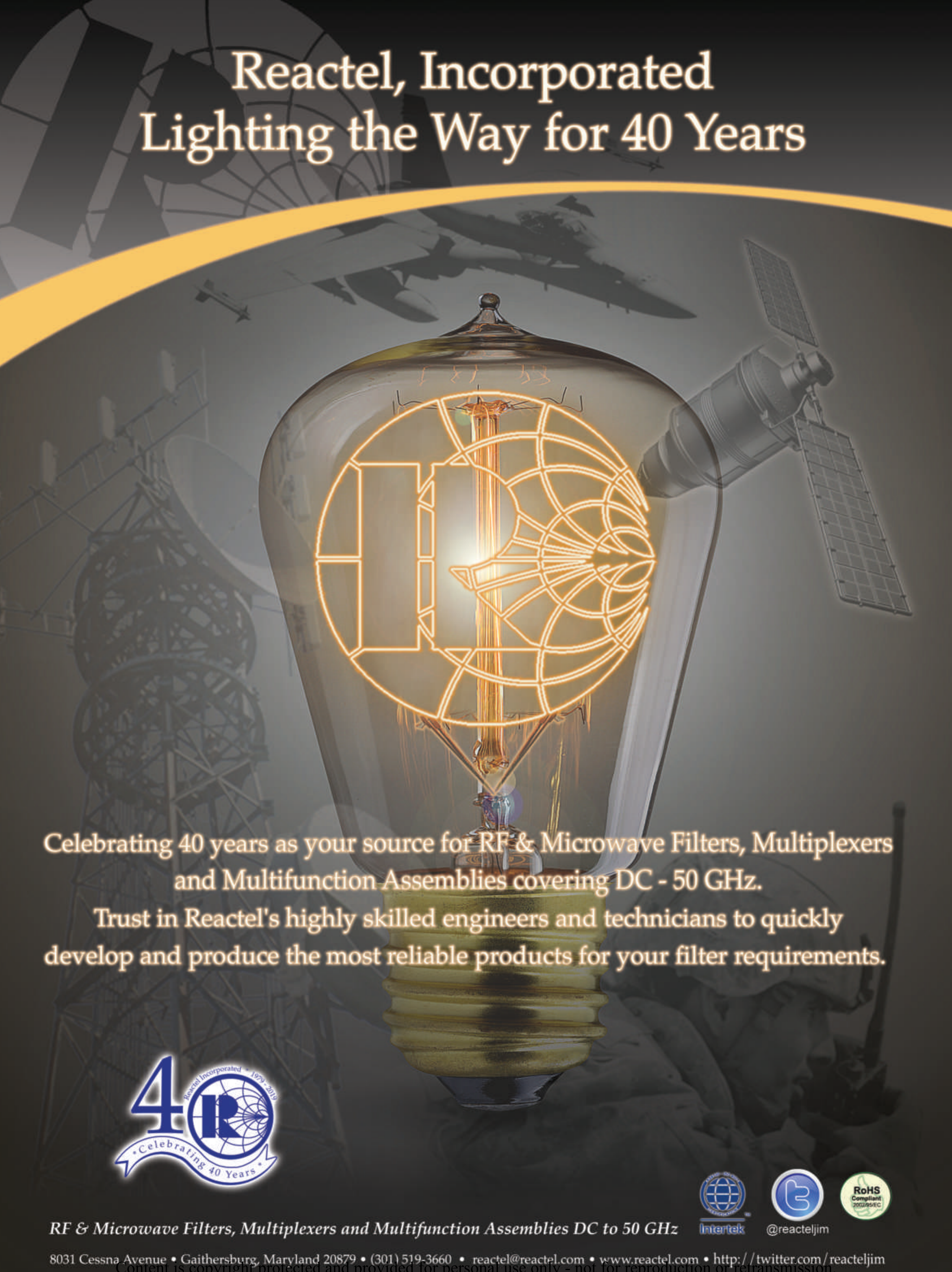
## NATO EW Training Equipment Upgrade

Leonardo has signed a contract worth approximately €180M to provide new electronic warfare (EW) training equipment for the NATO Joint Electronic Warfare Core Staff (JEWCS). Leonardo was selected in an international competition and will incorporate technology from partners Cobham and Elettronica. The contract was placed by the U.K. Ministry of Defence as the host nation for NATO JEWCS, which is based at the Royal Naval Air Station (RNAS) in Yeovilton. Equipment will be delivered in tranches over the next four years from Leonardo's EW centre of excellence in Luton, U.K.

NATO JEWCS is the Alliance agency responsible for the high-tech world of EW. When NATO forces go on operations, they can expect the enemy to try and disrupt their radars, GPS and communications. Therefore, to train realistically, it is important that NATO Forces experience these effects and practice how to counter them. Part of NATO JEWCS's remit is to improve armed forces training by simulating the effects of an enemy's latest EW equipment during exercises, creating a "hostile environment" in which to train. To deliver the service, NATO JEWCS deploys high-tech EW equipment at training sites around Europe, allowing armed forces to practice their skills in areas such as electronic surveillance and electronic countermeasures, while facing true-to-life attempts to disrupt their activity.

In delivering this support, it is important that the EW effects being simulated are state-of-the-art, keeping pace with opposing forces' latest tech developments. Leonardo is Europe's leading provider of EW technology and training and will be providing representative equipment across three domains: air, land and maritime.

In the air, highly capable and flexible pod-based EW systems will be supplied for deployment on aircraft, alongside a NATO Anti-Ship Missile Defence Evaluation Facility (NASMDEF). NASMDEF comprises a set of pods that can be installed on aircraft to simulate anti-ship missiles. They allow forces to train in the use of "soft-kill countermeasures" which are used to protect ships from incoming threats. Cobham will be Leonardo's principle sub-contractor for these elements. For land and maritime applications, fully ruggedized shelters and vehicles will be provided, equipped with modular and flexible EW simulators, stimulators and jamming equipment. Elettronica will act as Leonardo's principal sub-contractor for these elements.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Cliff Drubin, Associate Technical Editor

## 5G: A "Silver Bullet" for Smartphones to Arrest Declining Market Growth

Despite the smartphone market's slowing growth due to saturating addressable markets, ballooning average selling prices, prevailing consumer price fatigue and lengthening replacement cycles, all is not lost. According to ABI Research, the market is to witness a 4.1 percent rise in shipments in 2019, growing to just under 1.6 billion for the year. It is expected that the use of 5G and flexible displays will be the catalysts to galvanize the industry, creating improved user experiences (UX), while stimulating smartphone replacement rates.

"For too long, major vendors have been lambasted for upgraded devices looking far too similar to their predecessors, with iteration rather than design innovation becoming the norm," says David McQueen, research director, ABI Research. "In fairness, it has become increasingly difficult for vendors to differentiate on features, with price being one of the very few competitive factors left, but new technology innovation and features are just around the corner to help arrest this decline."

It is expected that 5G will be used initially as a point of differentiation, but it could actually be the "silver bullet" that smartphone vendors are pinning their hopes on. Through the launch of 5G with its enhanced mobile broadband speeds, plus the inclusion of flexible displays, users will be introduced to new innovative ways to interact with their devices.

> Latest innovations must provide a clear purpose.

Taking full advantage of these new functionalities, users will see improvements in the UX, including upgrades to voice assistance, artifical intelligence (AI) and smart biometrics. With 5G acting as the fulcrum, the market is also set to witness the introduction of new device form factors that leverage a host of new and improved technologies, activated by cues taken from the users' surroundings, applications or circumstances. However, vendors will need to ensure that these latest innovations provide a clear purpose to consumers, offering strong reasons for purchase, or else they run the risk of becoming low-volume niche products.

Expectations are that 5G smartphones will start to become available during the first half of 2019, and, by the end of 2020, all major vendors will have at least one high-end model that is 5G-ready. ABI Research forecasts that 5G smartphone shipments will reach 49 million in 2019—around 3 percent of global smartphone shipments—and will rise steadily to account for 43 percent of the total by 2023.

"It is incumbent on major smartphone vendors from Apple to ZTE, to ensure that they remain competitive in the next 18 months as these new technologies are introduced, continually providing a set of captivating and effective innovations in their portfolios," concludes McQueen. "If the established vendors are to take full advantage, they will need to modernize and refresh their strategies to strengthen their business competitiveness and technological leadership in the mid- to long-term. Failure to do so could result in a dramatic collapse in business, which would not be the first time in the smartphone industry where a prominent vendor has been caught out and fallen quickly from a position of market strength."

## Microwave Tube Market Still Strong at Over $1B for 2018

While microwave and mmWave high-power vacuum electron devices (VED) remain "below the radar" of many industry observers, the total available market for this segment is over $1 billion, finds ABI Research. Despite its size, and although these tubes remain essential elements in specialized military, scientific/medical and space communications applications, this market is generally under-reported and poorly understood by those not directly involved in it.

Essentially, this continues to be a stable industry despite several rounds of consolidation in the past decade. "While, there is some potential for further consolidation, there are no signs of that happening yet. However, one competitive RF semiconductor technology—GaN—will change the landscape. While it is not yet near monopolizing the microwave RF power industry, GaN is advancing steadily and is a technology that should be closely watched, as it will be a threat to some aspects of the microwave and mmWave VED marketplace," said Lance Wilson, research director, ABI Research.

> No other way to generate such high levels of RF power.

The size of this historic market continues to surprise and its longevity and firm resistance to RF power semiconductor encroachment is just as surprising; however, that will be changing to some degree as GaN devices move up in frequency and power.

"These specialized VEDs may at first seem anachronistic," Wilson adds. "But in some cases, there is no other way to generate such high levels of RF power within an acceptably small space. Certain microwave and mmWave VEDs can generate megawatts, and it would take tens of thousands of transistors to do that."

**For More Information** Visit mwjournal.com for more commercial market news.

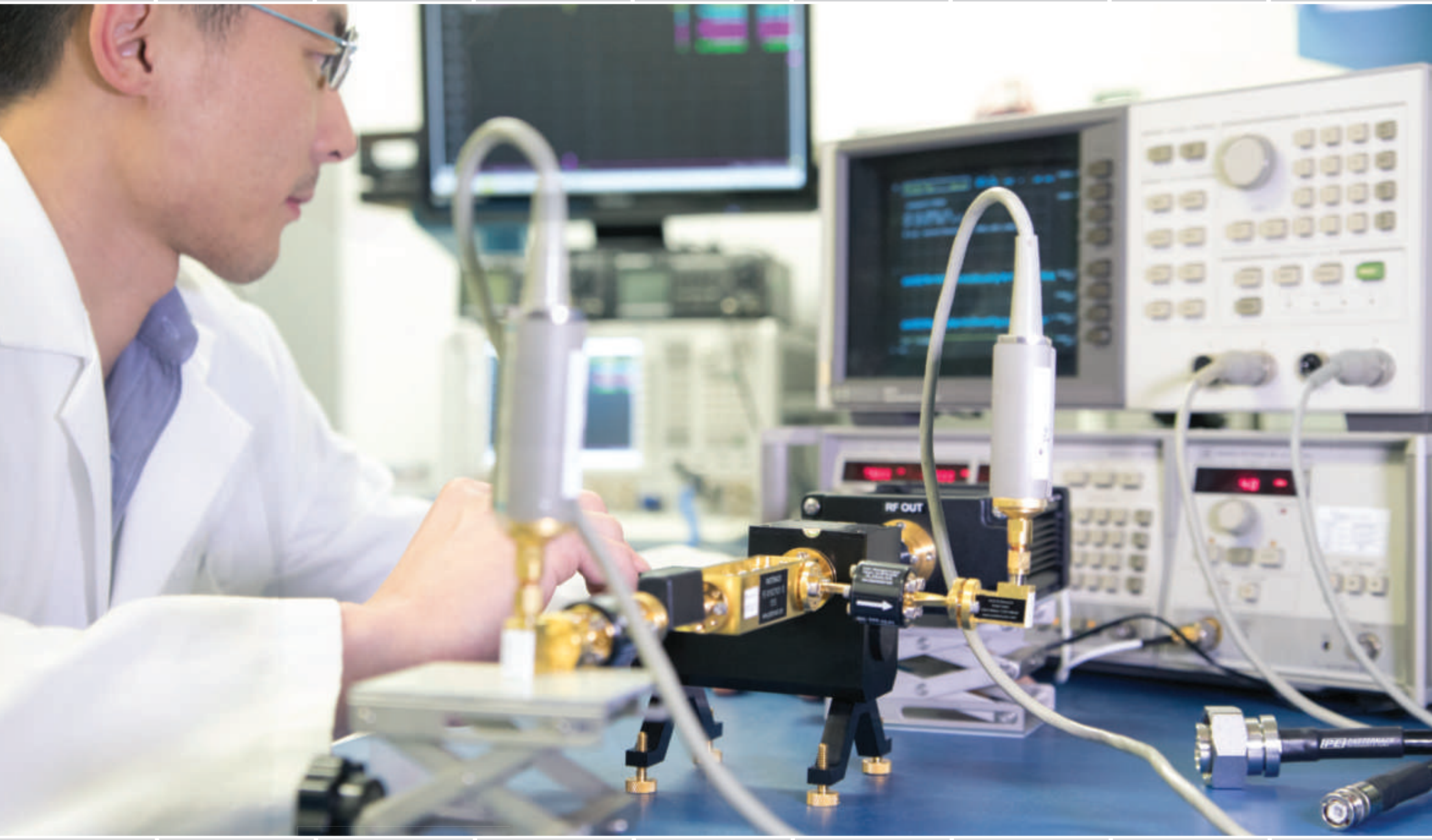
## IoT, UEM, RCS, LBS, 5G Networks to Shape Enterprise Technology Landscape

According to Strategy Analytics' latest Enterprise Survey, 42 percent of surveyed companies indicated IT spending will increase 1 to 6 percent in the next five years and another 25 percent will increase their spending 6 to 10 percent in the next five years. The outlook for operators is also positive for telco-based enterprise apps—compared to over-the-top (OTT) providers—and growing interest in location-based services (LBS). Rich Communication Services (RCS) and AI are ranked as the most important investment areas for many businesses, while Unified Endpoint Management (UEM) is a hot area for 2019 and beyond. On top of that, automation remains a key opportunity to boost productivity and efficiency. Enterprise mobility solutions can play a crucial role in this area."

Andrew Brown, executive director of Enterprise Research, Strategy Analytics, added, "Successful organizations are looking at agility, faster response to customer or user needs, and other efficiencies—including data protection and privacy. This translates into better outcomes that ensure business survival and success. We can expect more developments in areas like IoT, UEM, RCS, LBS and 5G networks that will shape the enterprise technology landscape in 2019 and beyond."

In summary, the key trends in 2019 include:

- The advent of 5G, AI and foldable screens will drive business mobile devices adoption in future, but not in 2019, where replacement cycles are generally becoming longer.
- Organizations will drive a demand for a holistic and harmonious view of all their data, and ultimately, an exploding intelligent multi-cloud strategy.
- RCS proved its capacity, not only to work as promised, but to make the brands using it some serious returns on investment. 2019 will see RCS deploy at scale.
- UEM will really start taking off in 2019 and eventually evolve to Intelligent Edge Management.
- AI voice-controlled assistants will breach the enterprise; 2019 will be the year that devices increase their overall knowledge and intelligence and add more value as augmented intelligence tools.
- Chatbots are on the rise and will dominate customer service.
- Organizations will scale real-time location systems (RTLS) deployments to the next level, 2019 will see more partnerships, broader interoperability of technologies and solutions, larger-scale rollouts.
- Realizing the promise of IoT and edge computing in order to help companies managing device, data and security efficiently.


RF OUT

# Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

## MERGERS & ACQUISITIONS

**ETL Systems** has acquired **Atlantic Microwave**, a provider of microwave components and SATCOM test equipment. ETL Systems operates globally with manufacturing and R&D sites based in the U.K. The U.K. facilities combined with offices in Washington, D.C. and Dubai support the firm in serving customers in 112 countries. ETL's key international clients include CNN, BBC, Airbus, Thales, General Dynamics, ESPN, DirectTV, Associated Press, Inmarsat, BAE Systems and SES Astra. Based in Braintree, U.K., Atlantic Microwave distributes 14 different SATCOM product lines covering 10 MHz to 110 GHz, which includes test loop translators and satellite simulators. They have specialist design, manufacture and test facilities and employ over 15 staff.

## COLLABORATIONS

**Keysight Technologies Inc.** announced that the company has extended its collaboration with **China Telecom** to accelerate commercial deployment of 5G technology. The extended collaboration supports China Telecom's 5G new radio (NR) device trials using Keysight's 5G NR network emulation solutions, based on the company's UXM 5G wireless test platform, for protocol and RF performance validation. Keysight's 5G test solutions enable China Telecom and its mobile device ecosystem ensure new 5G devices comply with the latest 3GPP 5G NR Release 15 specifications prior to market introduction.

**Nuhertz Technologies** announced new integrations capability with industry leaders **IMST** and **Mentor**. Seamless, one click, integrations capability between Nuhertz's FilterSolutions and IMST's Empire XPU, and Mentor's Hyperlynx now combines the design capabilities of these three terrific products into one seamless design tool. Nuhertz planar designs are accurately synthesized, circuits optimized and effortlessly exported into Empire XPU and Hyperlynx for efficient and accurate EM simulations and further analysis.

## ACHIEVEMENTS

Test & measurement specialist **Rohde & Schwarz** and semiconductor manufacturer **Marvell®** have demonstrated successfully, for the first time ever, all the 1000BASE-T1 compliance test cases for layer 1 (PHY). Using validated chipsets from Marvell and test equipment from Rohde & Schwarz, OEMs, Tier2, System Integrators and test houses can set up automotive Ethernet networks that are fully compliant with 1000BASE-T1 specifications.

**Nanotech Energy** announced that it has cleared a monumental hurdle in the production of high-quality graphene-based materials. The first patent for Graphene, now exclusively licensed to Nanotech Energy, was filed in 2002 by Dr. Richard Kaner, Nanotech co-founder and UCLA professor of Chemistry and of Materials Science and Engineering. Through its proprietary technology, Nanotech Energy is now able to produce graphene with an unsurpassed surface area of over 2,500 $m^2$/kg, almost the theoretical limit.

**Anritsu Corp.** announced that the Global Certification Forum (GCF) has approved the world's first 5G NR Protocol Conformance tests on the 5G NR Mobile Device Test Platform ME7834NR at their January 2019 CAG57 meeting. The 3GPP TS 38.523-defined 5G tests have been validated on multiple mmWave (FR2) frequency bands. The ME7834NR is registered with both the GCF and PCS Type Certification Review Board (PTCRB) as Test Platform (TP) 251.

**Skyworks**' SKY66430-11 Mobile IoT system-in-package (SiP) was recently named "IoT Semiconductor Product of the Year" by IoT Breakthrough. This award follows their recent accolades from Mobile Breakthrough for "GPS-based Solutions of the Year" and "Small Cell Technology Innovation of the Year" recognizing their GNSS low-noise amplifier front-end modules and family of small cell power amplifiers, respectively. The SKY66430-11, which integrates Sequans' Monarch LTE-M/NB-IoT chip, provides a fully certified all-in-one solution that incorporates the entire RF front-end, transceiver, power management, memory and baseband modem for IoT applications.

## CONTRACTS

The **U.S. Marine Corps (USMC)** has awarded **Harris Corp.** a $75 million order to provide MUOS (Mobile User Objective System) narrowband SATCOM upgrades to the service's Falcon III®AN/PRC-117G manpack radio fleet. The order is part of the Navy Portable Radio Program five-year IDIQ contract received in 2017. Harris has continued to invest in the development and deployment of MUOS and other advanced waveforms to add capability to the widely deployed AN/PRC-117G family of radios, as well as its next-generation of tactical radios. As a software-defined radio, the AN/PRC-117G was developed to be easily upgradable with new waveforms such as MUOS, enabling customers to increase capabilities economically.

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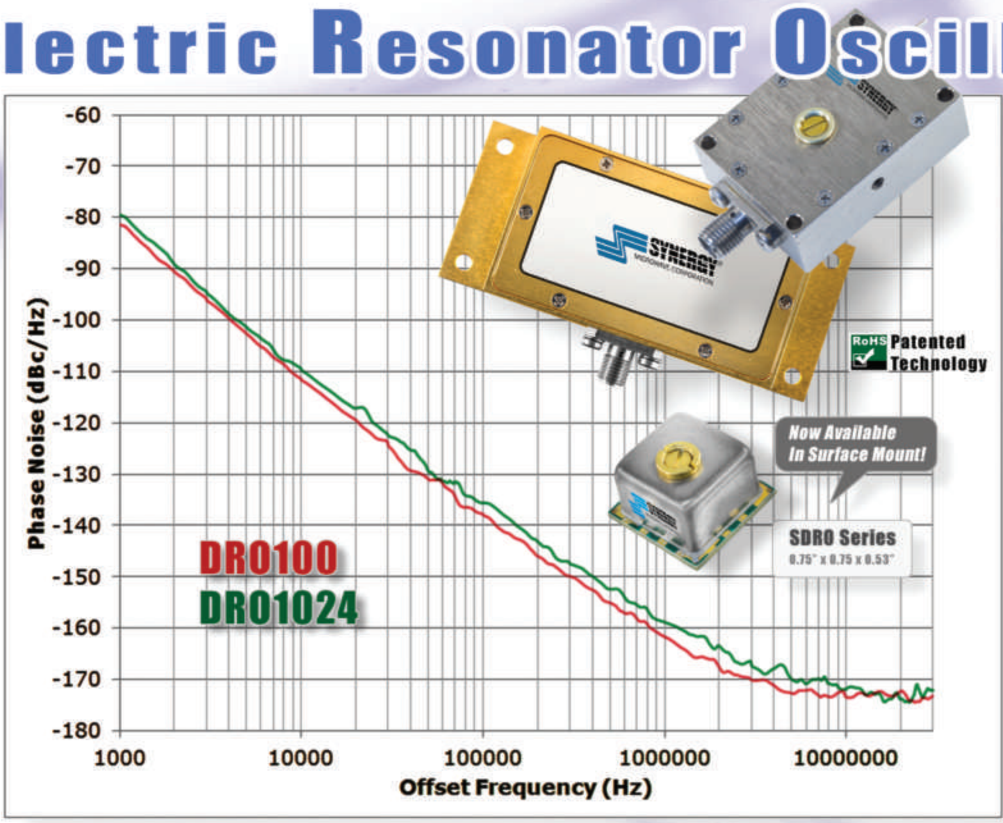


| Model | Frequency (GHz) | Tuning Voltage (VDC) | DC Bias (VDC) | Typical Phase Noise @ 10 kHz ( dBc/Hz ) |
|---|---|---|---|---|
| **Surface Mount Models** | | | | |
| SDRO1000-8 | 10.000 | 1 - 15 | +8.0 @ 25 mA | -107 |
| SDRO1024-8 | 10.240 | 1 - 15 | +8.0 @ 25 mA | -105 |
| SDRO1118-7 | 11.180 |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

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# Around the **Circuit**

**L3 Technologies** announced that it has been awarded a $26.3 million contract from the **U.S. Special Operations Command (USSOCOM)** to provide close-quarters sights and clip-on magnifiers from its EOTech brand for the Miniature Aiming System-Day Optics suite. The award marks the continuation of a 17-year relationship between USSOCOM and EOTech. Under this five-year IDIQ contract, with five option-years, EOTech will deliver an updated model of its holographic weapon sight and the G33 clip-on magnifier. All work will be performed at EOTech's headquarters in Ann Arbor, Mich. EOTech has provided Special Operations Forces with rugged and advanced holographic weapon sights since 2001.

**OSI Systems Inc.** announced that its security division received a contract valued at $12 million for operation and maintenance services from the **NATO Support and Procurement Agency (NSPA)**. The company will be responsible for operating and continuing service of the Rapiscan® Systems and AS&E® cargo, vehicle, parcel and personnel explosive and contraband detection systems.

**Mercury Systems Inc.** announced it received $6.4 million in follow-on orders from a leading defense prime contractor for advanced RF subsystems that are integrated into an airborne electronic warfare (EW) system. The orders were booked in the company's fiscal 2019 second quarter and are expected to be shipped over the next several quarters. Mercury's broad portfolio of SWaP-optimized RF and microwave solutions include high frequency amplifiers, filters, integrated microwave assemblies (IMA) and precision-engineered subsystems ruggedized for unpredictable, harsh operating environments. All of the company's RF and microwave solutions are designed and manufactured in scalable Advanced Microelectronics Centers (AMC) located throughout the U.S.

**Comtech Telecommunications Corp.** announced that during its second quarter of fiscal 2019, its Tempe, Arizona-based subsidiary, Comtech EF Data Corp., which is part of Comtech's Commercial Solutions segment, received a $1 million equipment order from a defense contractor. The equipment will be deployed to support a U.S. Air Force program. The order specified the DMD1050TS L-Band Satellite Modem Board. The DMD1050TS is Comtech EF Data's latest generation modem board set targeted at critical government and military applications. The product complies with the widest possible range of U.S. government and commercial standards and is compatible with the largest number of satellite modems in the industry.

**Airbus Defense and Space** has been awarded a contract from **DARPA** to develop a satellite bus for the Blackjack program. The goal of DARPA's Blackjack program is to show the benefits for the military to use low-Earth orbit (LEO) satellite constellations and mesh networks. Constellations of inexpensive satellites will

permit wide scale disaggregated architectures, enhancing the survivability of many different mission areas. DARPA's concept is to buy commercial satellite buses and pair them with military sensors and payloads. The satellite bus will generate the power, control attitude, provide propulsion, transmit spacecraft telemetry and provide a mounting system for military payloads such as military sensors.

## PEOPLE

▲ *Dr. Karine Brand*

**Laird Thermal Systems** has named **Dr. Karine Brand** as CEO, effective immediately. Dr. Brand has been a member of the management team since 2015, and recently led the transformation of the thermal system business unit into a standalone company. Dr. Brand previously served as the VP of engineering and technology at Laird. Dr. Brand's efforts have established Laird as the industry's leading thermal management solution provider for mission-critical and business-critical applications. Laird's diverse cooling product portfolio ranges from components and subsystems to full turnkey cooling solutions with multiple thermal technology options.

▲ *Dr. Masha Petrova*

**OnScale** announced the appointment of **Dr. Masha Petrova** as the VP of marketing. Dr. Petrova will oversee global marketing and communications with a focus on driving revenue and brand recognition for the company. Dr. Petrova will report directly to OnScale CEO, Ian Campbell. Prior to joining OnScale, Dr. Petrova led the marketing initiative for a new line of additive manufacturing software products at ANSYS Inc. Prior to joining ANSYS via an acquisition of 3DSIM, she was the director of global marketing at MSC Software.

▲ *Dr. Nitin Jain*

**Anokiwave Inc.** announced **Dr. Nitin Jain**, Anokiwave founder and CTO, has been named a Fellow of the IEEE for leadership in the development of physics-based models for mmWave system on a chip (SoC) ICs. The IEEE grade of Fellow is conferred in recognition of unusual and outstanding professional distinction. It is awarded at the initiative of the IEEE Board of Directors following a rigorous nomination and evaluation process. Individuals receiving this distinction have demonstrated extraordinary contributions to one or more fields of electrical engineering, or related sciences. The total number of Fellows selected in any one year does not exceed one tenth of 1 percent of the total voting Institute membership.

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▲ *Rodger Hosking*

**VITA** announced that **Rodger Hosking**, VP and co-founder of Pentek Inc., was elected to the VITA Board of Directors. With this election, the board will now consist of four members. Hosking is responsible for new product definition, technology development and strategic alliances at Pentek. With over 30 years in the electronics industry, he has authored hundreds of articles about software radio and digital signal processing.

## REP APPOINTMENTS

**MilesTek** announced that it has partnered with Phoenix-based, value-added distributor **Spirit Electronics**. Spirit Electronics is a veteran-owned, woman-owned business that provides superior supply-chain solutions and electronic component distribution for global technology leaders in the aerospace, defense and communication industries. From fighter jets to guided missiles, Spirit plays a vital role in supplying world-class products and services to meet the highly demanding and rapidly changing needs of its clients.

**Modelithics Inc.** and **Wavelength Electronics Ltd.** have recently signed a representation agreement for the support and sales of Modelithics' high frequency simulation model libraries and precision RF, microwave and mmWave measurement services in the U.K. region. Wavelength Electronics is a multi-line manufacturer's representative firm specializing in RF and passive components, offering their principal companies' products and services to support U.K. OEMs. Modelithics customers, or potential customers, in the U.K. will now have a local contact for information regarding Modelithics' products and capabilities. Wavelength Electronics will now be able to support their customers with RF and microwave simulation models and measurement services, complementing the high frequency component sales.

**Rosenberger North America** has signed an agreement with **Electronic Marketing Associates (EMA)** to represent it in the Southeastern territory in the U.S. EMA and its large network of sales representatives will oversee and cultivate sales of Rosenberger's product lines of RF/microwave connectors, cable assemblies and test & measurement products.

**Filtronic plc** announced that it has appointed **Quintel USA Inc.** as its exclusive distributor in North America to a number of mobile network operators (MNO) for certain antenna products. Quintel is an established designer and manufacturer of innovative antennas and has established a comprehensive sales channel in North America. Quintel has achieved approved vendor status with some of the major U.S. MNOs, including Tier 1 MNOs. Filtronic's range of antennas is complementary to Quintel's, with very little overlap in the product line up.

# Optimizing the Perennial Doherty Power Amplifier

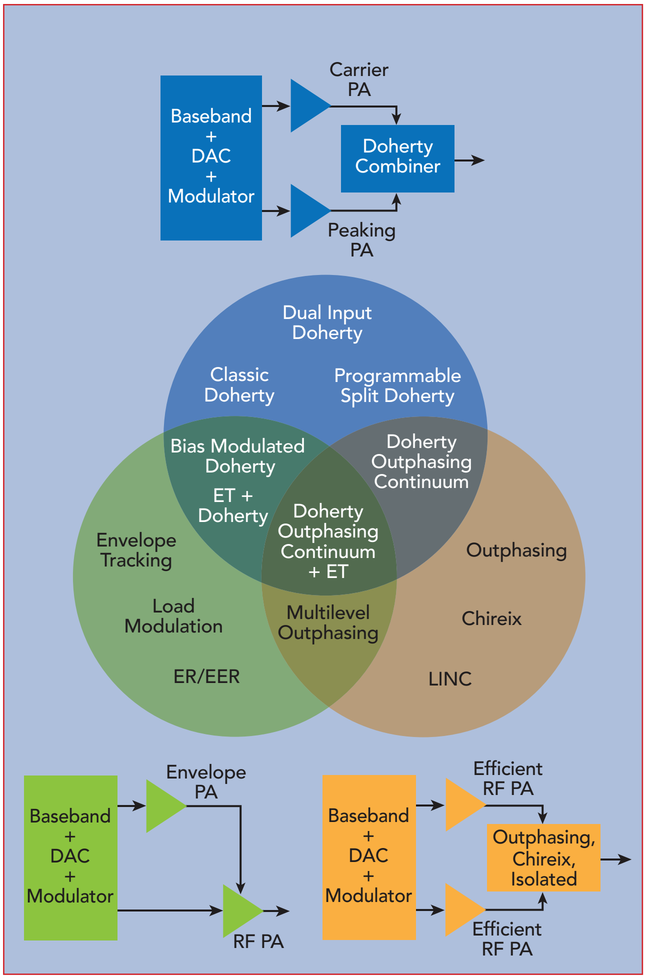
Gareth Lloyd
*Rohde & Schwarz, Munich, Germany*

The Doherty power amplifier (PA), invented almost 100 years ago, is used in an increasing number of radio transmitter applications to improve energy efficiency, with numerous ways to build the PA. This article begins with an overview of linearization and efficiency enhancement and, against that backdrop, highlights the associated challenges and some of the numerous solutions. Finally, there is an alternative design flow, illustrated with a case study providing insight into the design and how to achieve the best performance-cost compromise.

## LINEARIZATION TECHNIQUES

The four key technical performance parameters in a transmit (Tx) RF front-end (RFFE) are the efficiency, output power, linearity and bandwidth. The latter three are often dictated by system requirements, such as a communications standard. The former, (energy) efficiency, is the differentiator. All other performance parameters being equal, a higher efficiency for a front-end is preferred.

Devices used in the RFFE have imperfect linearity characteristics, preventing them from being fully utilized merely as drop-in components. The linearity of a Tx RFFE can be improved by implementing a linearization scheme. Typically, this will increase the raw cost of a Tx RFFE, trading that for a combination of efficiency, linearity and output power improvement. Numerous linearization methods have been published, stretching back at least to the feedforward[1] and feedback[2] patents. Arguably, the use of nonlinear predistortion dates similarly to the invention of companding.[3] These schemes may be classified according to their modus operandi (see ***Figure 1*** and ***Table 1***).[4] One way of dividing the linearization pie is to identify whether a scheme predicts or extracts its unwanted signal and whether that unwanted correc-




▲ Fig. 1 Amplifier linearization options using post-source, predicted/synthesized composition schemes.


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**TABLE 1**

**AMPLIFIER LINEARIZATION METHODS**

| | | Impediment Generation | |
|---|---|---|---|
| | | **Predicted/ Synthesized** | **Measured/Extracted** |
| **Correction Location** | **Pre-Source** | Digital Predistortion | Cartesian Feedback |
| | | Analog Predistortion | Polar Feedback |
| | **Post-Source** | Analog Post-Distortion | Feedforward |
| | | Composition Schemes | Fixed Filtering (e.g., Bandpass) |

tion is applied before or after its creation. Classification is useful to understand the general properties and identify the best approach for the application.

Feedforward is an example of a measured, post-correction scheme; feedback is a measured, pre-correction scheme; and predistortion is a predicted, pre-correction scheme. Predictive schemes rely on the unwanted signal being generated, which can potentially be onerous in wider band and lower power systems for digital predistortion (DPD). On the other hand, predictive schemes do not require that distortion exists and can, potentially, eliminate distortion completely.

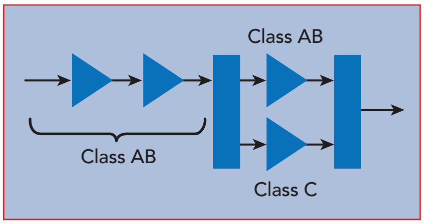


**Fig. 2** Simplest implementation of the Doherty amplifier.

Missing from these examples is a whole class of linearization techniques using predictive post-correction. This family of techniques has also been heavily researched and documented over the last 100 years. Outphasing,[5] envelope[6] and Doherty[7] transmitters, along with their hybrids by Choi,[8] Andersson[9] and Chung[10] are examples of such techniques, except they have been primarily marketed for efficiency enhancement rather than as linearization techniques. In their purest forms, envelope and outphasing schemes construct their signals from efficiently generated, nonlinear components, using multiplication and summing of their paths, respectively. A Doherty comprises a reference path, referred to as the "main" or "carrier," and an efficiency path, named the "peaking" or "auxiliary." A more comprehensive mathematical analysis of the Doherty design is beyond the scope of this article and is available in a plurality of texts. For further information, the reader is especially referred to Cripps.[11]

## DOHERTY IMPLEMENTATIONS

Arguably, the most common and often quickest starting point for a Doherty amplifier design is the "zeroth embodiment" (see ***Figure 2***), comprising a

- Fixed RF input to the final stage power splitter.
- Main and auxiliary amplifiers, differently biased (e.g., using class AB and class C).
- Doherty combiner made from a quarter-wavelength transmission line.

In most applications, this architecture does not provide sufficient power gain—at least not from a single, final stage—and additional gain stages are cascaded ahead of the power splitter. Criticism of this most commonly used implementation include

- No method for compensating gain and phase variations in any domain after the design is frozen.
- Both the efficiency and output power are traded-off because of the bias class. In effect, the class C bias, an open loop analog circuit, is driving this.
- Efficiency enhancement is limited to a single stage. With a multistage cascade, this limits the performance improvement, especially as gain diminishes at higher frequencies.

From another perspective, the Doherty engine is an open loop scheme, with several key functional mechanisms derived from the bias points of the transistors. Once the other variables are defined (e.g.,

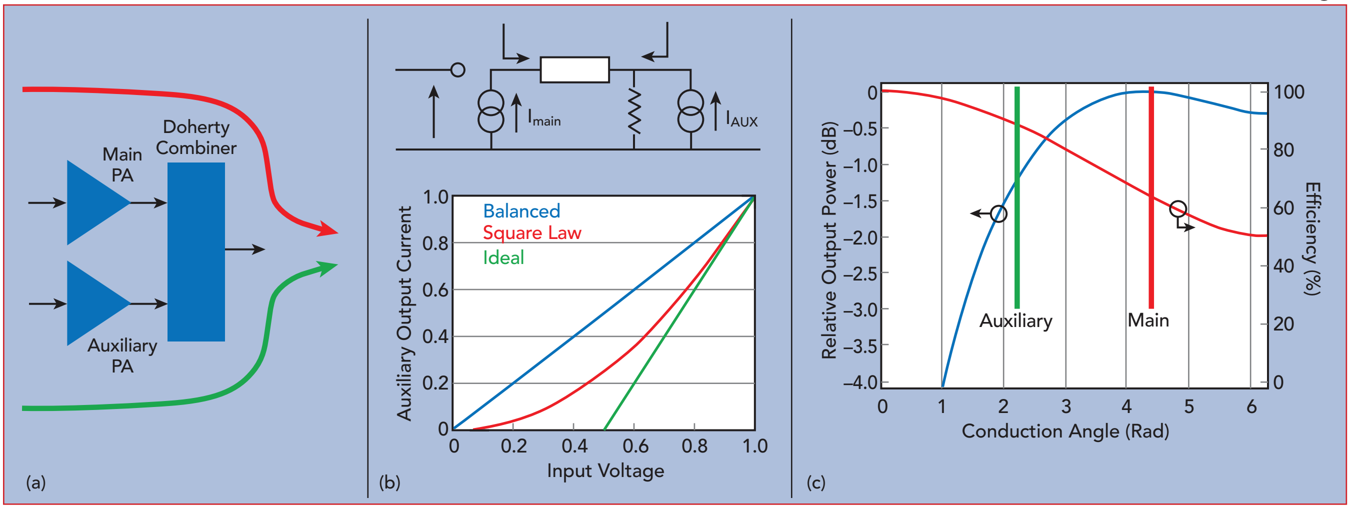


**Fig. 3** Doherty amplifier challenges: combiner amplitude and phase matching (a), auxiliary amplifier current response (b) and power-efficiency trade-off (c).

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phase offsets, splitter design, etc.), only one or two handles are provided, upon which multiple critical adjustments rely.

### Challenges

One of the ways the Doherty improves efficiency is load modulation. The engine that drives that is the difference in output currents, sourced into the combiner from two or more amplifiers. Since the engine can only approximate the Doherty operation, the challenge for the designer is to enable the engine to approximate it with the best, but still appropriate, cost-performance paradigm. Some of the potential hindrances or impediments to Doherty performance are 1) the amplitude and phase matching of the signals incident to the combining node, especially over frequency (see ***Figure 3a***). Deviation from the ideal degrades efficiency and output power. Potentially, this can be more destructive, as the devices are intentionally not isolated, with the efficiency enhancement relying on their mutual interaction through the combiner. 2) Ideally, the auxiliary path of the Doherty engine exhibits a dog leg or hockey stick characteristic (see ***Figure 3b***). Failure to achieve the ideal is often the primary reason for not realizing the famous efficiency saddle point. As the characteristic tends from the ideal to a linear response, the Doherty amplifier increasingly behaves like its quadrature-balanced relative—albeit with a non-isolated combiner—especially its efficiency performance. 3) The commonly used "differential biasing" of the main and auxiliary operating in class AB and class C, respectively, forces the output power and efficiency of both amplifiers to be degraded (see ***Figure 3c***). As Cripps showed,[11] the continuum of quasi-linear amplifier classes from A to C, which theoretically operate with sinusoidal voltages across their sources, varies their respective maximum output power and efficiency characteristics. At the same time, if biasing is used to create the difference engine, as is the case in the classical Doherty embodiment, there is intrinsically a trade-off between output power and efficiency. Simultaneously, differential biasing increases the Doherty effect, yet decreases the achievable performance.

## VARIANTS AND IMPROVEMENTS

The following variations on the basic concept may be more appropriate for some applications and, with the classical implementation, offer the designer performance and flexibility options.

- Multiple gain stages inside the Doherty splitter and combiner.
- N-way Doherty.
- Intentionally dispersive splitter.
- Programmable splitter.
- Bias modulation.
- Supply modulation, i.e., adding a third efficiency enhancement technique to the two leveraged by Doherty.
- Envelope shaping.
- Digital Doherty.

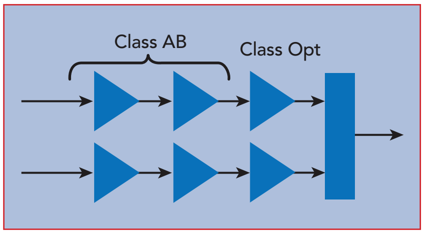


**Fig. 4** Digital Doherty amplifier, where the main and auxiliary amplifier operating class is digitally controlled.

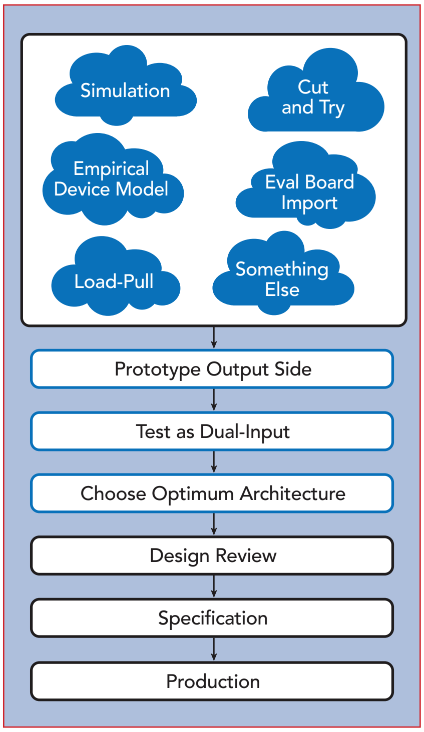


**Fig. 5** Measurement-aided design flow for a digital Doherty amplifier.

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In addition to the different architectures available to the designer, three points in the product life cycle allow adjustments. During the design phase, the design parameters can be modified, recognizing the parameters will be passed to production as fixed values (e.g., the input splitter design). During production, the parameters may be modified or tuned, typically based on measured data, and then frozen or fixed through programming. One example is the nominal bias voltage used to generate the target bias current in the devices. Once the equipment is deployed in the field, parameters may be updated, either continuously or at specific times, either open or closed loop. Open loop concepts rely on sufficiently predictable behaviors, while closed loop concepts might require built-in measurement and control. One example is circuitry for temperature compensation. These product life cycle options provide a plurality of solutions with no "best" solution. It is just as important for the designer to be aware of the manufacturing and supply capabilities following the design as the design challenges and trade-offs made during the design phase.

At the opposite end of the solution spectrum from the zeroth embodiment is the digital Doherty (see *Figure 4*). This architecture is characterized by an input split which stretches back into the digital domain, prior to the digital-to-analog conversion. The ability to apply digital signal processing to the signal applied to both amplifier paths potentially gives unsurpassed performance from a set of RF hardware. Compared to the standard Doherty implementation, the digital version can achieve 60 percent greater output power, 20 percent more efficiency and 50 percent more bandwidth without degrading predictive, pre-correction linearity.[12]

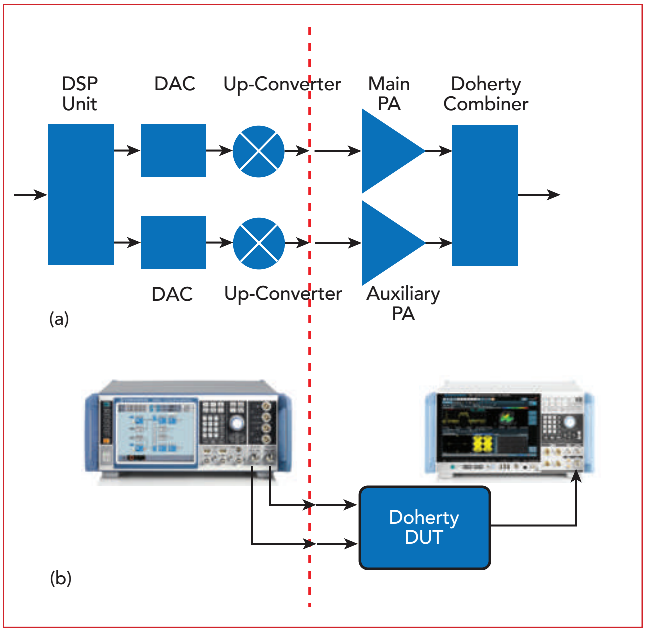


**Fig. 6** Simplified block diagram (a) and hardware setup (b) for designing a digital Doherty amplifier.

## MEASUREMENT-AIDED DESIGN FLOW

To optimize any Doherty design, it is advisable to build simulation environments that correlate well with the design, to understand trends and sensitivities. The simulation enables a significant part of the development to be covered quickly. Inputs to the first step might include load-pull data or models for the candidate devices, a theoretical study of the combiner and matching network responses, evaluation boards with measured data or other empirical data. Building on this starting point, the design flow can be supplemented with measurement-aided design (see *Figure 5*).

For the digital Doherty, the starting point for this approach is a Doherty comprising two input ports, input and output matching networks, active devices, bias networks and the Doherty combiner (see *Figure 6*). Measuring the prototype Doherty as a dual-input device provides greater insight into the performance limitations, trade-offs and reproducibility expected in a production environment. Critical to the test set-up are two signal paths, whose signals may be varied relative to each other. In addition to

applying precise, stable and repeatable amplitude and phase offsets to the signals, it is advantageous to be able to apply nonlinear shaping to at least one of the signal paths.

The measurement algorithm may be rapid or more exhaustive, programmed to seek the optimum values for desired parameters or configured to characterize a wide range of parameters. In a simple case, the designer may want to confirm the best-case quantities and their relative amplitude and phase balance values. More complicated, a detailed sweep to enable a sensitivity analysis or rigorous solution space search may be warranted. The post-processing of these measurements can be as simple or sophisticated as the user wishes.

## CASE STUDY

To demonstrate the design flow and achievable results, a digital Doherty PA for a 3.5 GHz, 5G New Radio (NR) base station was designed using a single stage unmatched GaN power transistor, the Qorvo® TQP0103. A dual-path R&S®SMW200A vector signal generator provided the two input signals to drive the GaN amplifier. For measurement of dependent quantities, the single RF output of the amplifier was connected to an R&S®FSW Signal Analyzer. DC power for the devices was sourced from an R&S®HMP power supply, which measured the DC power consumption. The amplifier was stimulated using differentially linear and nonlinear signals, the former sweeping the input power, am-

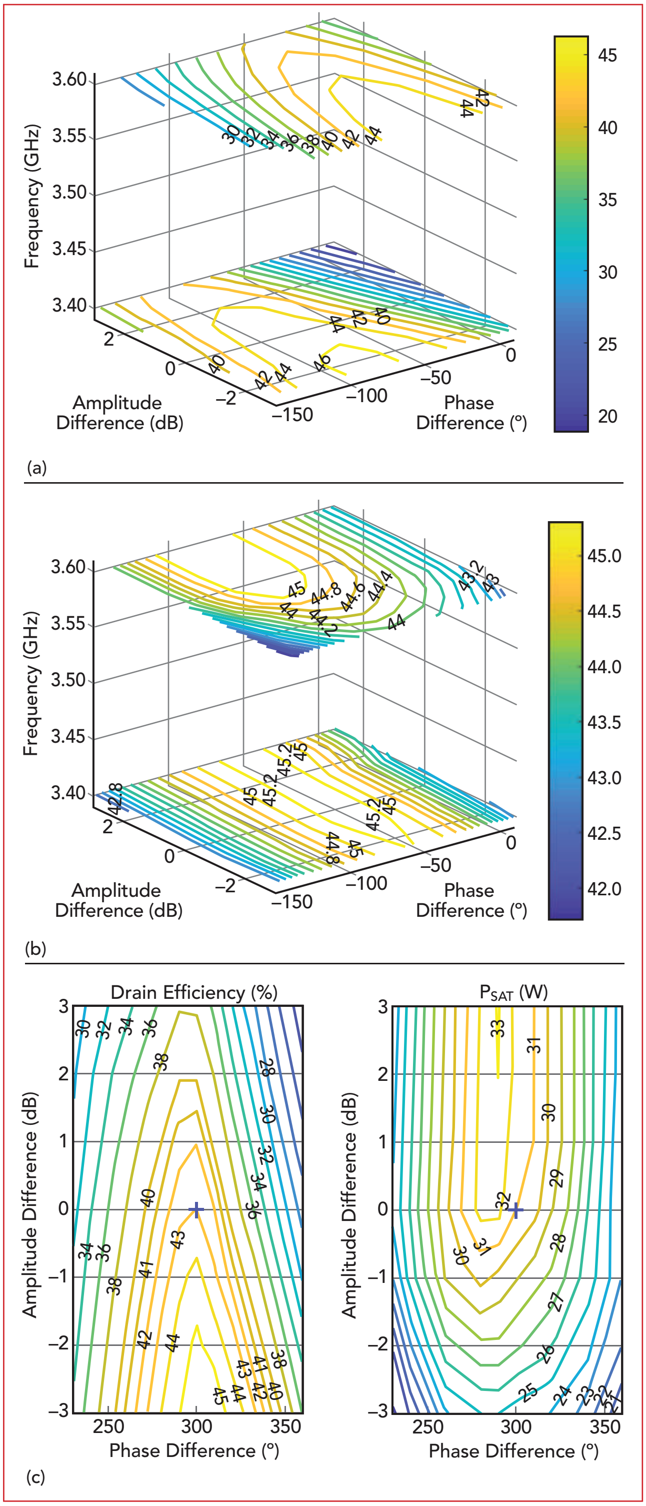


**Fig. 7** Dual-input Doherty in linear operation: measured efficiency at 35.5 dBm (a), saturated power (b) and worst-case efficiency and power (c).

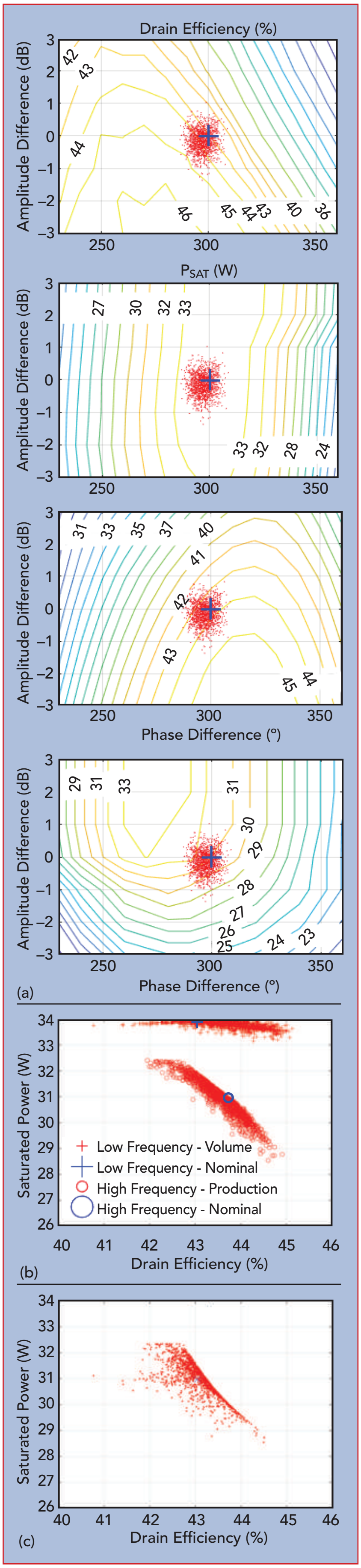


**Fig. 8** Gain and phase variation of a population of split digital Doherty amplifiers with a fixed RF input (a), saturated power and efficiency using a look-up concept (b) and cumulative, worst-case production distribution (c).

plitude and phase. The nonlinear tests used a variable shaping function, amplitude dependent, at two frequencies. Output power, output peak-to-average power ratio, adjacent channel leakage ratio (ACLR) and current consumption were measured, and the measurement results were analyzed using MATLAB®.[13]

Analyzing the linear measurements, efficiency at a specified power level and saturated power were plotted versus the amplitude and phase differences (see ***Figure 7***), with the worst-case efficiency and output power shown in Figure 7c. In the basic Doherty embodiment, a quasi-constant amplitude/phase split is chosen for the operating frequency. The efficiency and saturated power for these amplitude/phase values can be determined by extracting the worst-case performance at the test frequencies.

Selecting a nominal amplitude/phase split, a perturbation representing the natural variation in production may be added to the evaluation. Using a look-up table, the bulk effect of these part-to-part variations can be observed, as shown in ***Figure 8***. Figure 8a shows the drain efficiency and saturated output power at two frequencies, Figure 8b shows the estimated production spread of saturated output power and drain efficiency versus the nominal values for the same two frequencies. Figure 8c shows the cumulative production spread, aggregating the results from the two frequencies. Paradoxically, in this case, most of the part-to-part variation is in the target variable, efficiency.

By adopting an alternative approach to the input splitter design, this variation can be reduced. Using a dispersive input splitter design, meaning using different amplitude and phase differences at the two design frequencies, advantageously enables the stacked contour plots shown in Figure 8a to, in effect, slide over one another. Using the same part-to-part variation data with this dispersive splitter design yields a

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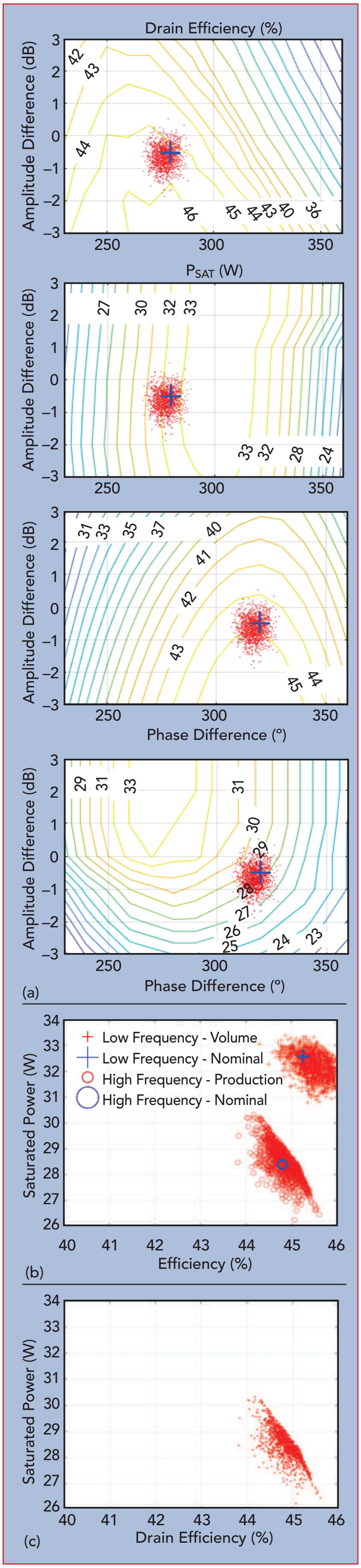


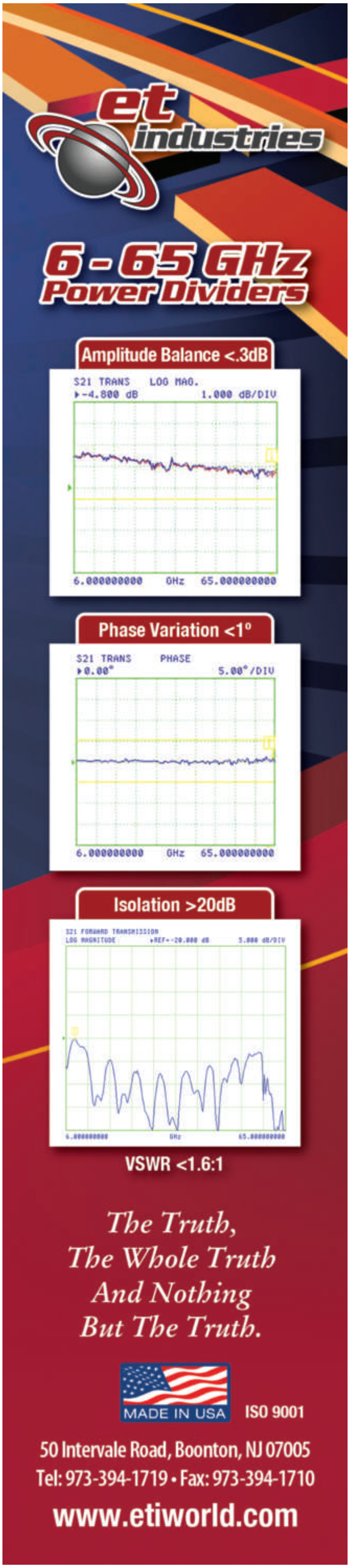

**Fig. 9** Digital Doherty amplifier population using a dispersive input split: gain and phase variation (a), saturated power and efficiency (b) and cumulative, worst-case production distribution (c).

better result (see ***Figure 9***), with a higher mean efficiency and lower standard deviation.

By directly generating signals for the two amplifier inputs in the digital domain, the deficiencies of the Doherty amplifier are significantly reduced. Additionally, the simple part-to-part amplitude/phase variations shown in the linear example may be eliminated. To illustrate this, albeit not exhaustively, the auxiliary path was programmed with a square law shaping function applied to both the amplitude and phase, with the phase "start" and "end" values—the phase with zero and maximum input amplitude—varied randomly. With a common bias for the two amplifiers, only a trade-off between output power and efficiency remains, rather than those and the Doherty difference engine magnitude.

To establish a baseline, driving the commonly biased amplifiers with a linearly differential signal enabled the equivalent "balanced" performance to be ascertained: the available saturated output power in this mode was 0.5 dB higher than the differential biased case (12 percent higher power). That represents the "cost" of operating the Doherty engine using differential bias points. The scatter plot of random shaping functions applied to the auxiliary path yields the locus of performance shown in ***Figure 10***, reflecting the distributions of average power versus efficiency and peak envelope power (PEP) versus average power. The saturated output power is 1.7 dB higher than the conventional Doherty amplifier (48 percent higher power), suggesting that 1.2 dB of the improvement (32 percent) is from better amplitude/phase matching of the signal paths.

The 1.7 dB improvement in saturated output means the amplifier may be operated at that increased output power without compromising headroom, and the increase in average power is associated with a 5 point increase in efficiency (from 44 to 49 percent). Alternatively, de-



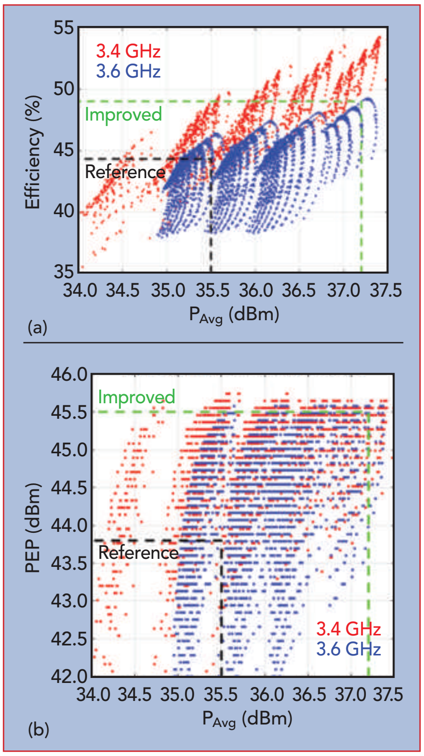




Fig. 10 **Efficiency vs. average output power (a) and PEP vs. average output power (b) for a dual-input Doherty amplifier using with square-law shaping and randomized phase.**

vices with 48 percent smaller periphery may be used to achieve the original target output power. Taking into account the expected part-to-part variation, this reduction in device periphery might be reduced further.

## CONCLUSION

Significant improvements in Doherty performance can be achieved by addressing the input side of the design. The use of either an intentionally dispersive or programmable input split can improve performance, especially considering manufacturing distributions. According to peer reviewed research,[12] the digital Doherty with nonlinear input splitting or shaping can achieve 60 percent more output power, 20 percent more efficiency and 50 percent greater bandwidth without any degradation in predictive linearization. The case study described in this article achieved 47 percent higher output power and 11 percent greater efficiency over a fixed bandwidth.

A measurement-aided methodology for extracting and understanding possible improvements was demonstrated. While efficiency and saturated power served as examples, they do represent the two most important parameters in most Doherty designs. Regardless of which Doherty architecture is used, this design methodology provides more detailed and rigorous insight and improves both time-to-market and the cost-specification paradigm.■

## ACKNOWLEDGMENTS

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INVITED PAPER

# Recent Advancements in mmWave Isolator Technology

David W. Porterfield, Jr.
*Micro Harmonics Corp., Fincastle, Va.*

Isolators are non-reciprocal devices, passing electromagnetic (EM) signals in one direction and absorbing them in the reverse direction. They are primarily used to suppress standing waves that arise due to impedance mismatches between highly-tuned components, such as those found in frequency multiplier chains. Standing waves cause dips—even nulls—in the output of the multiplier chain. They can be mitigated by inserting isolators between the multipliers, resulting in a much smoother frequency response and improved bandwidth.

Traditional Faraday rotation isolators provide greater than 20 dB of isolation over full waveguide bands, with some exceeding 30 dB. While there are more than a dozen vendors worldwide, the design has largely remained static since the 1970s. Insertion loss is low in the microwave bands, steadily increasing with frequency. At mmWave frequencies, the insertion loss becomes problematic: in the WR10 band (75 to 110 GHz), insertion loss can exceed 3 dB; in the WR3.4 band (220 to 330 GHz), the loss can be greater than 7 dB, making the isolators impractical. There are few suppliers in the bands above 110 GHz; isolators for the WR4.3 and WR3.4 bands, produced many years ago, are now difficult to find. At these frequencies, the constituent parts are very small, difficult to fabricate and align—and with more than 7 dB insertion loss, there is not much demand.

In 2001, Erickson[1] demonstrated that insertion loss can be dramatically reduced. Yet, for many years following that work, very little changed in the commercial market. In 2015, with funding from NASA JPL, Micro Harmonics Corp. developed a line of mmWave isolators designed for low insertion loss. These isolators have a typical insertion loss of less than 1 dB in the WR10 band and about 2 dB in the WR3.4 band. These numbers are game changers, and mmWave system developers are reconsidering their use. Micro Harmonics is currently the only worldwide producer of full band, low loss isolators in the WR4.3 (170 to 260 GHz) and WR3.4 (220 to 330 GHz) bands, and is developing designs for the WR2.8 (265 to 400 GHz) and WR2.2 (330 to 500 GHz) bands.

## FARADAY ROTATION ISOLATOR THEORY

At frequencies from 50 to 330 GHz, the dominant isolator topology is Faraday rotation with transitions to rectangular waveguide, as described by Barnes[2] in 1961. At the heart of the isolator are a cylindrical

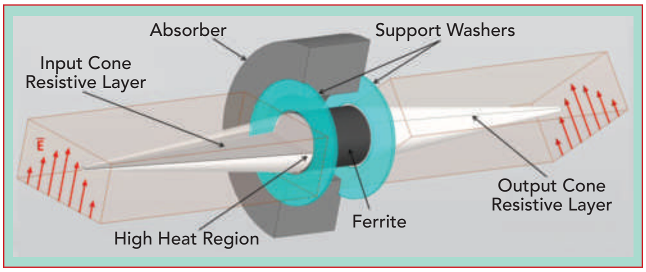


Fig. 1 **Structure of a Faraday rotation isolator.**

ferrite core and a pair of alumina cones bisected on their central axes by resistive layers (see ***Figure 1***). For improved visibility, the absorber is shown split in half, with the top half of the input cone semi-transparent. The cones couple the dominant TE10 waveguide mode to the HE11 hybrid dielectric mode in the ferrite. The ferrite and cones are suspended in the waveguide structure by a pair of washer-shaped supports. The output cone and waveguide are rotated 45 degrees with respect to the input cone and waveguide. An absorber is used to suppress higher-order modes near the ferrite core.

The E-field in the TE10 mode is normal to the resistive layer in the input waveguide. The field is rotated 45 degrees counterclockwise as it passes through the ferrite and emerges normal to the resistive layer in the output cone. No currents are generated in either resistive layer by the forward traveling wave, and there is no associated loss. The direction of rotation is the same for both the forward and reverse waves, giving rise to the non-reciprocal nature of the device. The reverse traveling wave is rotated into the input cone resistive layer and absorbed, i.e., converted to heat energy.

All materials have electron spin states which create magnetic dipoles. In non-magnetic materials, the dipoles are randomly aligned, and there is no net magnetic dipole moment. In ferrite materials, some of the magnetic dipole moments can be aligned. Application of a DC magnetic bias field causes additional dipoles to align, and the magnetic moment increases. Further increases in the magnetic bias field give rise to larger net magnetic dipole moments until a point of saturation, beyond which further increases in the bias field produce no change. This condition is referred to as magnetic saturation. The magnitude of the saturation magnetization ($4\pi Ms$) is a material property in the range of 300 to 5000 G for most commercial ferrites.

The magnetic dipoles precess around the magnetic bias field vector (see ***Figure 2***). As an EM signal passes through the ferrite, the fields interact with the dipole moments.

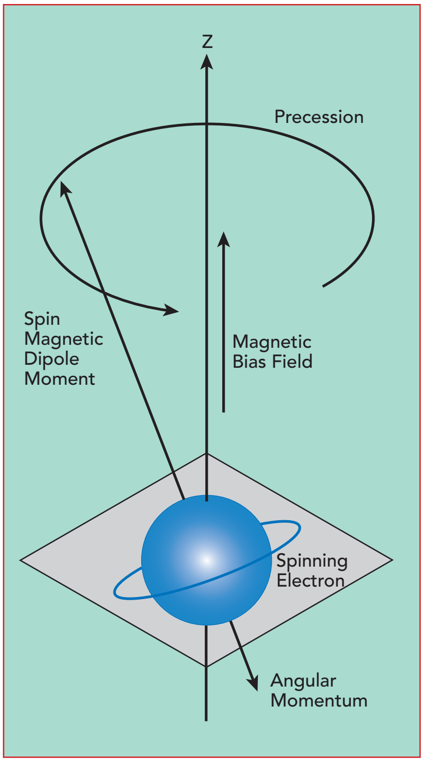


Fig. 2 **Spinning electron angular momentum and spin magnetic dipole moment vectors.**

Linearly polarized waves, like those passing through the isolator, can be decomposed into left hand and right hand circularly polarized waves, LHCP and RHCP, respectively. The interaction with the precessing dipole moments results in disparate propagation constants for the RHCP and LHCP waves. The difference in the propagation constants



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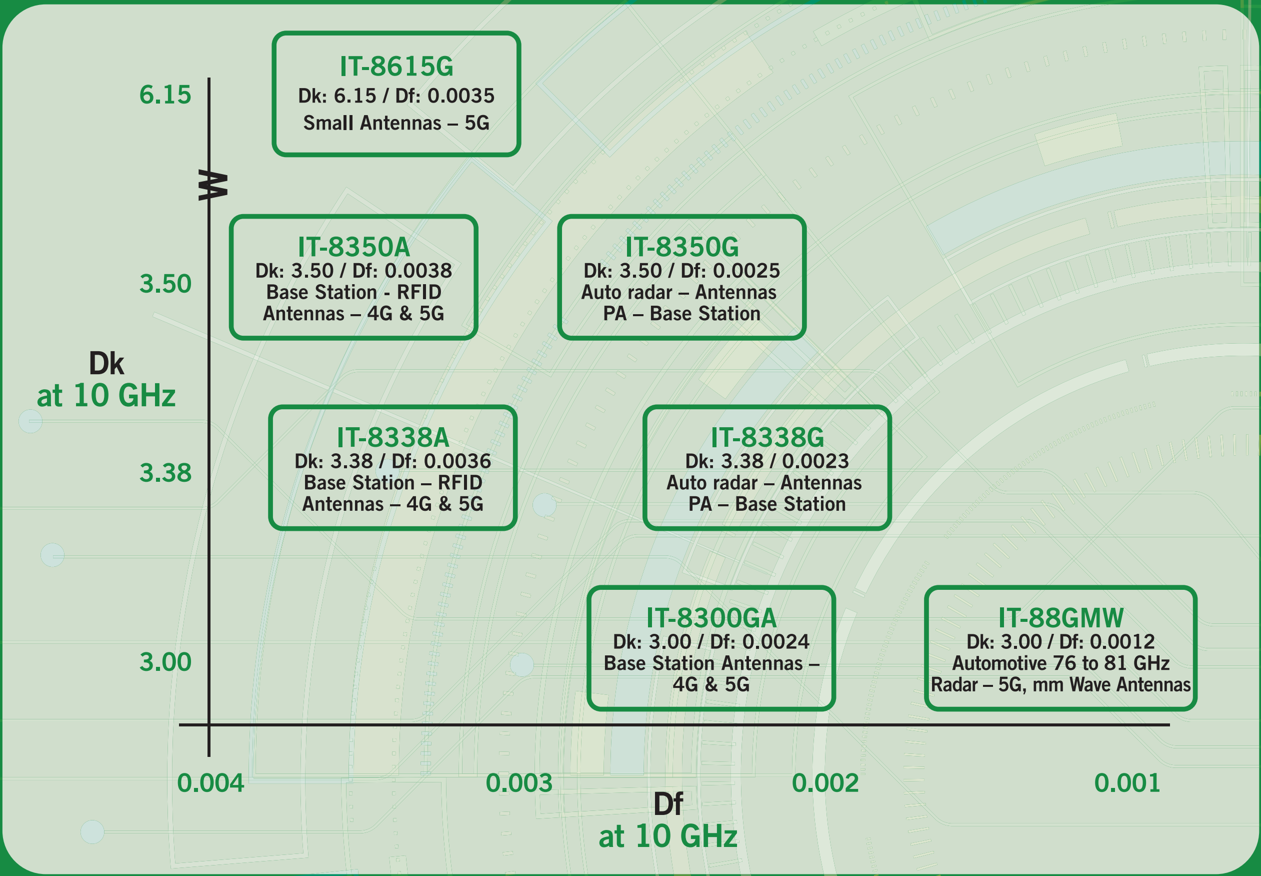


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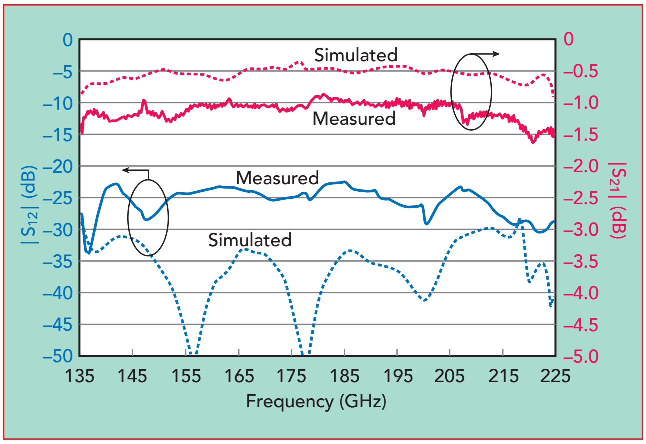
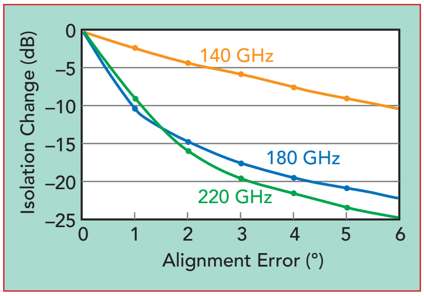



▲ Fig. 3 **Simulated vs. measured insertion loss and isolation of a WR5.1 isolator.**




▲ Fig. 4 **Isolation sensitivity to rotational misalignment of the input cone.**

is because one of the components (RHCP or LHCP) opposes the dipole precession and the other coincides. A phase shift occurs between the RHCP and LHCP waves as they travel through the ferrite, resulting in the rotation of the linearly polarized signal. A more in-depth discussion of Faraday rotation is given by Pozar,[3] Lax et al.[4] and Balanis.[5]

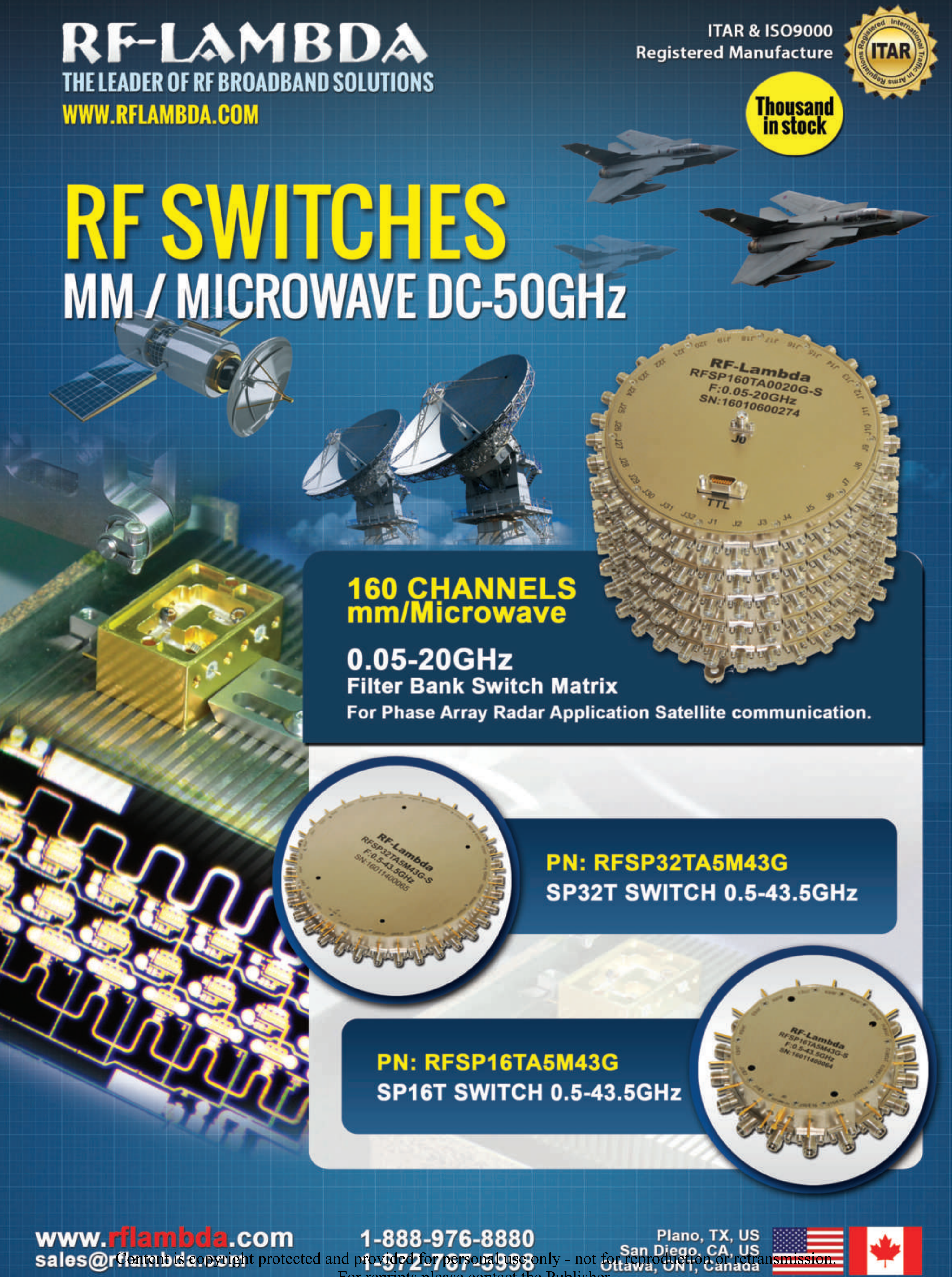
## SIMULATIONS

HFSS[6] is used to model and simulate isolator performance. The final models contain all relevant parts, including the core region surrounding the ferrite, the waveguides and twist steps. The simulations include the Faraday rotation effect using a magnetically biased ferrite, as well as ferrite dielectric loss and waveguide conductor losses.

***Figure 3*** compares the simulation and measured data for a Micro Harmonics WR5.1 isolator. The standard WR5.1 band is from 140 to 220 GHz, and the data in the figure covers an extended range from 135 to 225 GHz. The simulated insertion loss is about 0.5 dB lower than the measured data. The discrepancy is likely due to small misalignments in the assemblies and under-estimation of waveguide conductor loss in the models. The discrepancy between simulated and measured isolation (i.e., $|S_{12}|$) is also attributed to small alignment and fabrication errors in the constituent parts. Very little data is available on the material parameters at these frequencies, also contributing to model inaccuracies. Qualitatively, the data are in good agreement, and the measured insertion loss is much better than the typical insertion loss of old-style isolators, which was greater than 4 dB in this band.

HFSS simulations on the WR5.1 isolator model illustrate the sensitivity to alignment and fabrication errors. Incrementally rotating the input cone out of alignment, while every other part is held in perfect alignment, degrades isolation by approximately 10 dB for a 1 degree alignment error at the center and upper end of the WR5.1 band (see ***Figure 4***). A fabrication error of only ±0.001 in. in ferrite length also causes a 1 degree rotational error, with similar results.

There are challenges to fabricating and assembling mmWave isolators. The constituent parts are tiny and, as illustrated, small alignment errors can significantly degrade performance. Misalignment can also increase coupling to higher-order modes in the region near the ferrite core, resulting in unwanted structures in the response. The assembly process is an art, and no two isolators have the same signature, motivating continual efforts to improve the uniformity of the assemblies. Every isolator is thoroughly tested on a vector network analyzer to ensure conformity with specifications.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## MINIMIZING LOSS

Two of the largest contributing factors to insertion loss at mmWave frequencies are loss in the ferrite and waveguide conductor loss.

### Minimizing Ferrite Loss

The EM field rotation in a Faraday rotation isolator is described by the equation

$$\theta = \frac{4\pi M_z \Upsilon l \sqrt{\varepsilon}}{2c} \quad (1)$$

where $4\pi M_z$ is the axial magnetization, $\Upsilon$ is the gyromagnetic ratio ($8.795 \times 10^6 \times g$ rad/s/Oe), l is the ferrite length, c is the speed of light and $\varepsilon$ is the ferrite dielectric constant. This equation shows that field rotation is directly proportional to ferrite length and axial magnetization. Minimum insertion loss and maximum isolation occur when the EM field is rotated by 45 degrees as it passes through the ferrite. Ferrites are lossy at mmWave frequencies, so it is essential that the length be reduced as much as possible.

The traditional method to tune Faraday rotation isolators is to use ferrites substantially longer than the minimum required length and adjust the magnetic bias field to achieve a precise 45 degree rotation. This is a useful way to tune the isolator, but it comes at the cost of increased insertion loss: the ferrite is longer and unsaturated ferrites have higher loss per unit length.[3,7] In this precisely tuned state, isolators are sensitive to stray magnetic fields, which can cause under- or over-rotation of the signal. While a ferromagnetic sheath is typically employed to channel stray magnetic fields away from the ferrite, even with a sheath, there is some sensitivity.

Micro Harmonics uses a saturating magnetic bias field and the minimum possible ferrite length to yield the minimum loss in the ferrite core. The magnetic bias fields are measured to ensure ferrite saturation, and magnetic armatures are used to achieve a focused, uniform bias field in the ferrite. ***Figure 5*** shows the measured magnetic bias field near the surface of a ferrite. The measured peak value exceeding 2000 Oe, is substantially more than required for saturation. Only stray magnetic fields with a very strong axial component in the opposite polarity will degrade signal rotation.

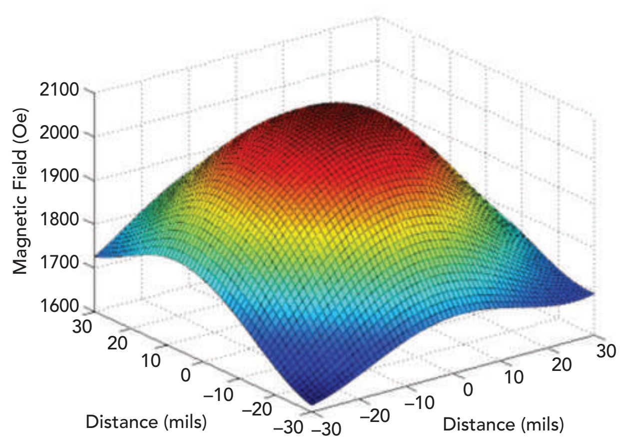


**Fig. 5** Measured magnetic bias field near the surface of the ferrite. The maximum field is 2056 Oe.


**Fig. 6** Faraday rotation isolator with extruded waveguide twist.

### Minimizing Waveguide Loss

Because the EM field is rotated by 45 degrees as it passes through the ferrite, it is necessary to realign the flanges. Traditionally, this is accomplished by twisting extruded waveguide as shown in ***Figure 6***, where the twist is implemented over a sufficiently long distance to avoid damaging the extruded guide. In the WR10 through WR3.4 bands, the total length of extruded waveguide is typically more than 2 in. Mi-

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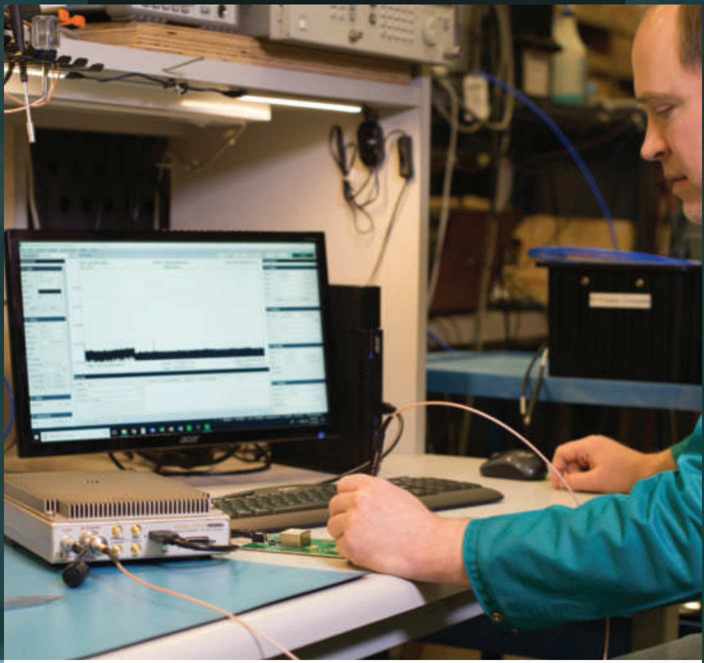


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cro Harmonics' designs replace the extruded twist with machined twist steps substantially shorter, which have broadband performance and reduced waveguide loss. Using this approach, the total flange-to-flange length of a WR3.4 isolator is only 0.45 in. For WR10, the reduction in waveguide loss is only 0.2 dB; however, for WR3.4, the loss reduction is close to 1 dB.

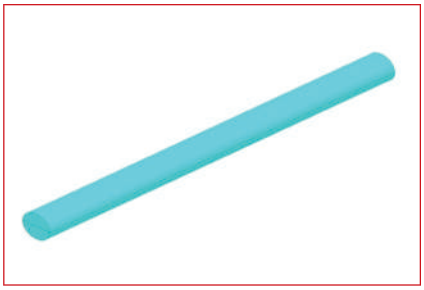

Fig. 7 Cored alumina cylinder with resistive layer.

## CONE FABRICATION

One of the biggest challenges at higher frequencies is fabricating the alumina cones. The traditional method begins by laminating two alumina plates together with a resistive layer at the interface. The plates are turned on their sides and cored, producing alumina cylinders with a resistive layer bisecting the central axis (see ***Figure 7***). The cylinders are then ground to a cone shape. Using this approach, tip diameters less than 0.004 in. are difficult to achieve, as few machinists can fabricate the cones for WR4.3 and WR3.4 waveguide isolators—the difficulty is even greater for WR2.8 and WR2.2.

Micro Harmonics is experimenting with alternative techniques to form the smallest cones by using cold laser ablation. This approach is appealing because no pressure is applied to the alumina; the process uses no heating, which can damage the epoxy and resistive layers; and forming cones with very small tips may be feasible. The cored cylinders have two ends that are flat and orthogonal to the central axis and suitable for cone bases. The alumina cylinder is then chucked and rotated (see ***Figure 8***), and as material is ablated, the cone eventually detaches from the cylinder.

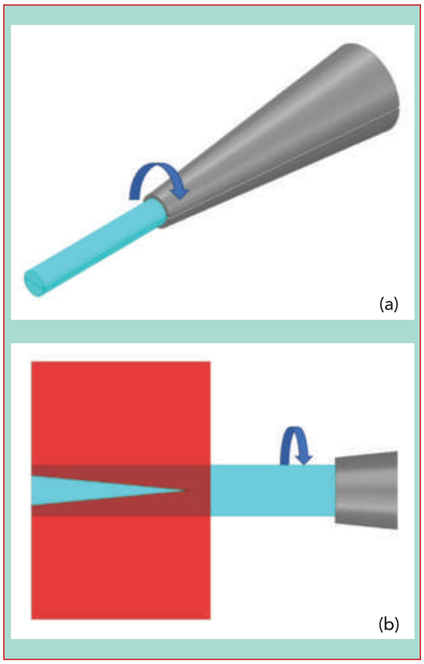


Fig. 8 Chucked alumina cylinder (a), rotating during cold laser ablation (b). The red area shows the exposure to the laser.

## DIAMOND HEATSINKS

In most commercial Faraday rotation isolators, the ferrite and cones are suspended by a pair of washer-shaped supports (see ***Figure 9***). The cone/ferrite assembly is inserted through the inner support holes and attached with a non-conductive epoxy. The support material is typically biaxially-oriented polyethylene terephthalate (BOPET), Styrene, a resin or some other material with a low dielectric constant and low loss at mmWave frequencies. Materials with these characteristics are generally thermal insulators, thermally isolating the cones and ferrite from the metal block.

In an isolator, absorbed power from the reverse traveling wave is converted to heat energy in the input cone. Very little of this heat can be channeled away by thermal conduction through the washer-shaped supports; rather, it must be dissipated by radiation or convection through the surrounding air. If too much reverse power is incident on the device, the resistive layers are subjected to high heat levels and

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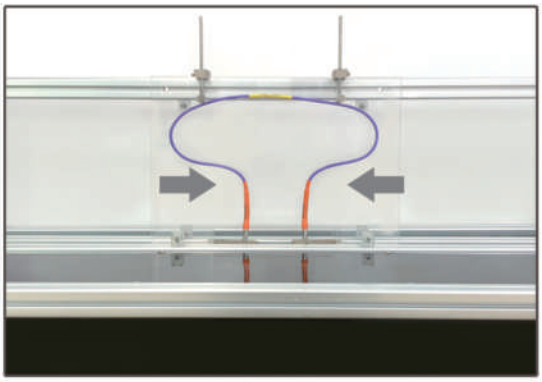

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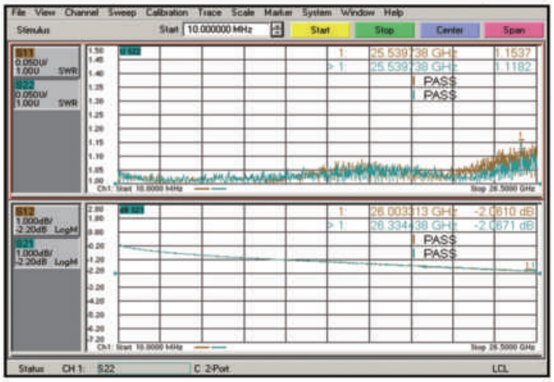

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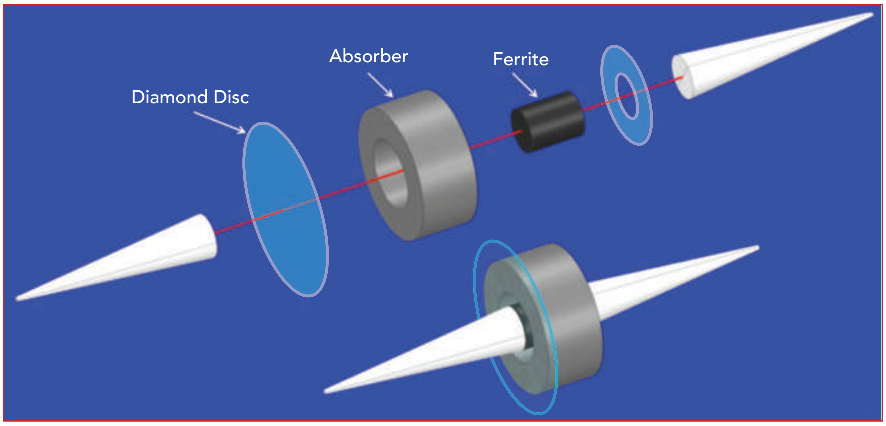



Fig. 9 **Exploded view showing the cones, absorber, ferrite, support washer and diamond disc.**

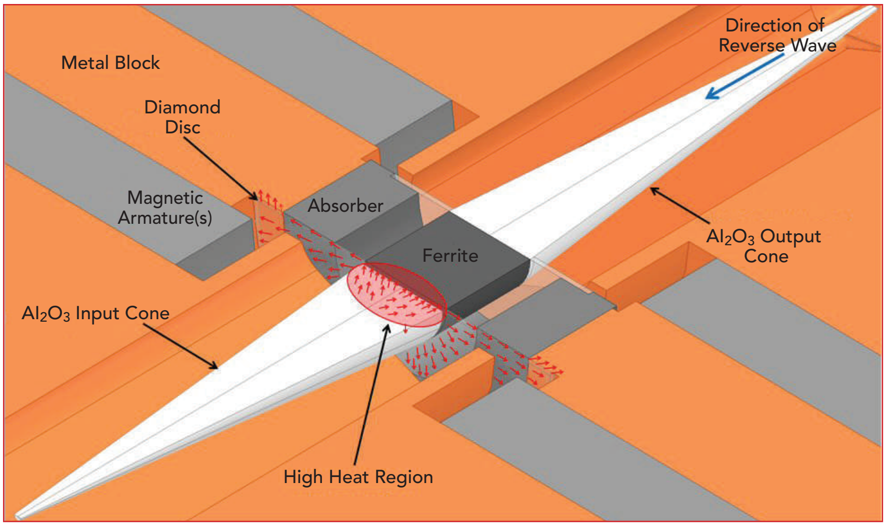



Fig. 10 **Thermal path through the diamond support disc.**

may be damaged. Higher power sources becoming available has renewed interest in improving the power rating of the isolator.

Micro Harmonics has addressed this by replacing the input support washer with a uniform, high grade, optical chemical vapor deposition (CVD) diamond disc, shown in Figure 9. The thermal conductivity of diamond is near 2200 W/mK, more than 5× higher than copper. The diamond disc is sandwiched between the base of the input cone and the ferrite, in intimate contact over the entire area of the cone base, which is the optimal location for the diamond disc since it is the region subject to the highest heat (see ***Figure 10***). The diamond disc is attached to the metal waveguide block over its entire periphery, providing an excellent conduit to channel heat from the resistive layer. The arrows in the figure illustrate the heat flow, showing this topology is superior for thermal conduction. This isolator design will handle higher reverse power levels while maintaining lower core temperatures, improving reliability.

## CRYOGENIC APPLICATIONS

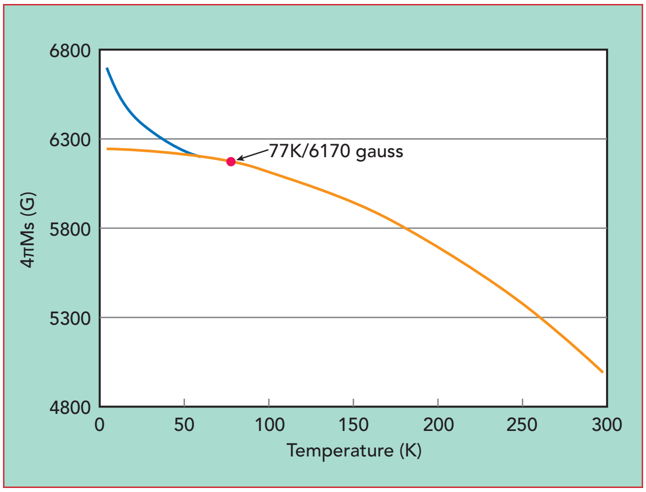
NASA recently awarded Micro Harmonics a contract to develop isolators optimized for cryogenic temperatures. In addition to the low temperature thermal stress, the substantial temperature dependence of the ferrite saturation magnetization is also a challenge. The measured isolation of a WR10 isolator drops from 30 dB at 290 K to 14 dB at 77 K, caused by a 10 degree over-rotation of the EM fields from higher magnetization at 77 K.

Ferrite magnetization follows a modified Bloch law:

$$M(T) = M(0) * \left(1 - \left(\frac{T}{Tc}\right)^{\alpha}\right) \quad (2)$$

where M(T) = magnetization, M(0) = magnetization at 0 K, $T_c$ = Curie temperature and $\alpha$ = the temperature exponent. The Curie temperature is the temperature at which materials lose their permanent magnetic properties. The Bloch law typically follows an $\alpha = 3/2$ form,[8] although evidence in the literature suggests that a modified Bloch law with $\alpha$ = 2 is a better fit for nickel spinel ferrites.[9-10] The decrease in magnetization at higher temperatures is caused by the increasing excitation of spin waves, which makes it more difficult to align the magnetic dipoles.

Fitting measured data to a modified Bloch law with M(77 K) = 6170 G, $T_c$ = 648 K, M(0 K) = 6250 G and $\alpha$ = 2.07 yields the solid curve in ***Figure 11***. Some literature says the magnetization can depart from the modified Bloch Law at temperatures below 50 K, depending on the ferrite particle size (the blue curve in the figure).[10]




▲ Fig. 11 **Temperature dependence of the saturation magnetization.**

## SUMMARY

This article described a new and innovative design approach for mmWave isolators, which has been used to develop isolators for every waveguide band from WR15 through WR3.4, i.e., 50 to 330 GHz. The designs employs diamond heatsinks for improved thermal conduction and achieve typical insertion loss less than 1 dB for WR10 (75 to 110 GHz) and less than 2 dB for WR3.4 (220 to 330 GHz)—a significant improvement over the previous state-of-the-art. The same design approach is being used to develop isolators for WR2.8 (265 to 400 GHz) and WR2.2 (330 to 500 GHz). NASA is also funding development of mmWave isolators for cryogenic systems.■


## ACKNOWLEDGMENTS

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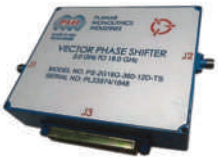

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| **PS-360-3237-8-292FF** https://www.pmi-rf.com/product-details/ps-360-3237-8-292ff- | 32 - 37 | 13.4 dB | 450 ns | 360° | Digital (8-Bit) | +15 VDC @ 90 mA, -15 VDC @ 60 mA | 1.15" X 1.8" X 0.4" 2.92mm Female |

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# High Speed Data Converters Enable Flexible RF Sampling Architectures

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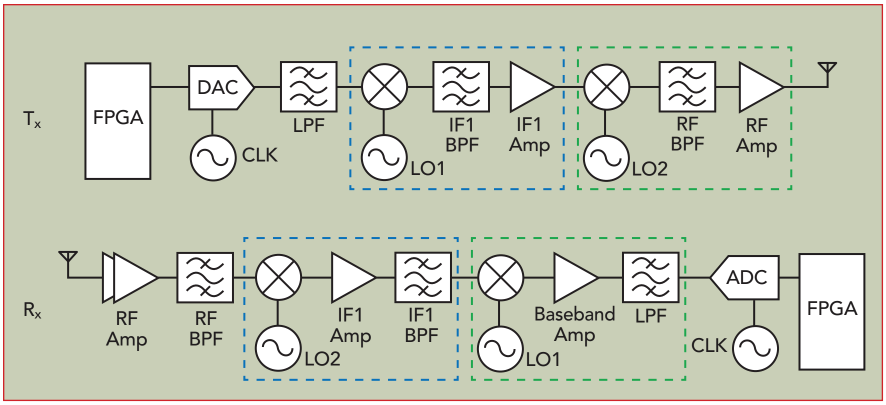
*Teledyne e2v, Hong Kong*

For many years, digital transceivers have been used in a wide variety of applications, including terrestrial cellular networks, SATCOM, radar-based surveillance and Earth observation and monitoring. Their capabilities will also directly impact the efficiency and system cost of new 5G mobile networks. Traditionally, transceiver systems have used intermediate frequency (IF) architectures for such applications. However, the most recent improvements in the capabilities of high speed data converters enable innovative architectures based on RF sampling, offering a number of benefits and efficiencies at the system level. These include not only SWAP-C, but also time-to-market and flexibility through the capabilities of software-defined radio (SDR) and software-defined microwave (SDM). SDR and SDM enable engineers to address multiple applications with unique system hardware, yet capable of supporting multiple configurations and requirements.

Before examining how the latest generation high speed data converters can help deliver these benefits, it is worth looking at the two transceiver system architectures.




▲ Fig. 1 $T_x$ and $R_x$ paths in a transceiver with two up- and two down-converter stages.

## IF ARCHITECTURE

The IF architecture consists of a hardware chain that generates the RF frequency through one or more IF stages. These stages are known as up-converters on the transmit (Tx) path, converting from a lower to a higher frequency, and down-converters on the receive (Rx) path, converting from a higher to a lower frequency. ***Figure 1*** shows this type of architecture with two stages of frequency conversion.

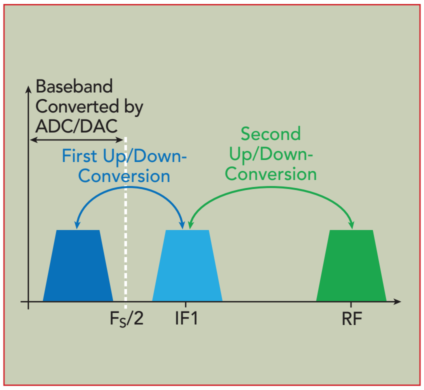



Fig. 2 Transceiver frequency plan with two frequency conversions.

The up-converter stage comprises a mixer, driven by a local oscillator (LO), which does the frequency conversion. This is followed by a filter, needed to remove images generated by the mixing process and, sometimes, by the amplification stage. ***Figure 2*** shows the successive conversion steps in this example with two frequency conversion stages. While not discussed in detail here, the image frequencies generated by this process must be filtered to avoid performance degradation through aliasing and power distortion. On the Tx side, the first up-conversion stage converts the baseband or first Nyquist signal to the intermediate frequency IF1, while the second stage converts the signal from IF1 to the RF frequency. The process is reversed on the Rx side (RF frequency to IF1, then IF1 to baseband), and the signal is converted by the analog-to-digital converter (ADC) and then digitally processed for demodulation, for example. The number of frequency converters and choice of IF vary according to the application and are not always the same for Tx and Rx.

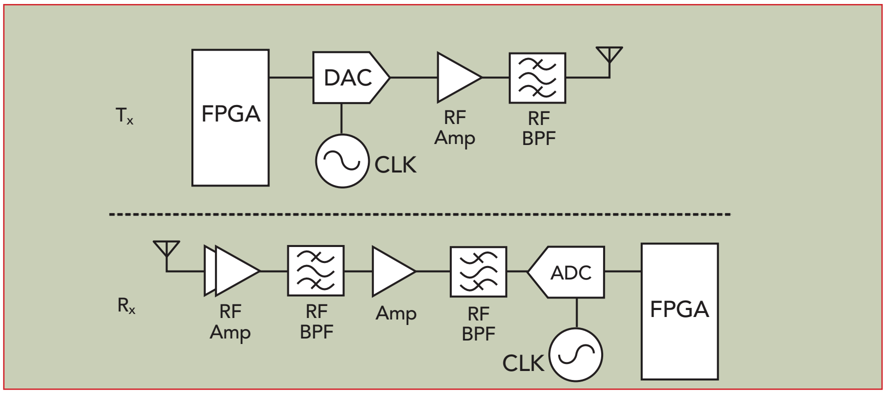
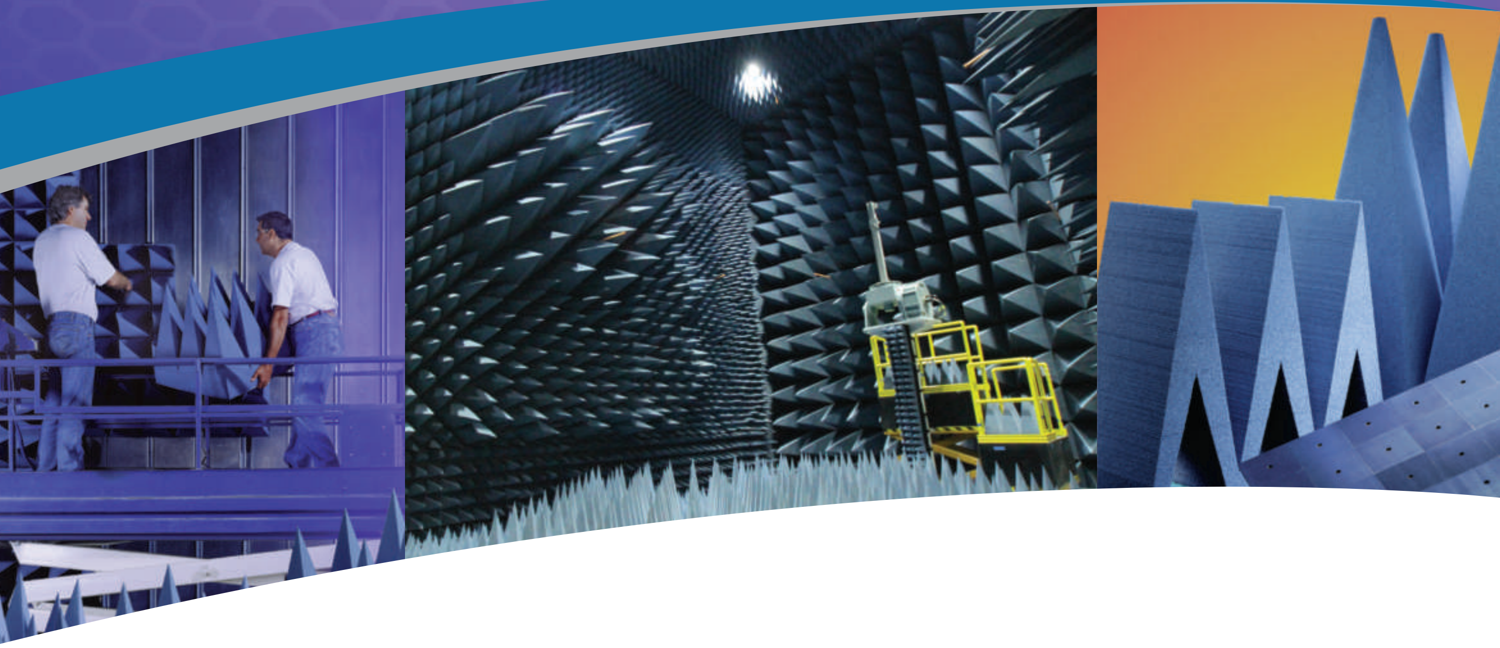



Fig. 3 $T_x$ and $R_x$ paths in a transceiver with an RF sampling architecture.

The IF architecture was invented during World War I and, since then, has been used extensively, mainly because it was the only solution enabling digital processing of RF signals. The ability to interface between a high frequency RF signal and a data converter handling the baseband remains its main benefit. Because data converter capabilities have, for many years, been limited to low frequency conversion from and to the digital domain, specific analog implementations were needed to use the RF frequency spectrum while taking advantage of increased digital processing power. The primary drawback of this solution is the increase in RF hardware, leading to SWAP-C and performance degradation. Another drawback—harder to identify without considering alternative architectures—is the lack of flexibility, because IF frequencies are fixed by the LO and the data converter input/output frequencies.

## RF SAMPLING ARCHITECTURE

Using broadband data converters, RF sampling directly converts the RF signal to the digital domain and removes the up- and down-conversion stages (see ***Figure 3***). RF sampling requires ADC and digital-to-analog converters (DAC) capable of converting signals directly from higher frequencies or Nyquist zones, where a Nyquist zone is a frequency band equal to half of the sampling frequency of the data converter, as defined by the Shannon-Nyquist theorem which is expressed as kFs/2 or (k+1)Fs/2, where k is an integer. ***Figure 4*** illustrates direct sampling of a signal in the fourth Nyquist zone.



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RF sampling has long been a key objective to minimize processing in the analog domain. The more done in the digital domain, the greater the flexibility of the system, reusing hardware for multiple applications and providing cumulative savings in time-to-market and qualification costs, as well as reducing risk. In addition to enhanced flexibility, RF sampling can reduce cost and power consumption by eliminating the analog frequency conversion components.

These improvements, made possible over several decades through advancements in data converter technology, provide the justification for many system engineers to adopt RF sampling. The main limitation for RF sampling has been the capability of the data converter. Current high speed converters are capable of meeting the needs of RF sampling up to C- and sometimes X-Band, but performance has not been sufficient to reach the higher frequency bands, such as K-, Ka-, E- and V-Bands, being used for 5G, backhaul and future communications systems.

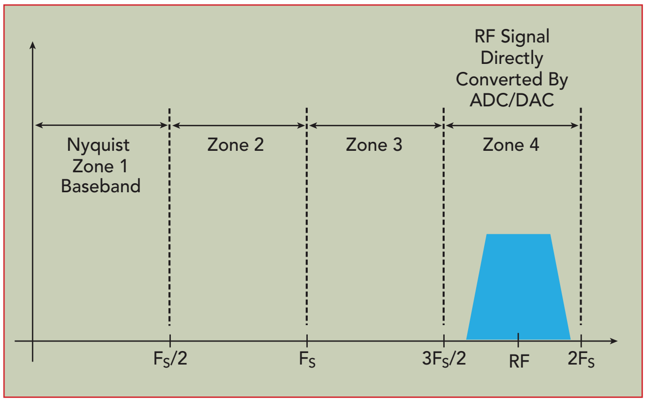


Fig. 4 Direct RF sampling in the fourth Nyquist zone.

**TABLE 1**

COMPARISON OF IF AND RF SAMPLING

| | IF | RF |
|---|---|---|
| Up to C-, X-Band | Capable | Capable |
| Above X-Band | Capable | ADC/DAC Not Yet Suitable |
| SWaP-C | Costly | Optimized |
| Flexibility | Poor | High |

*Table 1* compares the IF and RF sampling architectures based on current implementations of these two types. The benefits of RF sampling can be significant but, as with any innovation, RF sampling brings new challenges and requirements, notably the data converters.

## DATA CONVERTER SPECS

The performance of today's transceivers is often limited by the data converter, which plays a critical role interfacing between the digital and analog domains. While many performance requirements need to be considered for the ADC and DAC, regardless of the architecture chosen, the RF sampling architecture places additional focus on key specifications such as the data converter's analog bandwidth and the DAC output mode capabilities.

Before explaining why these parameters are important in such architectures, and how they drive system capabilities, it is worth reviewing how the Shannon-Nyquist theorem defines the theoretical capabilities of these implementations. The Shannon-Nyquist theorem states that a signal can be reconstructed when the sampling frequency is at least twice the total bandwidth of the signal being sampled, or $Fs \geq 2B$, where $B = fmax - fmin$. This rule is often translated as its first Nyquist equivalent, $Fs \geq 2fmax$. This is sufficient for baseband systems; however, to achieve RF sampling at the higher Nyquist zones, the full theorem must be used. With aliasing, the same information is contained in every odd Nyquist zone and reversed in every even Nyquist zone. RF sampling is possible with anti-


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| TABLE 2<br>ESTIMATED PERFORMANCE COMPARISON WITH LATEST-GENERATION ADC | | | |
|---|---|---|---|
| | *Two Down-Conversion Stages* | *Single Down-Conversion Stage* | *RF Sampling* |
| Receive Chain Gain (dB) | 47 | 47 | 47 |
| Receive Chain Noise Figure (dB) | 2.64 | 2.55 | 2.53 |
| Total Analog Power Consumption (W) | 15 | 13.5 | 12 |

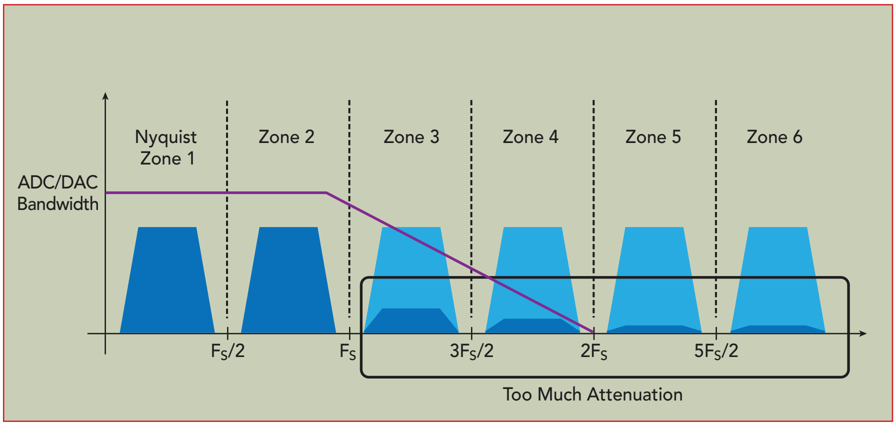


**Fig. 5** Effect of ADC/DAC analog bandwidth on RF sampling.

aliasing filtering around the Nyquist zone of interest, to segregate a single instance of the information.

The first key specification to consider for RF sampling is the ADC/DAC analog bandwidth, which is similar to a low pass filter, limiting the frequency that can be converted with sufficient precision. ***Figure 5*** shows a simple example where the signal above the second Nyquist zone has too much attenuation caused by the bandwidth of the ADC and DAC. It is important to consider the total bandwidth of the analog front-end, as the amplifiers and filters with ADC and DAC will also impact the total bandwidth that can be recovered by the transceiver.

Bandwidth is not the sole parameter driving the capability for direct RF sampling. The data converter process and architecture can cause large differences in performance. For example, some ADCs and DACs using CMOS processes specify bandwidths above 6 GHz but have considerable performance degradation as low as 3 to 5 GHz. This is one of the main reasons for using bipolar and BiCMOS processes, as these enable very good performance, even when converting frequencies higher than the converter's bandwidth. At higher frequency, the bandwidth affects the output power that can be generated, which limits the performance in some applications. However, certain applications do not require very high output power and can work with RF sampling using a device capable of generating frequencies above its specified analog bandwidth. Consider both bandwidth and performance at high frequencies when choosing a data converter for RF sampling.

Another parameter that influences the suitability of a DAC for RF sampling is its output mode capability—more precisely, its effect on the output power it can generate. DACs generate output signals in different output modes, which provide different benefits. For example, the latest generation of DACs offers four different output mode configurations:

- Non-Return to Zero (NRZ)—This mode is the best known and consists of outputting the value of the sample over the full sampling period.
- Return to Zero (RTZ)—This mode is also well known and consists of outputting the value of the sample


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over half of the sampling period, zero for the other half.

- Narrow Return To Zero (NRTZ)—This output offers a flexible solution between NRZ and RTZ, by outputting the value of the sample over a certain percentage X of the sampling period, surrounded by return to zero for (1 – X)/2 before and after.
- RF—This is the main target for RF sampling and involves outputting the value of the sample for half of the sampling period and the inverted value of the sample for the other half.

The impact of the output mode on the generated output power is better understood when looking at the frequency responses of these modes. The mode should be chosen depending on the Nyquist zone of interest, with the objective of maximizing output power. The choice will depend on the sampling frequency and RF frequency to be generated. For example, a sampling frequency of 6 GSPS and an output frequency in C-Band (between 4 and 8 GHz) equates to either the second or third Nyquist zone, and the RF mode provides the maximum output with only about 5 dB impact on the power. The output mode frequency response depends on the sampling frequency. A DAC at 12 GSPS with output frequency in C-Band would only be up to the early second Nyquist and could be addressed successfully with the NRZ mode.

To be suitable for RF sampling, data converters, in addition to the regular requirements, need to provide sufficient output power and performance up to the target RF frequencies, which translates to analog bandwidth, dynamic performance and output mode (DAC only) specifications. Once appropriate data converters have been identified, the system can be implemented using the RF sampling architecture.

## ARCHITECTURE COMPARISON

To highlight the differences and benefits of RF sampling over the IF architecture, Teledyne e2v simulated the performance of its latest-generation ADC in three different transceiver configurations: dual-stage IF, single-stage IF and RF sampling architectures. ***Table 2*** shows the estimated power consumption and noise figure. This shows how the system power consumption reduces with every down-conversion stage removed, achieving a reduction of 20 percent between the dual down-converter and RF sampling architectures, while the noise figure performance essentially stays constant. This is because the noise figure performance is mostly determined by the first stage amplification, provided it adds sufficient gain.

Even though the long history of IF architectures in their various forms has made them the default choice for transceivers, new possibilities from advances in data converter performance and capabilities are making the historical architecture less and less relevant for RF applications. RF sampling yields considerable SWAP-C benefits and improves its capabilities with each generation of high speed and high bandwidth converter. The industry will continue to extend the capability of data converters, enabling direct RF sampling at ever higher frequencies.■

# Analytical Calculations for TRL Calibration

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*Normandie Université,[1] Caen, France*
*Presto Engineering Europe,[2] Caen, France*

*The well known TRL calibration method eliminates measurement errors at the input and output of a device under test (DUT). It uses a matrix formalism, which is not easy to realize in experimental software. In this article, we provide the analytical version of this calculation which may be easier to implement.*

Vector network analyzers (VNA) are calibrated at their own reference planes, which are generally different from the DUT reference planes. In the case of S-parameter measurements using VNAs, the DUT is measured through connecting devices, such as cables and connectors that introduce measurement errors due to phase shifts, losses and mismatches (see ***Figure 1***). The true behavior of the DUT is obtained when these errors are removed through calibration. Various calibration methods—such as short, open, load, thru (SOLT); thru, reflect, line (TRL); and thru, reflect, match (TRM)—are used to determine the error terms. Most require accurate standards. The TRL calibration, however, does not rely on perfectly known standards.[1-4]

## TRL CALIBRATION

The S-parameters of the DUT are represented by the signal flow graph shown in ***Figure 2a***. The measured S-parameters of the DUT, including measurement errors, are represented by the signal flow graph shown in ***Figure 2b***. The S-parameters of the error terms, represented by the error boxes shown in Figure 1, are determined as follows.

In the forward direction, three ratios are measured:

$$A_F = \frac{b_0}{a_0};\ B_F = \frac{b_3}{a_0};\ C_F = \frac{a_3}{a_0} \tag{1}$$

$$A_F = S_{m11} + C_F S_{m12} \tag{2a}$$

$$B_F = S_{m21} + C_F S_{m22} \tag{2b}$$

In the reverse direction, three more ratios are measured:

$$A_R = \frac{b_3}{a_3};\ B_R = \frac{b_0}{a_3};\ C_R = \frac{a_0}{a_3} \tag{3}$$

$$A_R = S_{m22} + C_R S_{m21} \tag{4a}$$

$$B_R = S_{m12} + C_R S_{m11} \tag{4b}$$

The resulting S-parameters are

$$S_{m11} = \frac{A_F - C_F B_R}{1 - C_F C_R} \tag{5a}$$

$$S_{m21} = \frac{B_F - C_F A_R}{1 - C_F C_R} \tag{5b}$$

$$S_{m22} = \frac{A_R - C_R B_F}{1 - C_F C_R} \tag{5c}$$

$$S_{m12} = \frac{B_R - C_R A_F}{1 - C_F C_R} \tag{5d}$$

## CALIBRATION STEPS

$S_{ij}$ are the DUT parameters and $e_{ij}$ describe the error terms. A lim-

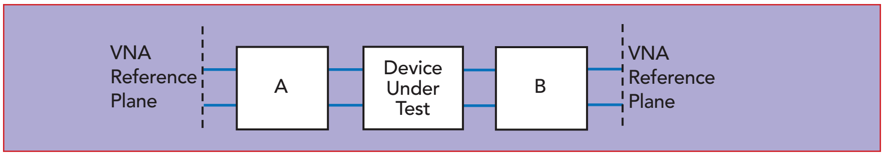



**Fig. 1** Calibration model comprises the DUT with input and output transitions to the VNA reference planes.

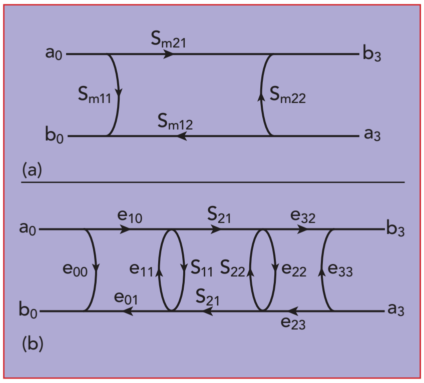



**Fig. 2** S-parameter flow graph for the DUT (a). The DUT with the eight-term error model (b).

ited number of values for the standards must be known in advance. This is called the "calibration kit."

$$\text{Thru}: S^{thru} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

The thru standard fixes the reference planes of the DUT, obtained when the DUT reference planes coincide.

$$S^{thru}_{m11} = e_{00} + e_{10}e_{01}\frac{e_{22}}{1-e_{11}e_{22}} = R_{F1} \quad (6)$$

$$S^{thru}_{m12} = \frac{e_{01}e_{23}}{1-e_{11}e_{22}} = T_{R1} \quad (7)$$

$$S^{thru}_{m21} = \frac{e_{10}e_{32}}{1-e_{11}e_{22}} = T_{F1} \quad (8)$$

$$S^{thru}_{m22} = e_{33} + e_{32}e_{23}\frac{e_{11}}{1-e_{11}e_{22}} = R_{R1} \quad (9)$$

$$\text{Line}: S^{line} = \begin{pmatrix} 0 & X \\ X & 0 \end{pmatrix}$$

The line standard is generally an actual line with $|X|$ close to unity, although it can be any passive reciprocal symmetrical two port.[5] Then, the reference impedance corresponds to the characteristic impedance of this two port. The phase of X used in the calibration kit must be known within 90 degrees.

$$S^{line}_{m11} = e_{00} + e_{10}e_{01}\frac{e_{22}X^2}{1-e_{11}e_{22}X^2} = R_{F2} \quad (10)$$

$$S^{line}_{m12} = \frac{e_{01}e_{23}X}{1-e_{11}e_{22}X^2} = T_{R2} \quad (11)$$

$$S^{line}_{m21} = \frac{e_{10}e_{32}X}{1-e_{11}e_{22}X^2} = T_{F2} \quad (12)$$

$$S^{line}_{m22} = e_{33} + e_{32}e_{23}\frac{e_{11}X^2}{1-e_{11}e_{22}X^2} = R_{R2} \quad (13)$$

$$\text{Reflect}: S^{ref} = \begin{pmatrix} \Gamma_B & 0 \\ 0 & \Gamma_B \end{pmatrix}$$

Generally $|\Gamma_B|$ is close to unity. The phase of the reflection coefficient must be the same on both ports. If it is not, the references planes must be shifted until phase equality is found. The phase of $\Gamma_B$ in the calibration kit must be known within 90 degrees.

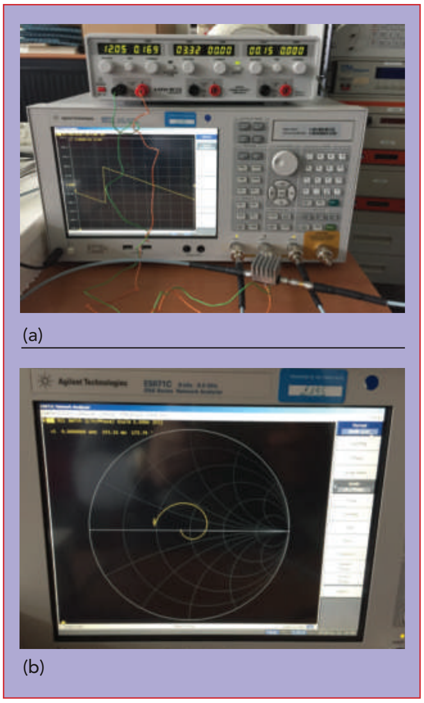


**Fig. 3** VNA (a) and Smith chart display of $S_{11}$ (b).

$$S^{ref}_{m11} = e_{00} + \frac{e_{10}e_{01}\Gamma_B}{1-e_{11}\Gamma_B} = R_{F3} \quad (14)$$

$$S^{ref}_{m22} = e_{33} + \frac{e_{32}e_{23}\Gamma_B}{1-e_{22}\Gamma_B} = R_{R3} \quad (15)$$

## CALCULATIONS

From Equations 6 and 10 and 9 and 13:

$$R_{F1} - R_{F2} = \frac{e_{10}e_{22}}{e_{32}}\left(T_{F1} - T_{F2}X\right) \quad (16a)$$

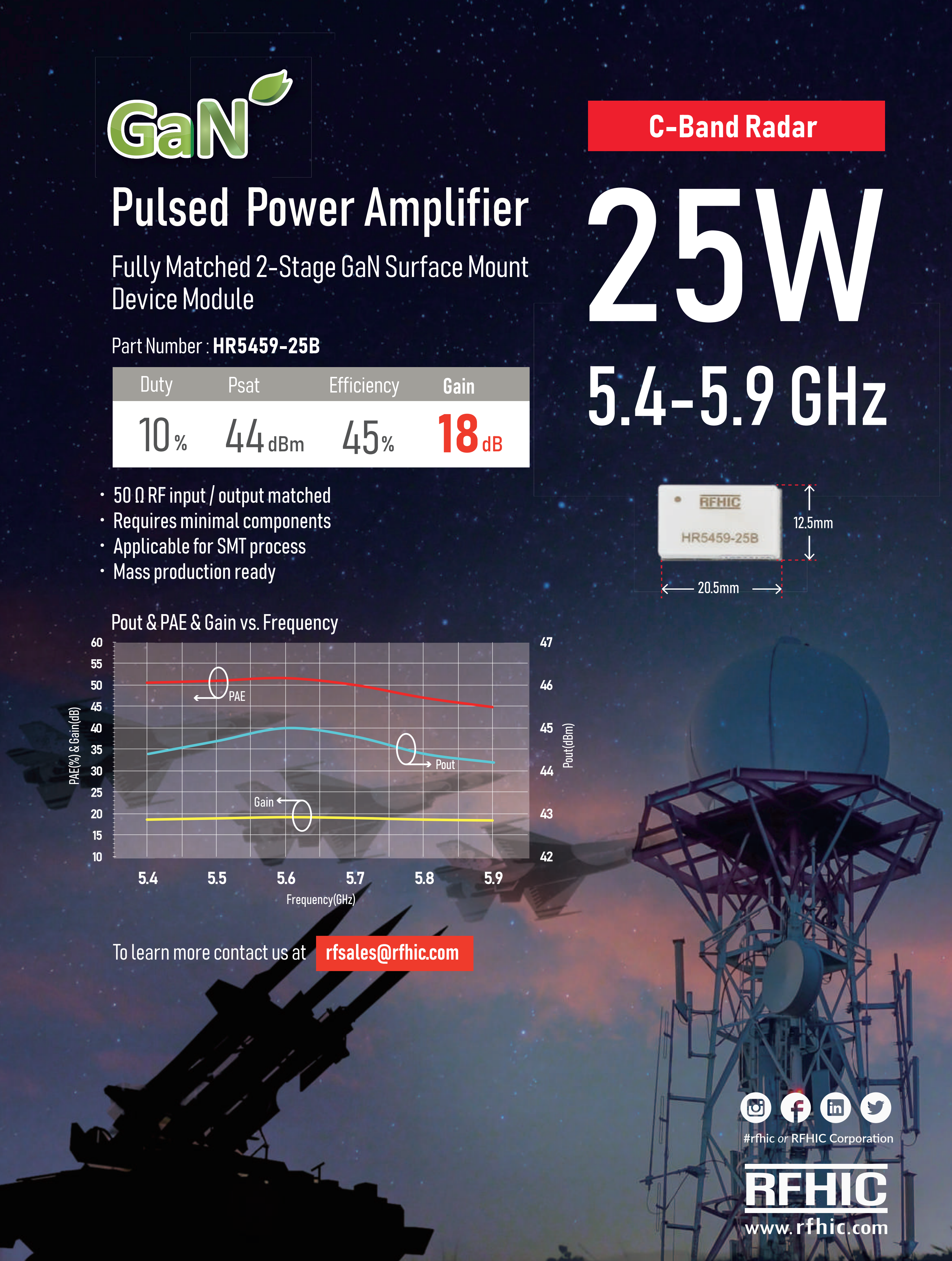
$$R_{R1} - R_{R2} = \frac{e_{32}e_{11}}{e_{01}}\left(T_{R1} - T_{R2}X\right) \quad (16b)$$

If

$$\alpha = e_{11}e_{22} \text{ and } \beta = \left(R_{F1} - R_{F2}\right)\left(R_{R1} - R_{R2}\right) \quad (17a)$$

$$\begin{cases} \beta = \alpha\left(T_{F1} - XT_{F2}\right)\left(T_{R1} - XT_{R2}\right) \\ \dfrac{T_{F1}}{T_{F2}} = \dfrac{1-\alpha X^2}{(1-\alpha)X} \end{cases} \quad (17b)$$

we obtain two expressions for $\alpha$: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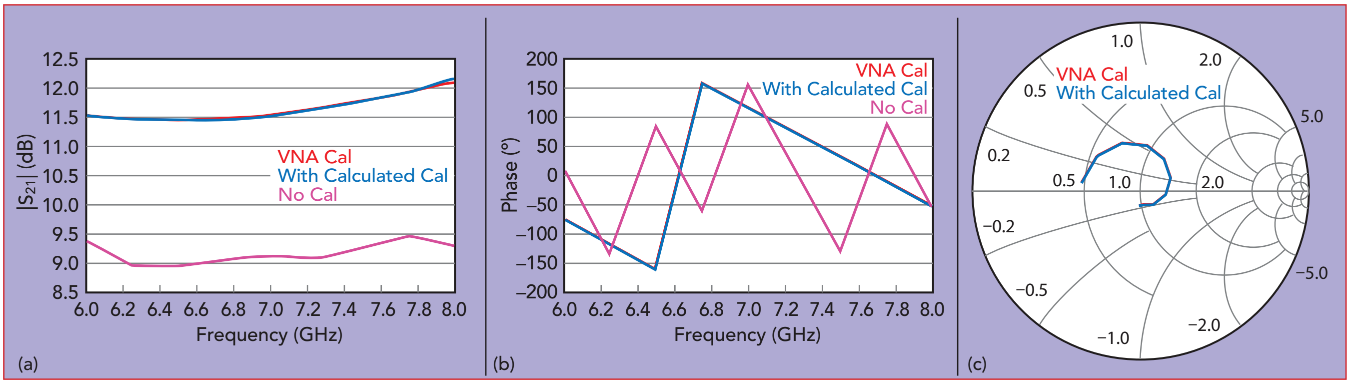


▲ Fig. 4 $|S_{21}|$ (a), $\angle S_{21}$ (b) and $S_{11}$ (c) measurements using the internal VNA and calculated TRL calibrations.

$$\begin{cases} \alpha = \dfrac{\beta}{(T_{F1} - XT_{F2})(T_{R1} - XT_{R2})} \\ \alpha = \dfrac{T_{F2} - XT_{F1}}{X(XT_{F2} - T_{F1})} \end{cases} \quad (18)$$

That gives a second degree equation in X:

$$X^2 + \frac{\beta - T_{F1}T_{R1} - T_{F2}T_{R2}}{T_{F1}T_{R2}} X + \frac{T_{R1}T_{F2}}{T_{F1}T_{R2}} = 0 \quad (19)$$

There are two solutions for this equation, and both values for $|X|$ are close to unity for a line with small losses, making it difficult to choose the right solution. It is safer to choose $|\alpha| << 1$.

$$\alpha = \frac{\beta}{(T_{F1} - XT_{F2})(T_{R1} - XT_{R2})} \quad (20)$$

From Equations 5 and 9, the directivity ($e_{00}$ and $e_{33}$) is the ratio of the leakage of the incident signal to the reflected signal:

$$e_{00} = \frac{R_{F1}(1-\alpha)X^2 - R_{F2}(1-\alpha X^2)}{X^2 - 1} \quad (21a)$$

$$e_{33} = \frac{R_{R1}(1-\alpha)X^2 - R_{R2}(1-\alpha X^2)}{X^2 - 1} \quad (21b)$$

$$R'_{Fi} = R_{Fi} - e_{00} \text{ and} \quad (22)$$
$$R'_{Ri} = R_{Ri} - e_{33}$$

From Equations 14 and 6:

$$\frac{\Gamma_B}{e_{22}} = \frac{R'_{F3}}{R'_{F1} + \alpha(R'_{F3} - R'_{F1})} \quad (23a)$$

From Equations 15 and 9:

$$\Gamma_B e_{22} = \frac{R'_{R3}\alpha}{R'_{R1} + \alpha(R'_{R3} - R'_{R1})} \quad (23b)$$

So

$$\Gamma_B = \left(\frac{R'_{F3}R'_{R3}\alpha}{(R'_{F1} + \alpha(R'_{F3} - R'_{F1}))(R'_{R1} + \alpha(R'_{R3} - R'_{R1}))}\right)^{1/2} \quad (24)$$

The port mismatch ($e_{22}$ and $e_{11}$) is

$$e_{22} = \frac{R'_{F1} + \alpha(R'_{F3} - R'_{F1})}{R'_{F3}} \Gamma_B \quad (25a)$$

$$e_{11} = \frac{\alpha}{e_{22}} \quad (25b)$$

All the following results correspond to transmission elements. They only need to be known by their products.

Transmission tracking:

$$e_{10}e_{32} = T_{F1}(1-\alpha) \quad (25c)$$

$$e_{01}e_{23} = T_{R1}(1-\alpha) \quad (25d)$$

Reflection tracking:

$$e_{10}e_{01} = \frac{R'_{F3}(1 - e_{11}\Gamma_B)}{\Gamma_B} \quad (25e)$$

$$e_{23}e_{32} = \frac{R'_{R3}(1 - e_{22}\Gamma_B)}{\Gamma_B} \quad (25f)$$

## DE-EMBEDDING TO EXTRACT THE DUT

$S_{ij}$ corresponds to the extracted behavior of the DUT alone. The de-embedding technique described below extracts the parameters of the DUT by eliminating the embedded system of errors.

$$S_{11} = \frac{A_{11}(1 + A_{22}e_{22}) - A_{12}A_{21}e_{22}}{(1 + A_{11}e_{11})(1 + A_{22}e_{22}) - A_{12}A_{21}e_{11}e_{22}} \quad (26)$$

$$S_{12} = \frac{A_{12}(1 + A_{11}(e_{22} - e_{11}))}{(1 + A_{11}e_{11})(1 + A_{22}e_{22}) - A_{12}A_{21}e_{11}e_{22}} \quad (27)$$

$$S_{21} = \frac{A_{21}(1 + A_{22}(e_{22} - e_{11}))}{(1 + A_{11}e_{11})(1 + A_{22}e_{22}) - A_{12}A_{21}e_{11}e_{22}} \quad (28)$$

$$S_{22} = \frac{A_{22}(1 + A_{11}e_{11}) - A_{12}A_{21}e_{11}}{(1 + A_{11}e_{11})(1 + A_{22}e_{22}) - A_{12}A_{21}e_{11}e_{22}} \quad (29)$$

With $S_{mij}^{DUT}$ representing the S-parameters of the measured DUT between the VNA reference planes,

$$A_{11} = \frac{S_{m11}^{DUT} - e_{00}}{e_{10}e_{01}} \quad (30a)$$

$$A_{12} = \frac{S_{m12}^{DUT}}{e_{01}e_{23}} \quad (30b)$$

$$A_{21} = \frac{S_{m21}^{DUT}}{e_{10}e_{32}} \quad (30c)$$

$$A_{22} = \frac{S_{m22}^{DUT} - e_{33}}{e_{32}e_{23}} \quad (30d)$$

## VALIDATION

A 4 to 8 GHz amplifier with 10 dB nominal gain was used as a DUT and measured with a VNA to validate the TRL calibration method and efficiency (see ***Figure 3***). ***Figure 4a*** shows the magnitude of the DUT's transmission coefficient, $|S_{21}|$, and ***Figure 4b*** shows its phase. The traces correspond to $S_{21}$ measured without calibration, $S_{21}$ measured using the calibration algorithm internal to the VNA and $S_{21}$ calculated using the method described in this article, showing virtually no difference between the two calibration methods. ***Figure 4c*** shows $S_{11}$ plotted on the Smith chart; the two traces represent measurements using the VNA's built-in calibration and the calculated values using the method described in the article. All the curves show coincidence between the analytically calculated values of $S_{11}$ and $S_{21}$ and those determined by the VNA's internal calibration algorithm.

## CONCLUSION

Analytic calculations associated with the well-known TRL calibration method reduce calculation complexity compared with the classical matrix formalism.[3] This approach can be extended for further measurement configurations, particularly for differential inputs and outputs.[6-7] ■

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# High Performance Spectrum Analyzer for 5G OTA Testing

Anritsu
*Morgan Hill, Calif.*

2019 will be the year 5G becomes a reality, with initial field deployments and commercial services. As the industry converges on the best practices for installation and maintenance, a new generation of test equipment is needed to support both existing LTE networks and the unique technology used by 5G networks: mmWave frequencies, active antenna systems, beamforming and dynamic physical layer attributes. RF technologies are touching ever more areas of our lives, with the RF spectrum becoming more crowded. In addition to the demands of cellular systems below 6 GHz, 5G radios are now deployed at 28 and 39 GHz. The ability to view the RF spectrum and measure transmissions from all these systems is important to avoid interference and guarantee performance.

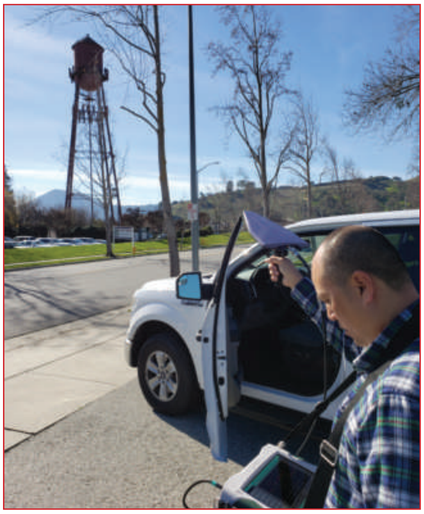

**Fig. 1** **The compact, handheld Field Master Pro MS2090A has the performance of a benchtop analyzer in a handheld, battery-powered instrument.**

As the leading designer and manufacturer of high performance, handheld RF spectrum analyzers, Anritsu introduces the Field Master Pro MS2090A spectrum analyzer, a compact, handheld instrument delivering performance not previously available and providing field service engineers and technicians with the performance of a benchtop analyzer in a handheld, battery-powered instrument (see ***Figure 1***). With continuous frequency coverage from 9 kHz to a wide range of upper frequency options (9, 14, 20, 26.5, 32, 44 and 54 GHz), the Field Master Pro MS2090A was designed to meet the challenges of 5G test, while maintaining support for the range of wireless technologies in use, including wireless backhaul, satellite systems, radar and other aerospace and defense applications.

## PERFORMANCE CAPABILITIES

The Field Master Pro MS2090A delivers the highest levels of RF performance available in a handheld, touch screen spectrum analyzer, with a displayed average noise level (DANL) less than −160 dBm and a third-order intercept of +20 dBm (typical). This makes measurements such as spectrum clearing, radio alignment, harmonics

# PHASE ADJUSTERS 2019


## DC to 63 GHz

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Elektrotechnik GmbH

**80905 Munich, Germany** **P.O. Box 450533**

**Telephone: +49-89-3548-040** **Facsimile: +49-89-3548-0490**

**WWW.SPECTRUM-ET.COM * Email: sales@spectrum-et.com**

and distortion more accurate than previously possible. For modulation measurements on digital systems, 100 MHz modulation bandwidth coupled with best-in-class phase noise maximizes measurement accuracy, and 0.5 dB typical amplitude accuracy provides confidence when testing transmitter power and spurious levels.

Ruggedized for field use, all versions of the Field Master Pro MS2090A provide a comprehensive range of features to speed and simplify measurements, as well as enhancing usability. The built-in real-time spectrum analyzer (RTSA) provides the ultimate signal analysis and interference capture tool, with spans of 20 (standard) to 100 MHz (optional) providing the capability for cellular interference monitoring to full ISM band signal analysis. In addition to being a full span, swept tuned spectrum analyzer, all versions include a spectrogram display to monitor the RF spectrum for intermittent or interfering signals. Integrated channel power and occupied bandwidth measurements simplify the characterization of common radio transmission. I/Q data capture of 5G frames enables the capture and saving of I/Q data for off-line processing on a PC using standard data analysis tools.

## APPLICATION SUPPORT

The Field Master Pro MS2090A supports a variety of critical applications used in the installation, commissioning and maintenance of wireless networks. 4G and 5G coverage mapping provides a clear representation of the signal strength of 5G transmitters over geographic areas. The Field Master Pro MS2090A provides continuous measurement of RF data, including 5G channel power, effective isotropic radiated power (EIRP) or reference signals received power (RSRP). When combined with the NEON® MA8100A signal mapper, users have a powerful indoor and outdoor coverage mapping solution that displays results on a digital map or in a building floor plan.

As cellular and broadcast operators expand their networks, new technologies are moving into the sub-6 GHz bands. Many national regulatory authorities now auction the spectrum for exclusive access, and the new owners need to validate that legacy users have stopped all transmissions, so that networks are efficiently deployed. The Field Master Pro MS2090A fast sweep speeds, low distortion front-end and spectrogram displays make it a powerful tool for spectrum clearance. Using omnidirectional antennas, all signals are captured across a defined frequency band, while the built-in preamplifier optimizes the sensitivity to capture low-level signals.

With microwave radio links becoming central building blocks for cellular and data networks, the Field Master Pro MS2090A helps installation crews align radios over distances from a few 10s of meters to several kilometers. Using a waveguide

Fig. 2 The summary screen displays all measurement results to validate 5G base station performance.

horn antenna, the power and modulation bandwidth can be verified during installation and ongoing maintenance testing.

With the introduction of the 5G New Radio (NR) network, instruments are needed to validate the performance of gNB base stations in a field environment (see ***Figure 2***). In the 3.5, 28 and 39 GHz bands, the adoption of active antenna systems means new test methods need to be developed and used. With full compliance to the 3GPP TS 38.104 V15 requirement, the Field Master Pro MS2090A provides support for essential measurements, including frequency error, time offset, cell/sector ID, modulation quality, unwanted emissions, occupied bandwidth, adjacent channel leakage ratio, EIRP and transmitter spurious to 12.75 GHz. Measurements of the synchronization signal block (SSB) are also supported, enabling over-the-air (OTA) transmitter testing on a live gNB.

## NEXT-GENERATION SPECTRUM ANALYSIS

With the launch of the Field Master Pro MS2090A, Anritsu has introduced the world's first field portable solution with continuous frequency coverage for sub-3 GHz, sub-6 GHz and mmWave 5G NR measurements. The instrument was developed closely cooperating with all the leading 5G base station manufacturers and is being used to install the first commercial 5G NR networks. With a continuous frequency coverage from 9 kHz to 54 GHz, 100 MHz analysis bandwidth, 5G NR demodulation capabilities, RTSA for interference hunting, built-in EIRP and gated sweep for transmission testing and a 10.1 in. multi-touch screen user interface, the Field Master Pro MS2090A spectrum analyzer is the most comprehensive solution for field service engineers and technicians supporting the installation, commissioning and maintenance of the RF industry's wireless technologies.

VENDOR**VIEW**

**Anritsu**
**Morgan Hill, Calif.**
**www.anritsu.com**

# Automatic Direction-Finding Antenna

The engineers at Narda Safety Test Solutions (STS) have developed an automatic direction-finding antenna for signals between 200 MHz and 2.7 GHz. Used with the SignalShark real-time receiver, the ADFA 1 quickly identifies a bearing — a complete measurement cycle takes just 1.2 ms — and is insensitive to reflections, ever present in urban environments. The antenna is compact, weighing just 5.6 kg with a diameter of 480 mm, making it well-suited for cellular network providers and security applications.

Direction finding measures the phase differences of a signal among several antenna elements. The heart of the ADFA 1 is an array of nine antenna elements around a central omnidirectional reference antenna. Combining the array with phase shifters and complex algorithms enables the ADFA 1 to precisely determine signal direction using only a single-channel receiver, at a much lower cost than multi-channel direction-finding systems. The central reference antenna receives signals from all directions, observing the broadband spectrum simultaneously with determining the direction of the signal being traced. The ADFA 1 also determines the elevation angle of the signal, which is important in urban settings where localizing to an individual floor may be needed.

In most applications, the ADFA 1 is attached to the roof of a vehicle with a magnetic mount, which does not require drilling holes or other modifications to the vehicle. The immunity of antenna performance to the mounting surface means that correction tables for the specific vehicle are not needed. Once the vehicle-mounted system identifies the building, an additional handheld antenna can be used with the SignalShark to determine the floor and room where the source is located.

**Narda STS**
**Pfullingen, Germany**
**www.narda-sts.com**

# 100 W, 6 to 18 GHz GaN PA

The latest addition to Comtech PST's solid-state power amplifier (PA) product line, the BME69189-100 is a 100 W GaN PA developed to replace TWTs and microwave power modules (MPM) in communications, electronic warfare and radar transmitters, where space, cooling and power are limited.

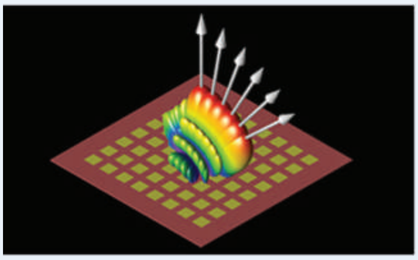
Compact and light weight, the PA delivers 100 W saturated output power (typical) with greater than 46 dB gain from 6 to 18 GHz. The linear class AB design has a typical gain flatness of ±2 dB. Harmonics are less than −12 dBc for 2f0 and less than −22 dBc for 3f0, with spurious less than −60 dBc.

The PA can be biased with either +28 or +270 VDC and consumes less than 30 W standby power. A 9-pin combo D connector provides the DC power and control, including an enable/disable function via a 5.0 V TTL signal, which switches within 2 μs. The PA has a built-in test capability, triggering for excessive current, over temperature and high reflected power faults.

The BME69189-100 is housed in a compact 8 in. x 6 in. x 2.5 in. module, weighs 5.5 lbs. and, attached to an external heat sink, operates over a baseplate temperature range from −40°C to +75°C. The PA meets the shock and vibration levels of MIL-STD-810F.

This 6 to 18 GHz PA is compact, rugged and reliable, well-suited for replacing TWT/MPM amplifiers in many applications, with the added advantage of a soft failure mode.

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



# Improved EM Simulation of 5G mmWave Arrays

The latest release of Remcom's XFdtd® 3D EM simulation software enhances the design tools for 5G mmWave antenna arrays, matching network design and simulation accuracy for higher frequency antennas.

XFdtd provides performance metrics for 5G beam steering applications, including the effective isotropic radiated power (EIRP). By simulating the radiation patterns with the different phasing used to steer the array or subarrays, XFdtd predicts the cumulative distribution function (CDF) of the EIRP of the full array. EIRP is an important quality indicator of an array's coverage, particularly valuable for analyzing 5G devices supporting multi-user MIMO (MU-MIMO). The CDF of the EIRP is important because carriers are requiring devices to meet stricter quality and performance thresholds, and customers designing mobile devices must compute the gain of many signals propagating in different directions. The new EIRP CDF simulation helps engineers design devices for the demands of 5G. Remcom is at the forefront of this emerging technology.

The matching network design workflow has also been enhanced by expanding XFdtd's integration with Optenni Lab™ matching circuit optimization software. Optenni's optimized matching topology data can now be imported into XFdtd, providing users with immediate feedback on circuit behavior and eliminating additional simulations. S-parameters, efficiency and dissipated power are provided for analyzing system performance, which greatly simplifies the matching process for intricate devices with many frequency bands.

This release introduces new modeling options to improve the simulation accuracy for the higher frequency antennas used in the latest-generation devices, including a new feed designed for exciting microstrip, surface current measurement and a user-defined input for the surface roughness of conductors.

VENDORVIEW

**Remcom, Inc.**
**State College, Pa.**
**www.remcom.com**

## New Landing Page for 50th Anniversary

VENDORVIEW


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

**AR RF/Microwave Instrumentation**

www.arworld.us

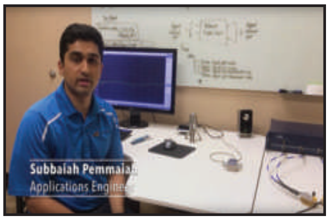
## New Online Store


Centerline Technologies has launched an online store providing a variety of precision-finished substrate materials in small quantities. For those seeking quantities of less than 10 pieces or adhering to a tight deadline, the web store is an excellent opportunity for sourcing affordable materials. All products are processed by Centerline to achieve optimal surface finish, size and tolerance.

**Centerline Technologies**

https://shop.centerlinetech-usa.com/

## New Quick How-To Video Guide




Differential signal impairment caused by transport through various media is becoming more important with the ever-increasing demand for high data rates in digital data systems. This drives the need for differential transmission lines to be properly characterized in frequency and time domain. Copper Mountain Technologies' Application Engineer Subbaiah Pemmaiah provides a quick guide on differential measurements on a cable in frequency and time domain analysis.

**Copper Mountain Technologies**

https://cpmt.link/dcmmwj

## New Website Update


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

**K&L Microwave**

www.klmicrowave.com

## New PIM Video


Kaelus' has a new video that can help you learn how to calibrate your PIM instruments in the field. The ACE-1000A is the industry's first analyzer calibration extender that allows customers to self-calibrate their PIM instruments in the field. With successful calibration, ACE will extend your analyzer's calibration while reducing downtime to less than one hour and increasing productivity by retaining instruments in the field.

**Kaelus**

www.kaelus.com/en/resource-center/

## New Website Update


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

**KRATOS General Microwave**

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

## New Video

MilesTek has a new video on their new line of 78 and 124 Ohm twinaxial cables with plenum rated jackets. Plenum cable jackets reduce the amount of smoke and flame emitted during combustion, when compared to PVC jacketed cables. Typically used in air handling spaces such as ceilings and walls or in poorly ventilated areas, plenum cables are widely used in military applications. MilesTek's new plenum rated twinaxial cables are in stock and available for immediate shipment.

**MilesTek**

www.youtube.com/watch?v=nxXwHFPqCkQ

## New Videos Added

VENDORVIEW


New PA and filter design videos given by NI AWR software customer and partners during EuMW 2018 have now been added to AWR.TV. Topics include load pull, filter synthesis and optimization, measurements and models for PAs and LNAs, UWB filter design and acoustic wave filter design. These videos as well as the complete suite of NI AWR Design Environment platform videos can be viewed at awr.tv.

**NI AWR Design Environment**

awr.tv

## New Website

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

**Quest Manufacturing**

www.questmanufacturing.net

## New Website Showcases Services

VENDORVIEW

SemiGen Inc. has launched their new website showcasing their expanded RF products, services and solutions. Their website allows your team to manage, deploy and deliver needed requirements utilizing modern manufacturing equipment and technology that meet today's demanding quality requirements. All tech briefs, guidelines and resources are easily accessible and their technical support team is standing by to assist when needed. This new website leverages SemiGen as an on-demand extension of your engineering team and production facility, and a trusted link in your supply chain.

**SemiGen Inc.**

www.semigen.net/

## New Products Updated on Website

VENDORVIEW


SPINNER added its new E Connector product family to their website. As the market for mmWave sensors for self-driving vehicles expands, the demand for proper RF connections in testing environments is also growing. The SPINNER E Connector is ideal for making high performance RF measurements in the E-Band without being held up by fragile 1 mm coaxial connectors or wasting time reassembling WR 10 waveguides. SPINNER designed the new 1.35 mm E Connector to close the gap between the 1.85 and 1 mm coaxial connectors.

**SPINNER GmbH**

www.spinner-group.com/

## New Website Launched

Have you noticed a change recently? SV Microwave is excited to announce the launch of their new website. Compatible across multiple devices, SV Microwave's newly launched site strives to deliver an awesome user experience. See for yourself and start browsing today. SV Microwave is a world leader in the RF/microwave industry with over 50 years of proven performance for the military, satellite, aerospace, commercial and telecommunications markets.

**SV Microwave**

www.svmicrowave.com/

# NEW PRODUCTS

FOR MORE NEW PRODUCTS, VISIT WWW.MWJOURNAL.COM/BUYERSGUIDE
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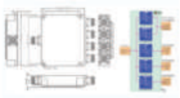
## COMPONENTS

### Combiner

3H's new low PIM, AWS+WCS+PCS+LAA+Band 41, Pentaplexer Combiner offers < 0.25 dB passband insertion loss in all passbands. The Combiner offers > 30 dB co-channel isolation with IMD 164 dBc typical in Rx band with two 43 dBm tones in the Tx bands. Used for multi-band antenna sharing without increasing channel insertion loss. Available for indoor and outdoor use. Package size is 4.5 x 5 x 1.6 in.



**3H Communication Systems**
**www.3hcommunicationsystems.com**

### Waveguide Power Divider/Combiner

VENDORVIEW

Cernexwave's CDPW Series waveguide power dividers/combiners, model CDPW23260604 are offered in more than a dozen different waveguide bands to cover frequencies from 8 to 110 GHz. They feature low insertion loss, low VSWR and high isolation in 2-, 4- and 8-way configurations.

**Cernex/Cernexwave**
**www.cernexwave.com**

### Cross Guide Couplers

VENDORVIEW

Fairview Microwave Inc. now offers a line of cross guide waveguide couplers with 4-, 3- and 2-ports with coax interfaces that work across C- to K-Bands. Fairview Microwave's comprehensive line of cross guide couplers is made up of 160 parts in three sub-categories: cross guide couplers (4 waveguide ports), cross guide couplers with terminations (3 waveguide ports) and cross guide couplers with terminations and waveguide to coax adapters (2 waveguide ports with either an SMA, Type-N or 2.92 mm coaxial connector).

**Fairview Microwave**
**www.fairviewmicrowave.com**

### MCV 5G and UNII 1, 2 & 3 Ceramic Filter

VENDORVIEW

MCV Microwave introduces a series of ceramic waveguide filters for 5G New Radio (NR) MIMO base stations. Covering the major communications bands—L-Band, Citizens Broadband Radio Service (CBRS), lower C- to Ku- and Ka-Band—the ceramic waveguide filters have 1 to 2 dB insertion loss, 20 dB rejection 20 MHz from the band edge and 100 W power handling, with 10 to 40 percent bandwidth (typical performance). MCV's 3 mm ceramic filters are already in mass production for 5 GHz Wi-Fi 6, also known as 802.11ax applications.

**MCV Microwave**
**www.mcv-microwave.com**

### Broadband 6-Way SMA Power Dividers

VENDORVIEW

MECA Electronics' latest new product offering, 6-way compact broadband of power dividers covering 0.5 to 6 GHz (806-2-3.250) encompassing public safety through ISM bands. With typical performance of VSWR's of 1.3:1 and 1.25:1, isolation 17 dB, insertion loss 2 dB and exceptional amplitude and phase balance of 1.5 dB and 15 degrees max. This is in addition to the family of 2-, 4-, 8- and 16-way splitters in various connector styles and IP60 and 67/68 ratings. Made in the U.S. with 36 month warranty.

**MECA Electronics**
**www.e-MECA.com**

### Ultra-Wideband Coaxial 2-Way 0° Splitter/Combiner

VENDORVIEW

Mini-Circuits' ZN2PD-E653+ is an ultra-wideband coaxial 2-way 0° splitter/combiner providing coverage from 10 to 65 GHz, supporting a wide range of applications including 5G, Ku-, K- and Ka-Band SATCOM, microwave point-to-point backhaul, instrumentation and more. This model provides 10 W power handling as a splitter with 1.2 dB insertion loss, 22 dB isolation, 0.1 dB amplitude unbalance, 1° phase unbalance and DC passing up to 440 mA. The splitter/combiner comes housed in a rugged, aluminum alloy case measuring 3.5 × 2 × 0.5 in. with 1.85 mm-F connectors.

**Mini-Circuits**
**www.minicircuits.com**

### Frequency Converter

VENDORVIEW

Pictured is a NDC1840I0217N14 frequency converter that operates at 18 to 40 GHz. With extensive experience in design and manufacturing, Norden can always deliver high quality converters 500 MHz to 110 GHz. Although they offer standard products, the company also offers engineering support for converters that require custom design and packaging, custom LO and IF frequency selection, conversion gain and linearity requirements. Look to Norden for custom solutions to your frequency conversion applications.

**Norden Millimeter**
**www.nordengroup.com**

### Broadband Ceramic Capacitors

PPI has the 01005BB Broadband 100 nF ceramic capacitors. The 01005BB104—the industry's smallest 100 nF broadband part characterized for RF performance—has a case measuring 16 × 8 × 8 mils, and offers resonant-free RF coupling/DC blocking from 16 kHz (lower 3 dB frequency) to beyond 65 GHz with < 1 dB insertion loss and < –15 dB return loss on suitable substrates. The 01005BB104 is rated at a DC working voltage (WVDC) of 4 and is available in a nickel-tin termination.

**Passive Plus Inc.**
**www.passiveplus.com**

### High Bandwidth, Compact, SDR

Per Vices introduced their newest software-defined radio (SDR), Cyan. It is designed to offer users with a customizable number of independent, phase coherent channels, up to 16, each with a standard BW of 1 GHz, customizable to 3 GHz. This high gain transceiver and signal processing platform provides the highest RF and digital bandwidth with an onboard DSP in a compact form factor. Ideal for radar, communications, (counter) EW, signals intelligence and test & measurement applications.

**Per Vices Corp.**
**www.pervices.com**

# Ultra Low Phase Noise
# Phase Locked Clock Translators

Up to 3.0 GHz

| Model | Frequency (MHz) | Ref. Input (MHz) | DC Bias (VDC) | Typical Phase Noise (dBc/Hz) 100 Hz | 1 kHz | 10 kHz | 100 kHz | Package |
|---|---|---|---|---|---|---|---|---|
| FCTS800-10-5 | 800 | 10 | +5, +12 | -87 | -116 | -144 | -158 | |
| KFCTS800-10-5 | 800 | 10 | +5, +12 | -87 | -116 | -144 | -158 | |
| FCTS1000-10-5 | 1000 | 10 | +5, +12 | -75 | -109 | -140 | -158 | |
| FCTS1000-10-5H | 1000 | 10 | +5, +12 | -84 | -116 | -144 | -160 | |
| FCTS1000-100-5 * | 1000 | 100 | +5, +12 | -75 | -109 | -140 | -158 | |
| KFCTS1000-10-5 * | 1000 | 10 | +5, +12 | -75 | -109 | -140 | -158 | |
| FCTS2000-10-5 * | 2000 | 10 | +5, +12 | -80 | -105 | -135 | -158 | |
| FCTS2000-100-5 * | 2000 | 100 | +5, +12 | -80 | -105 | -135 | -158 | |
| KFCTS2000-100-5 * | 2000 | 100 | +5, +12 | -80 | -105 | -135 | -158 | |
| FSA1000-100 | 1000 | 100 | +3.3, +5, +12 | -105 | -115 | -145 | -160 | |
| KFSA1000-100 | 1000 | 100 | +12 | -105 | -115 | -145 | -160 | |
| FXLNS-1000 | 1000 | 100 | +5, +12 | -120 | -140 | -149 | -154 | |
| KFXLNS-1000 | 1000 | 100 | +12 | -120 | -140 | -149 | -154 | |

** New for 2018*

## Features

- Cost Effective
- Replaces Noisy Frequency Multipliers
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## Applications

- Scanning & Radar Systems
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# NewProducts

## Passive Amplitude Equalizer

PMI Model No. EQL-17D6G21D6G-6DB-292MF is a passive amplitude equalizer that

operates over the frequency range of 17.6 to 21.6 GHz. This unit has a max input power of 0.5 W CW and a max VSWR of 2:1. The unit is supplied with 2.92 mm female and male connectors in a housing that measures 1.1 × 0.67 × 0.22 in.

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

## Modular SDR Development Kit

Richardson RFPD Inc. announced the availability and full design support capabilities for a new modular software-defined radio (SDR) kit. The ADI-DPD-DEVKIT is a small cell development kit with a scalable RF front end board. It is optimized for FDD-LTE Bands 14 and 28 but scalable to other bands and configurations. The new development kit is intended to reduce customer development time and risk. It consists of three boards—DE705, ADRV9375-W/PCBZ and EVAL-TPG-ZYNQ3—as well as documentation and support.

**Richardson RFPD Inc.**
**www.richardsonrfpd.com**

## 12.4 GHz SPDT Switch

RLC Electronics announced the addition of a high power 12.4 GHz SPDT switch with N connectors to its product capabilities. The switch can handle up to 400 W CW at 12.4, and provides high-reliability, long life and excellent electrical performance characteristics over the frequency range, including high isolation. Options on the switch include operating mode (failsafe or latching) and coil voltage (12 or 28 VDC), as well as indicator circuitry and a TTL driver.

**RLC Electronics Inc.**
**www.rlcelectronics.com**

## Waveguide Module

Fully integrated 60 GHz radio transmitter module, model RFS-640000-V60-282. Small and lightweight, the waveguide module features a unique chip to waveguide transition that is compatible with the WR-15, UG-385/U waveguide flange interface. This

radio transmitter operates in the license-free frequency range of 57 to 64 GHz. The waveguide module supports up to 1.8 GHz modulation bandwidth. Potential applications of these waveguide modules include multi-Gbps digital communications, HD video transmission, mmWave radar and imaging and ATE at 60 GHz.

**RF Superstore**
**www.RFsuperstore.com**

# CABLES & CONNECTORS

## Low-PIM Coaxial Cable Assemblies

Pasternack has launched a new line of low-PIM coaxial cable assemblies that are ideal for distributed antenna systems (DAS) and are available in standard and custom lengths with same-day delivery. Pasternack's new series of low-PIM coaxial cable assemblies consists of 18 standard configuration that boast PIM levels of < –160 dBc. This product line is made with lightweight, flexible UL910 plenum-rated SPP-250-LLPL RF coaxial cable which can operate in temperatures from –55°C to +125°C.

**Pasternack**
**www.pasternack.com**

## Continuum Field-Configurable Cable Kit

Velocity Microwave continues to deliver modular, cost-saving solutions through the Continuum Field-Configurable Cable Kit. Depending on the application, users can change the connectors on these cables using Type N, 3.5 mm, SMA or 2.92 mm. Male or female, standard or NMD connectors can be used. To maximize flexibility and value, each end of these 28 or 39 in. cables can be configured independently.

**Velocity Microwave**
**www.velocitybygte.com**

# AMPLIFIERS

## 500 W from 80 to 1000 MHz

AR's new 500W1000C solid-state amplifier provides 500 W of Class A CW output power from 80 to 1000 MHz when driven with 0 dBm from an RF sweep generator. It has superior gain flatness, high mismatch tolerance, exceptional noise figure, better efficiency and harmonics than competitive products for radiated susceptibility testing.

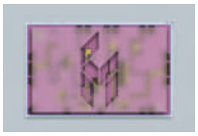
**AR RF/Microwave Instrumentation**
**www.arworld.us/html/18200.asp?id=1158**

## Solid-State Power Amplifier

Model BM2719-125 is a Class AB linear amplifier, which operates over the full 20 to 1000 MHz frequency range with output power of 125 W into a load VSWR of 3:1. The amplifier is very compact (6.8 × 6.8 × 1.5 in.) and weighs only 5 lbs.

**Comtech PST**
**www.comtechpst.com**

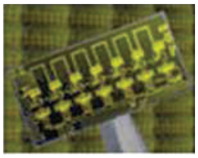
## Driver Amplifier



Custom MMIC has just released the CMD291, a new wideband driver amplifier MMIC. The CMD291 is a wideband GaAs MMIC driver amplifier die which operates from 16 to 24 GHz. The CMD291 delivers 22.5 dB of gain with a corresponding output 1 dB compression point of +26 dBm and output IP3 of 32.5 dBm at 20 GHz. The broadband device is ideally suited for applications requiring high dynamic range.

**Custom MMIC**
**www.custommmic.com**

## Driver Amplifier IC



EMD1211-D is a GaAs MMIC general purpose driver amplifier IC. This device is ideal for applications that requires a typical output of +30 dBm at 10 GHz, while requiring only 300 mA from a +12 V supply. Gain flatness is less than 2 dB across the DC to 20 GHz band. The EMD1211-D is also available in a small connectorized package.

**ECLIPSE Microwave**
**www.eclipsemicrowave.com**

## Solid-State Power Amplifier System

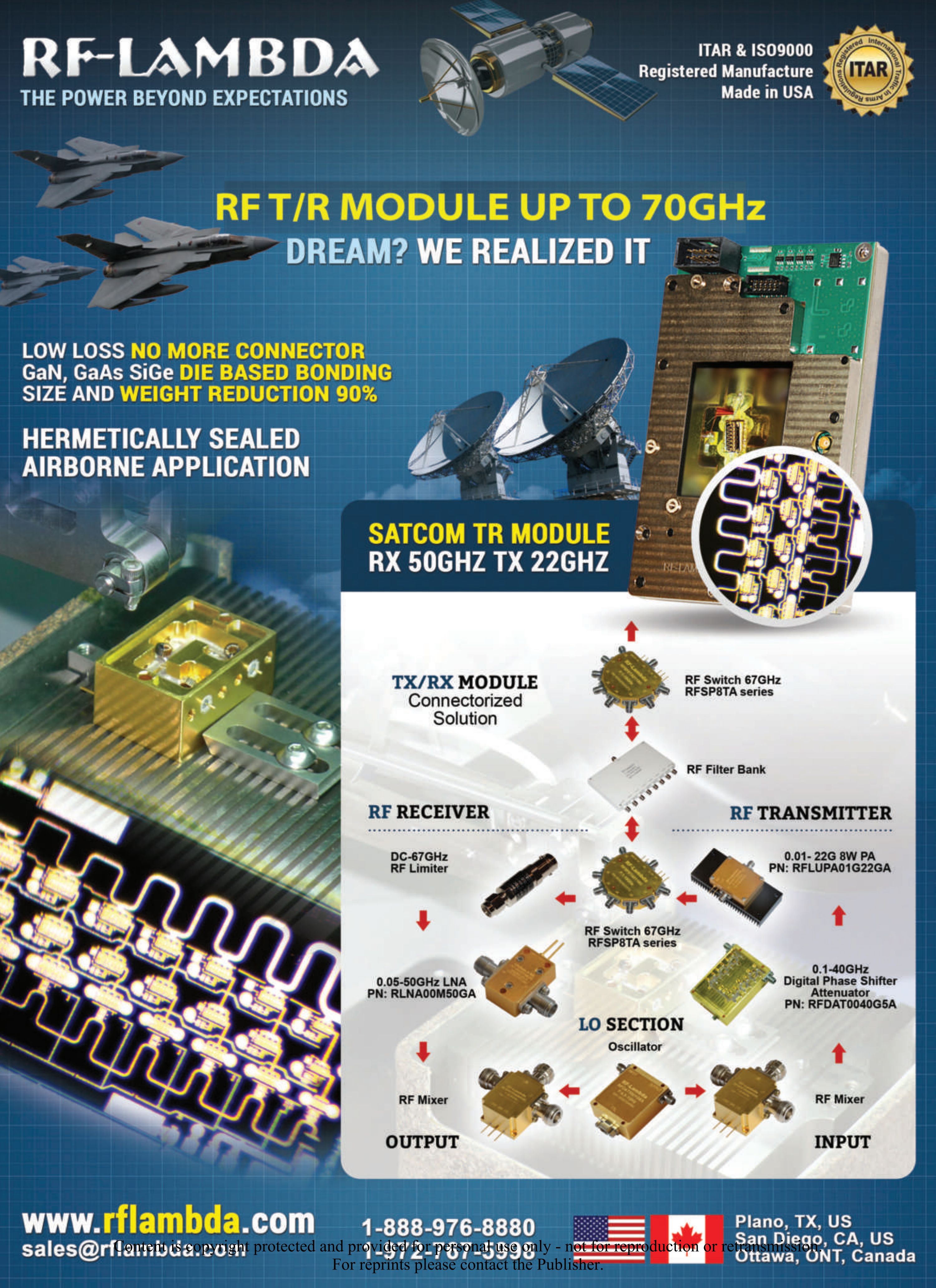
Exodus Advanced Communications introduced their high-power 7 to 10 GHz 150 W amplifier. Exodus AMP4021-1 provides 200 W nominal with a min. power gain of 53 dB. The unit has excellent gain flatness, < 5 μs switching speeds for enable/disable functions. Included are amplifier monitoring parameters for forward/reflected power, as well as voltage, current and temperature sensing for optimum reliability and ruggedness for all applications. Nominal weight is < 70 lbs and dimensions of 19 × 22 × 7 in.

**Exodus Advanced Communications**
**www.exoduscomm.com**

## SGA/SGN Series SSPA

KRATOS General Microwave's SGA/SGN Series SSPA's offer GaAs/GaN technology reliability that can be customized to meet specific pulse or CW output powers. The product line supports both X- and Ku-Band applications with bandwidths up to 10 percent and offers peak power outputs up to 400 W. Designed for demanding defense, aerospace and SATCOM applications. General Microwave SSPAs have excellent power efficiency with demonstrated field-proven performance and reliability. General Microwave's vertical integration process affords flexible layouts and architectures to meet individual specifications for electrical, mechanical and environmental parameters.

**KRATOS General Microwave**
**www.kratosmed.com**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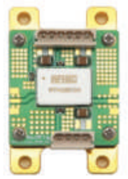
## 10 W GaN Hybrid PA Module



RFHIC Corp. launched the world's first and smallest 10 W GaN hybrid power amplifier (PA) module for 5G massive MIMO and small cell applications. The RTH35010X is a fully matched two stage Doherty PA module, designed to deliver 10 W of average output power with an exceptional power added efficiency of 43 percent (PAR 8 dB). The RTH35010X has 28 dB of gain and operates from 3.4 to 3.6 GHz.

**RFHIC Corp.**
**http://rfhic.com/main.html**

## Dual-Die Differential DOCSIS 3.1 Amplifier

VENDORVIEW

RFMW Ltd. announced design and sales support for a broad bandwidth CATV amplifier. The Qorvo QPB7464 supports DOCSIS 3.1 applications from 50 to 2600 MHz including satellite frequency distribution. Gain measures 11.5 dB, while noise figure measures 4.5 dB. The QPB7464 is a replacement for 5 V SOIC-8 amplifiers with 75 Ω impedances and offers 37 dBm OIP3.

**RFMW Ltd.**
**www.rfmw.com**

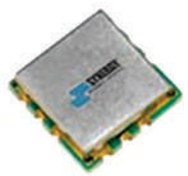
## 60 W Power Amplifier

The TTRM1123 is a high-power bi-directional amplifier (BDA) that utilizes the latest LDMOS technology to provide over 60 W of linear power in S-Band. The unit is designed to be integrated in any system that requires high-power, high efficiency and high linearity in the entire 2200 to 2500 MHz band. In transmit mode, the amplifier provides 28 dB of small signal gain and can produce over 10 W of 64 QAM OFDM power across the band.

**Triad RF Systems**
**www.triadrf.com**

# SOURCES

## Miniature Surface Mount VCO



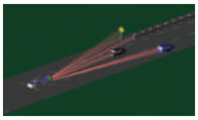
This C-Band miniature surface mount VCO model DCO608634-3 delivers a powerful performance from an optimized fundamental frequency planar resonator design covering the band of 6.08 to 6.34 GHz with just 0.5 to 5 V of tuning. The 3 V supply voltage (VCC) draws only 26 mA max current. It achieves superb low phase noise of –86 dBc/Hz at 10 kHz offset. The output power is a modest –6 dBm min. with excellent harmonic suppression of 25 dB typical.

**Synergy Microwave Corp.**
**www.synergymwave.com**

# SOFTWARE

## WaveFarer™ Automotive Radar Simulation Software

VENDORVIEW



Remcom announced a new software product for automotive radar design and placement. WaveFarer™ Automotive Radar Simulation Software enables OEMs and Tier 1 suppliers to set up virtual scenarios and refine sensor performance earlier in the design process. WaveFarer uses ray-tracing algorithms specifically adapted for radar applications to predict the scattered returns from a scene, with support for frequencies up to and beyond 79 GHz. Near-field propagation and scattering methods compute raw radar returns from target objects while considering multipath interactions from ground reflections and other structures.

**Remcom Inc.**
**www.remcom.com**

# MICRO-ADS



# NewProducts

## ANTENNAS

### 4×4 MIMO Antenna

VENDORVIEW

HUBER+SUHNER SENCITY®Occhio 4×4 MIMO antenna is developed for indoor small cell connectivity. Thanks to its multiband capability between 1.7 to 6 GHz and 2×2/4×4 MIMO configurations, the Occhio antenna fulfills multiple requirements of 5G standard and equally meets current 4G applications. The unique combination of stylish design and innovative engineering makes Occhio robust and reliable, while enabling a simplified densification of the network. The innovative smart-connect system simplifies installation process that antenna can be mounted safely and efficiently with one hand. No tools required.

**HUBER+SUHNER**
**www.hubersuhner.com**

## TEST & MEASUREMENT

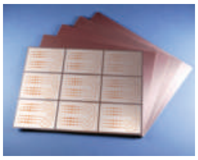
### M Series VNA

Copper Mountain Technologies announced the release of the new M Series VNAs for two-port, two-path measurements. Its M Series VNAs deliver highly accurate measurements in one affordable package. They all have a starting frequency of 300 kHz and the M5065 goes to 6.5 GHz, M5090 to 8.5 GHz and the M5180 up to 18 GHz. The dynamic range is 130 dB typ. All CMT VNAs include excellent customer service, automation support and years of engineering expertise at your disposal.

**Copper Mountain Technologies**
**https://cpmt.link/mvnamj**

## MATERIALS

### Next-Generation Laminates



Rogers Corp. announced the latest addition to its RO3000®Series PTFE circuit materials: RO3003G2™ high frequency laminates. RO3003G2 laminates build on Rogers' industry leading RO3003™ platform to provide radar sensor designers with improved insertion loss and reduced dielectric constant (Dk) variation. The combination of their optimized resin and filler content along with the introduction of very low profile ED copper translates to Dk of 3 at 10 GHz (clamped stripline method) and 3.07 at 77 GHz (microstrip differential phase length method).

**Rogers Corp.**
**www.rogerscorp.com**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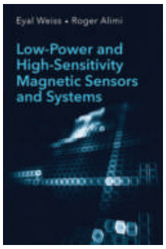


## Low-Power and High-Sensitivity Magnetic Sensors and Systems

Eyal Weiss and Roger Alimi

This comprehensive new resource analyzes sources of noise and clutter that magnetic sensing system developers encounter. This book guides practitioners in designing and building low noise and low-power consumption magnetic measurement systems. Various examples of magnetic surveillance and survey systems are provided. This book enables system designers to obtain an all-inclusive spectral understanding of typical sources of noise and clutter present in the system and environment for each application, in order to successfully design stable and sensitive low-power magnetic sensing devices. Detection and localization methods are explored, as well as deterministic and heuristics algorithms which are an integral part of any magnetic sensing system.

This book is aimed to eliminate some of the "black magic" manipulations present during low noise magnetic measurements. The book meticulously describes, analyzes and quantifies the variables that affect low noise measurement systems. Readers are able to understand sources of measurements irregularities and how to effectively mitigate them. Moreover, this book also presents low-power magnetometers and dedicated low noise sampling techniques.

**To order this book, contact:**

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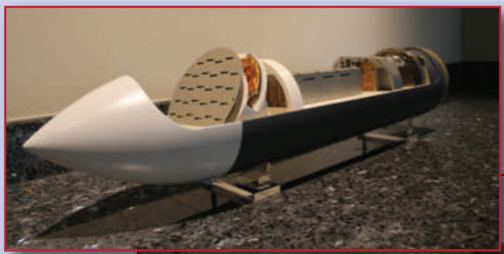
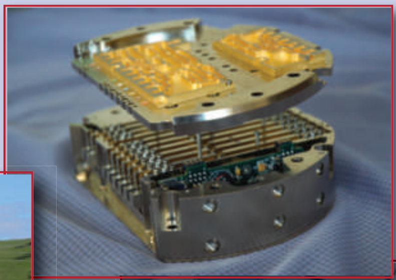
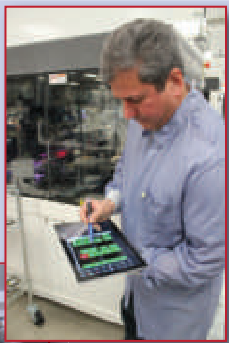
## Nothing Escapes Cobham Guided Munitions Microelectronic Solutions








In 2014, the Guided Munitions Microelectronic Solutions (GMMS) division of Cobham, driven by a major customer, initiated RMS ZERO Policy and Product Escapes focusing on their operations and quality standards. ZERO stands for Zero Escapes to the customer's Operations but represents more of an overall strategy to strive toward zero defects using continuous improvement and team work. We saw clear evidence of this with their extensive factory automation and formal failure reporting and corrective action system (FRACAS). Each day production teams meet to discuss quality issues and assign teams to find the root cause of any defects or out of control processes. They are surrounded by charts and graphs in a large common area with white boards where they review their assembly operations and share ideas for improvement.

The facility has developed and implemented an extensive equipment monitoring system that associates can access via tablets to see that status of all equipment and log any issues including corrective actions taken to fix the problems. This allows employees to diagnose any long term issues early and take corrective action before processes go out of control. The employees use data driven information to drive continuous improvement in the facility and are accountable for their processes and actions. You can see their passion and pride in their operations as they present their data and review their processes.

GMMS employs close to 500 people in the San Jose area and has about 160,000 square feet of operations. They produce custom microwave assemblies for missile, EW and telemetry applications. They excel at designing and producing high quality mmWave assemblies in custom form factors. While most of their business is defense related their mmWave test expertise has involved them in some 5G test setups for commercial customers too.

Their market differentiators include expertise in MMIC design (including GaN), industry leading phase noise performance, highly dense microwave packaging, DSP and embedded software, high power transmitter and receiver protection, design margin and simulation, and factory automation/SPC for high quality manufacturing. Some of their key products include wideband/narrowband multichannel frequency conversion, RF and digital receivers and exciters, transmit and receive modules and transceivers, AESA arrays, high performance direct frequency synthesizers and LO sources, multi-octave solid-state high-power amplifiers and transmitters and telemetry/data link modules.

Their facility is impressive with about 200 custom test stations in operation including classified stations with protected networks. About 150 of the 200 test stations are automated to test over temperature without an operator and all connected to a classified local area network. They manufacture most of their packaging making their own glass seals, substrates and housings for many applications. They have a wide range of manufacturing equipment in their assembly operations including die/substrate attach, wire bonding, encapsulation/sealing, automated visual inspection, environmental screening/testing and high frequency/high-power testing. They focus on automation with pick and place machines, auto wire bonding and auto visual inspection. Greater than 95 percent of their wire bonding is automated reducing labor and improving consistency and yield.

GMMS has grown over the last eight years and achieved a high level of quality. The leadership has driven a team-based zero defect approach and automated complicated processes that have streamlined their operations. Nothing escapes their quality system and missiles that they equip.

**www.cobham.com/advanced-electronic-solutions/**

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2019

# Cables & Connectors

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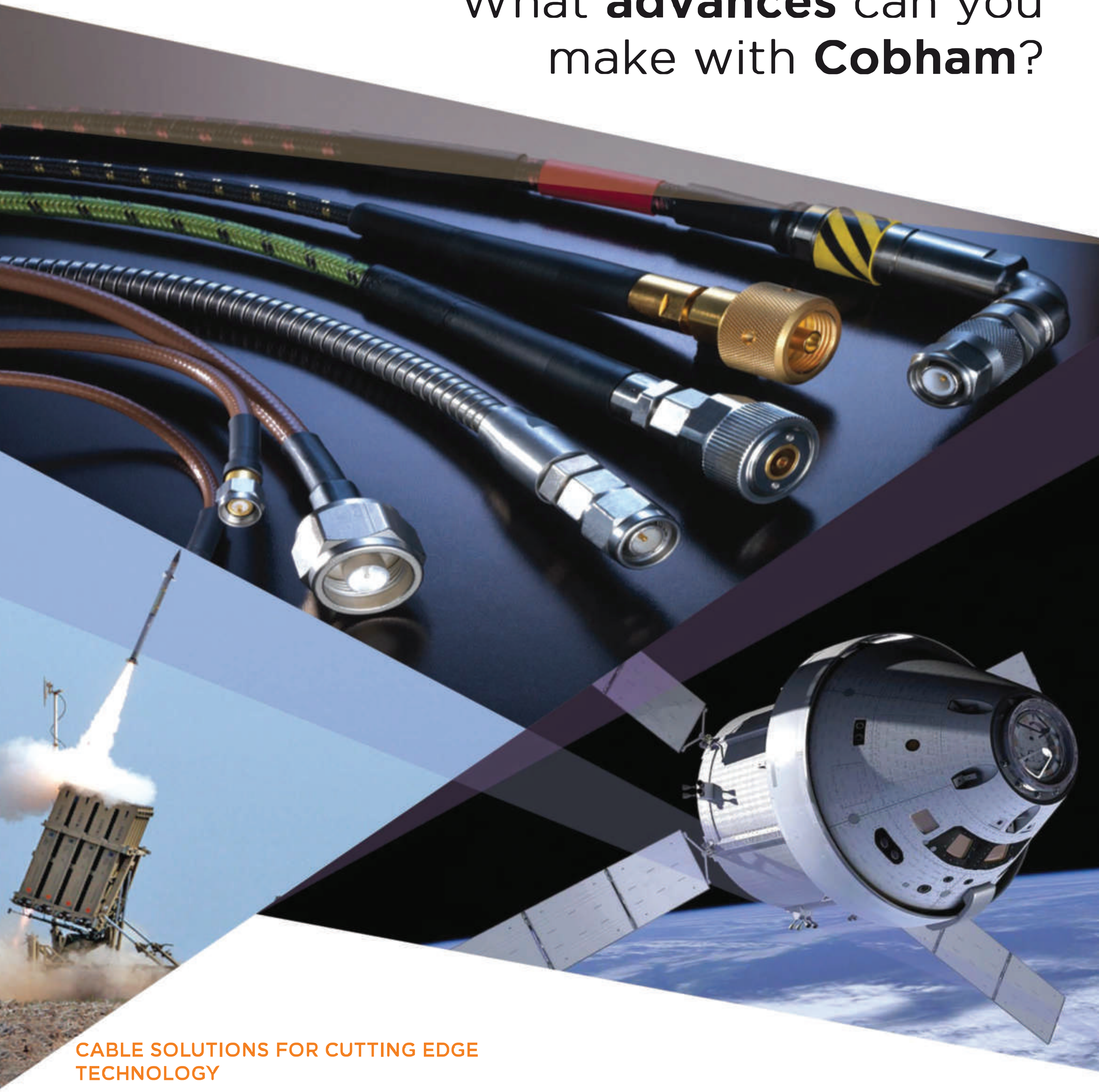


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INVITED PAPER

# 0.8 mm Connectors Enable D-Band Coaxial Measurements

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*The evolution of electronics technology is driving communications data transfer rates, which means larger bandwidth. To get larger bandwidth, systems must move up in frequency, and moving up in frequency to get more bandwidth requires higher performance connectors.*

W-Band applications, i.e., from 75 to 110 GHz, have grown significantly over the last few years, such as automotive radar and wireless communications backhaul. To support the development and production of these and future systems, broadband device characterization extending beyond 110 GHz, i.e., into D-Band, is required. To address this need, Anritsu has developed the first 0.8 mm connector.

For a new frequency band, connectors were historically created ahead of or in parallel with the test and measurement equipment supporting the applications. Connectors like K, V and W1 have enabled new test equipment capabilities. In some cases, the connector was developed first, with the equipment developed quite a few years later, like the 1 mm connector, which extended coaxial measurements to 110 GHz.

Typically, waveguide has been used for interconnections at the higher end of the frequency spectrum. Waveguide accomplishes the task of sending signals through devices with low loss; however, it is not the optimal solution. As a frequency-banded component, waveguide lacks the advantage of broadband frequency coverage and single-sweep measurements. Waveguide adds complexity for any measurement to characterize broadband performance from low frequency to mmWave frequencies past 110 GHz.

Coaxial connectors are preferred for interconnections, especially for test and measurement. They have advantages like single-sweep capability, ease of use for measuring and testing devices and frequency scalability. Coaxial connectors avoid impedance variations between interfaces, like coaxial to waveguide, which introduce uncertainty.

## DESIGN CONSIDERATIONS

To understand the 0.8 mm connector design, consider the electrical and mechanical characteristics of a connector. IEEE P287 is the standard for precision coaxial connectors covering DC to 110 GHz, outlining the electrical and mechanical properties for connectors down to 1 mm. IEEE P287 does not currently define the 0.8 mm connector; however, because frequencies above 110 GHz will be important in the future, 0.8 mm will eventually be included in the spec. The electrical characteristics of a connector define the frequency coverage and impedance, while the mechanical characteristics address how the connector design supports repeatability and mating. Combined, these characteristics, which are generally listed in a technical datasheet, are important design considerations.

The upper frequency of a connector is determined by the equation

$$f_c = \frac{c}{\lambda_c \sqrt{\mu_r \varepsilon_r}}$$

**TABLE 1**
**COAXIAL CONNECTOR ELECTRICAL AND MECHANICAL PARAMETERS**

| Connector | Air Cutoff Frequency (GHz) | Maximum Rated Frequency (GHz) | Pin Gap Impedance (Ω) | Center Conductor (mm) | Size of Bead (mm) |
|---|---|---|---|---|---|
| Type N | 19.4 | 18 | NA | 3.04 | NA |
| SMA | NA | 18 | NA | 1.27 | NA |
| 3.5 mm | 38.8 | 33 | 80 | 1.52 | 3.6 |
| 2.92 mm | 46 | 40 | 69 | 1.27 | 3.05 |
| 2.4 mm | 56 | 50 | 93 | 1.042 | 2.1 |
| 1.85 mm | 73 | 70 | 77 | 0.803 | 1.5 |
| 1 mm | 133 | 110 | 83 | 0.434 | 1.15 |
| 0.8 mm | 166 | TBD | 82 | 0.347 | 0.559 |
| 0.6 mm | 222 | TBD | 65 | 0.26 | 0.406 |
| 0.4 mm | 332 | TBD | 63 | 0.174 | 0.28 |

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| Part Number | Length (in) | Length (mm) | Insertion Loss (max) |
|---|---|---|---|
| 095-902-466-001 | 24.00 | 610 | 1.84 dB |
| 095-902-466-002 | 36.00 | 914 | 2.61 dB |
| 095-902-466-005 | 39.37 | 1000 | 2.84 dB |
| 095-902-466-003 | 48.00 | 1219 | 3.37 dB |
| 095-902-466-004 | 72.00 | 1829 | 4.90 dB |

### Technical Specifications

| Electrical | |
|---|---|
| Impedance | 50 Ω |
| Frequency Range | DC – 20 GHz |
| Dielectric Withstanding Voltage | 1000 VRMS |
| Insulation Resistance | 500 MΩ m |
| Phase Stability (with bending) | 5.0° max |
| Amplitude Stability | 0.16 dB max |
| VSWR | 1.27 max |
| Velocity of Propagation | 70% |
| Capacitance | 29.4 pF/ft |
| Shielding Effectiveness | < -95 dB |

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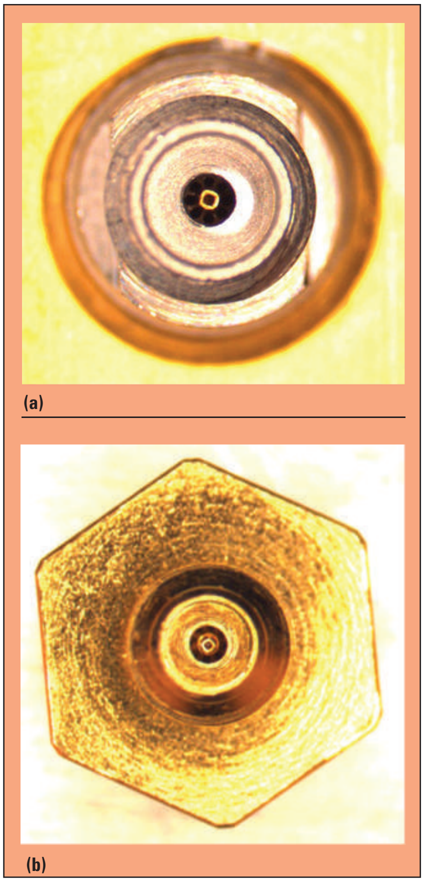
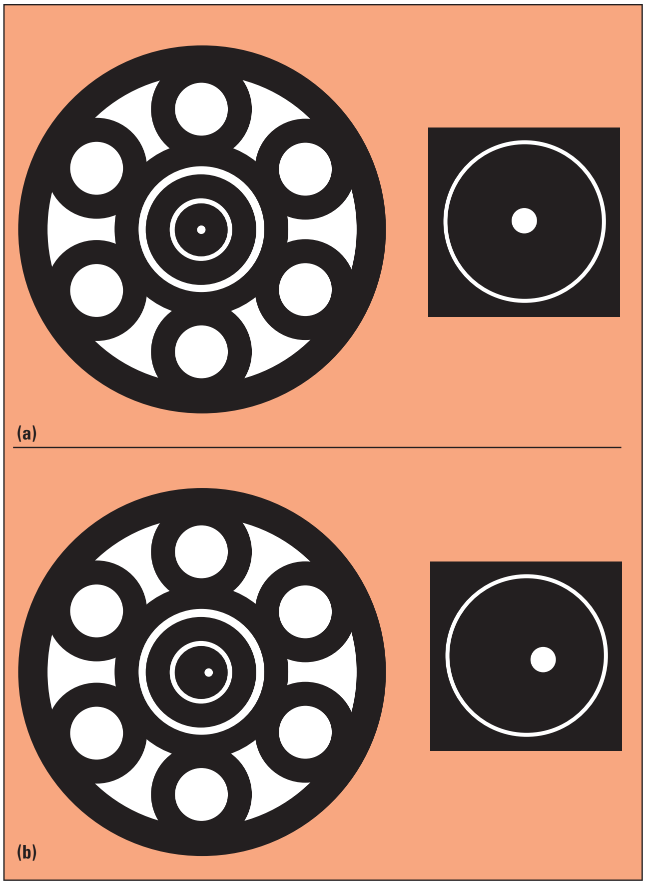
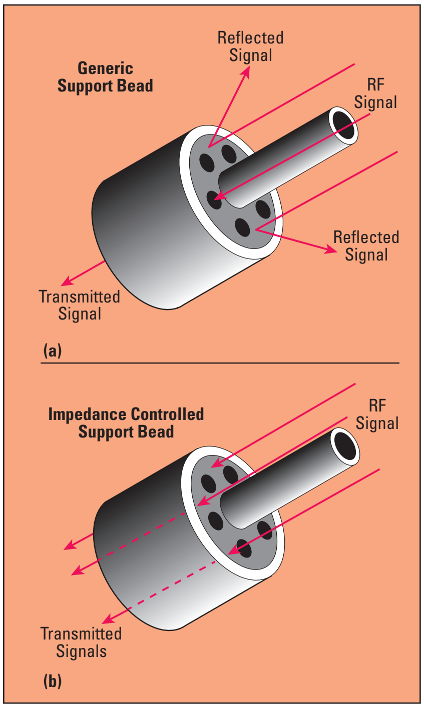


▲ Fig. 1 1 mm (a) and 0.8 mm (b) connectors.



▲ Fig. 2 Male center pins: 100 percent concentric (a), not concentric (b).



▲ Fig. 3 A generic support bead (a) reflects the RF signal, while an impedance controlled support bead (b) minimizes reflections.

where $f_c$ is the air cutoff frequency, c is the speed of light ($3 \times 10^8$ m/s), $\epsilon_r$ is the relative permittivity, μr is the relative permeability and $\lambda_c$ is the line length.[1] For the 0.8 mm connector, $f_c$ is approximately 166 GHz, assuming a perfect air dielectric. This maximum frequency is hard to achieve; the actual usable frequency is a percentage of the ideal because the internal components of a connector introduce transitions between air and the various materials, creating resonances that degrades the upper frequency. Although the 0.8 mm connector does not have a defined maximum frequency, which is still to be specified, connectors operating to 145 GHz are commercially available. A summary of RF connector types, including the 0.8 mm, is provided in ***Table 1***.[2]

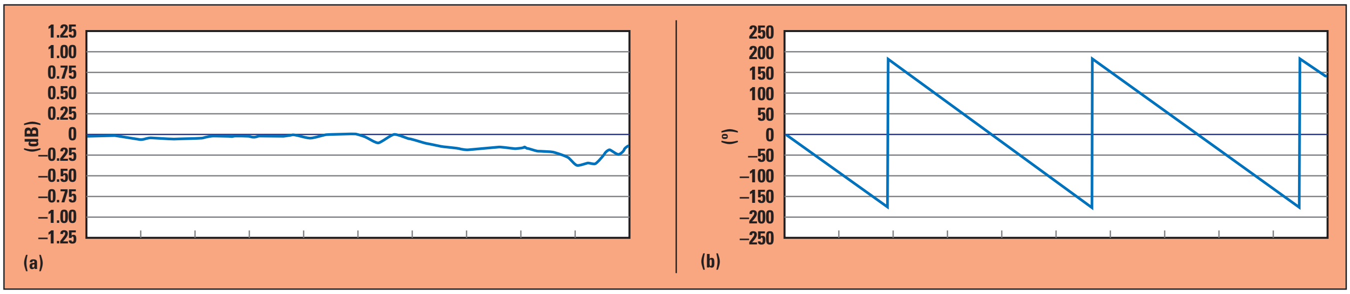
Impedance is a primary electrical requirement, because system performance is based on the ability to prevent or design around impedance mismatch. For connectors in this frequency range, 50 Ω is the standard impedance; designs must ensure that the connector and all internal parts are as close to this impedance as possible. Impedance must be well controlled for a connector that spans from DC to above 110 GHz. The center conductor and dielectric support beads play crucial roles keeping the impedance within an acceptable tolerance.

Most mechanical characteristics are defined by a connector standard, such as IEEE P287, which outlines the mechanical properties, such as coupling nut tolerances, line size and dimensions. The standard assures mechanical compatibility between connector manufacturers. While the general mechanical assembly is outlined, additional connector details are required to ensure good performance: slot-less or slotted, pre-alignment before mating and environmental classification based on the end product.

## THE 0.8 MM CONNECTOR

Moving up in frequency past W-Band starts with the requirement that the new connector must provide low insertion loss with metrology-grade and mode-free performance to the desired upper frequency. This is not easy, requiring many design decisions. The 1 and 0.8 mm connectors are similar—they are very close in mechanical size and share many external physical similarities—however, there are many internal differences (see ***Figure 1***). While some 1 mm technology could be leveraged, the 0.8 mm connector needed several new design elements to optimize performance.

In the frequency domain, a good interface should minimize insertion loss to minimally degrade the loss budget of a system. Unknown impedances between interconnects can cause reflections, affecting insertion loss even before the signal reaches the device being tested. The signal should be preserved between interfaces. Impedance variation is also an issue in the time




▲ Fig. 4 Measured insertion loss (a) and phase (b) of an Anritsu 0.8 mm female-to-female adapter, from 100 MHz to 145 GHz.

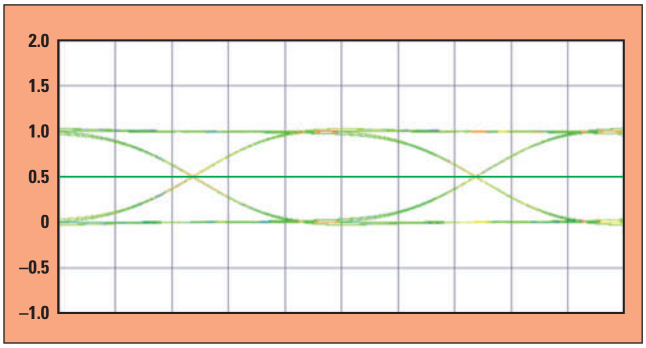
domain, so the eye diagram of an interface should have an optimal opening to ensure a clear and undistorted signal. The eye diagram is a figure of merit for designers creating digital circuits operating to mmWave frequencies. Whether for RF or high speed digital, the connector should be designed and built to provide performance that makes the connector transparent in the measurement environment.

What does it take to get the connector's upper frequency past 110 GHz with good impedance matching, metrology-grade performance and a mechanical design that makes it durable and performing well? It requires identifying the mechanical issues influencing performance above 110 GHz, quantifying and correlating simulations with fabricated connectors and exploring materials for novel new assemblies. Because the scope of the design is so wide, this article focuses on the mechanical issues and new assemblies.

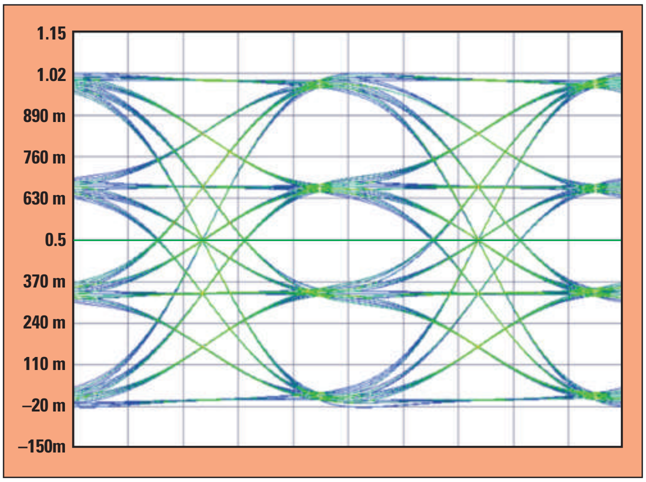
## CONCENTRICITY AND IMPEDANCE

Mating two connectors to pass signals is the starting point for transferring data, accomplished through a pin and slotted receptacle. Published literature describes various mechanisms for mating connectors to 110 GHz. Often, what is not described is that designers must account for repeatable and proper concentricity as the dimensions for both the pin and slotted receptacle get smaller. The performance of a connector is only as good as how well it mates with another connector. Concentricity describes how balanced and centered the male or female mating receptacle is. Ideally, the concentricity would be 100 percent. Without sufficient concentricity, proper mating will be impossible and damage to the connector inevitable (see ***Figure 2***).

Concentricity is a mechanical parameter, and decisions to address it will affect the connector's electrical performance. One approach to ensuring proper concentricity is evaluating the subassembly. For 1 mm connectors, the assemblies are threaded and easily manufacturable. The thread assembly removes the need for very fine tolerances. Concentricity, in this case, is trivial. Because the 0.8 mm connector requires accuracy over a broader frequency range—theoretically up to 166 GHz—tolerances cannot be relaxed. Assembly tolerance error will determine whether a pin or receptacle will sit perfectly in the center of the connector, so assemblies must account for this. Press fitting the 0.8 mm parts is the alternative to threaded assembly. Press fitting the connector allows for shorter connectors and improves concentricity, since the distance from the reference plane to the support bead is shorter.



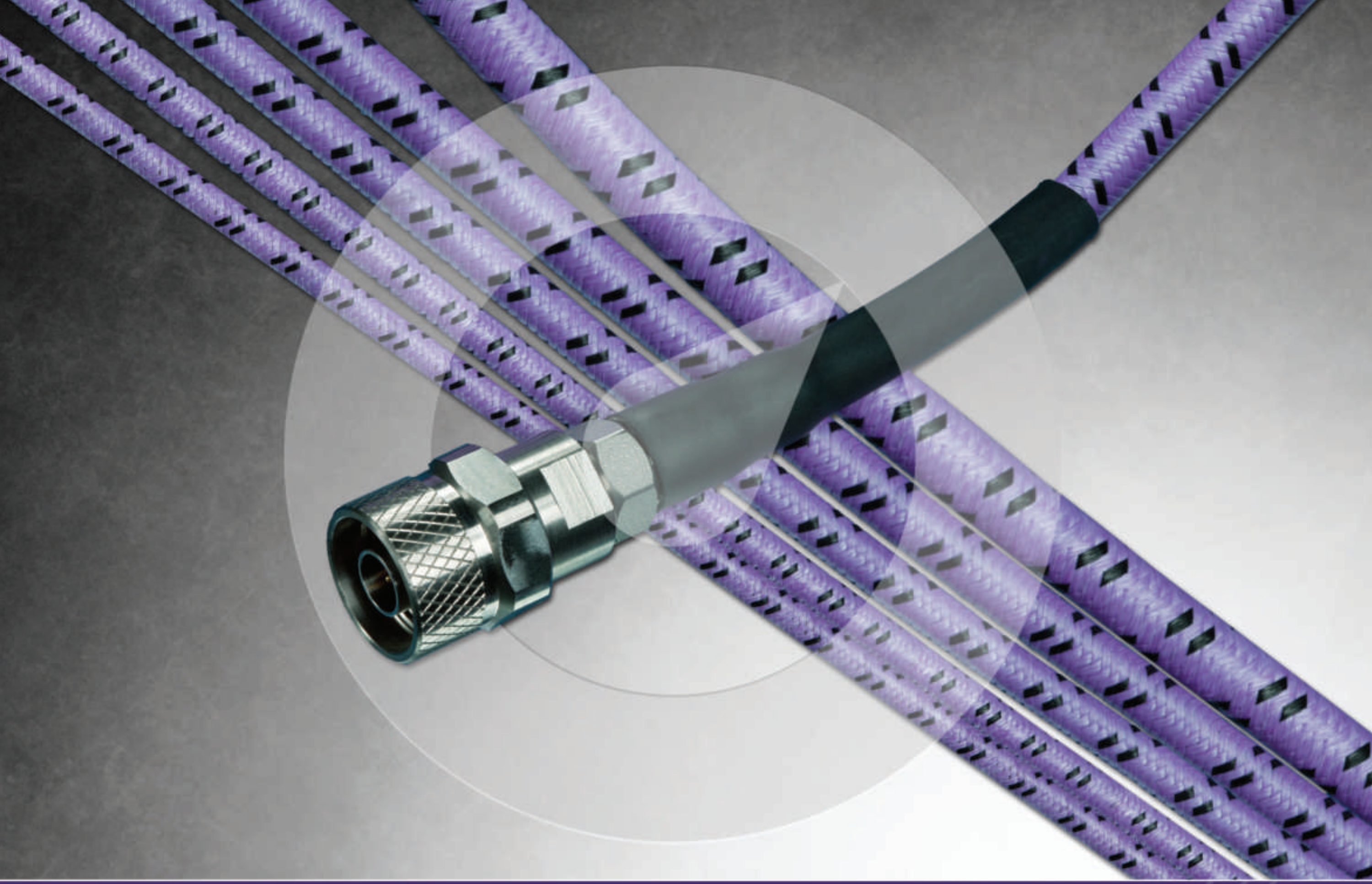

▲ Fig. 5 90 Gbps eye diagram of the Anritsu 0.8 mm female-to-female adapter.




▲ Fig. 6 90 Gbps PAM 4 signal through the 0.8 mm female-to-female adapter.

After changing assemblies from threaded to press fit for proper mating, the next obstacle is controlling the impedance, choosing the right internal components to keep the impedance close to 50 Ω. The 0.8 mm connector, like most high frequency connectors, has a center conductor requiring support beads, which is an integral part of the design for both the connector and housing. Several types of beads can support a connector's center conductor, with various impedance profiles and dielectric signatures. The support bead must provide mechanical stability and minimize reflections through the connector. Support bead design is critical to the overall electrical performance, the key parameter being the impedance. The center conductor support bead, in the middle of the connector and in the path of the RF signal, has holes to simulate air dielectric. To minimally influence the signal passing through it requires a controlled impedance with tight tolerances, to get the support bead impedance as close to 50 Ω as possible to avoid reflecting signals and degrading performance (see ***Figure 3***).

In the initial phase of creating the 0.8 mm connector, we tested various beads and found that many of them,



including glass, have impedance tolerances of 5 percent of the nominal value. For a metrology-grade connector, impedance control must be better than 5 percent. This bead should be transparent to the measurement. After much testing and research, a proprietary, high temperature bead was developed that offers the desired performance: good VSWR and low insertion loss, as well as ensuring mechanical stability and environmental ruggedness. Using a proprietary Anritsu bead enabled an 0.8 mm connector with a typical insertion loss of 0.5 dB at 145 GHz.

Another design consideration is whether the connector should be compatible with 1 mm connectors. By choice, the 0.8 mm connector is not compatible with the 1 mm connector, as damage will occur when mating them. This was addressed by adding a fine thread to the connector to prevent the 0.8 mm from mating with a 1 mm connector, also preventing the connector from becoming loose during operation.



## TESTING AND PERFORMANCE

After much design and evaluation, the finished 0.8 mm connector has a typical insertion loss of 0.6 dB from low frequencies to 145 GHz. After achieving this performance in the connector, Anritsu applied the same technology to cables and adapters. An 0.8 mm female-to-female adapter, tested with a 145 GHz vector network analyzer (VNA), has less than 0.5 dB insertion loss and linear phase response (see ***Figure 4***).

To assess the time domain performance for applications using an 0.8 mm connector to carry a digital signal, ***Figure 5*** shows the eye opening of the same Anritsu female-to-female adapter with a 90 Gbps data rate signal; ***Figure 6*** shows a 90 Gbps PAM 4 signal, both measured with a VNA with non-return-to-zero and PAM 4 eye diagram options. Both figures show excellent performance with high speed digital signals.

## AVAILABILITY

The 0.8 mm connector technology provides metrology-grade performance from DC to 145 GHz and is currently the only 0.8 mm connector on the market. Anritsu is integrating this platform in new components and test systems, such as screw-in sparkplug connectors, cables and test equipment. The 0.8 mm sparkplugs are pin and socket connectors covering DC to 145 GHz with 0.7 dB (typical) insertion loss. Anritsu has developed armored semi-rigid cables with 0.8 mm male-to-female connectors, available in 10 cm and 16 cm lengths. The cables have excellent insertion loss and return loss performance.

Anritsu test equipment with the 0.8 mm connector provides coaxial frequency coverage to 145 GHz. The VectorStar VNA with optional mmWave modules and 0.8 mm connectors covers from 70 kHz to 145 GHz with one sweep. An 0.8 mm calibration kit for the VectorStar VNA includes metrology-grade adapters and standards for the highest performance. ■

## References

1. R. J. Collier and A. D. Skinner, "Microwave Measurements, Third Edition," *Stevenage: Institution of Engineering and Technology*, 2007.
2. B. Oldfield, "The Importance of Coax Connector Design Above 110 GHz," *Anritsu Co.*, 2007, https://dl.cdn-anritsu.com/ja-jp/test-measurement/reffiles/About-Anritsu/R_D/Technical/E-22/22_07.pdf.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# Understanding Skew and Delay-Matched Coaxial Cables

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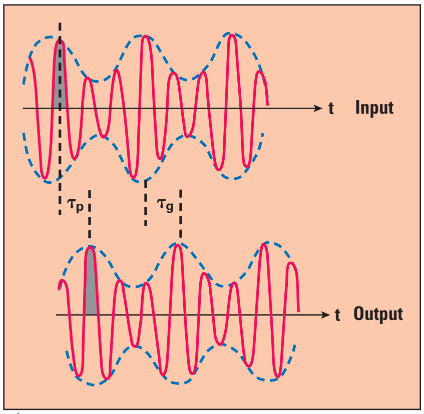
*A plethora of information discussing skew-matched data cables, such as Ethernet, is available for signal integrity applications. Data cables carrying differential signals over multiple internal wires necessarily have key parameters such as skew—any delay offset between the propagating signals means signal distortion and a perceptible loss of quality. In contrast, there is a noticeable lack of information about skew-matched coaxial cables and considerations for their respective application. This article discusses skew and applications for skew-matched coaxial cables.*

Skew for data cables is typically defined as the difference in propagation delay or time delay between a differential pair cable assembly with the least delay and the differential pair with the most delay. Similarly, skew is inherent to individual pairs and is due to differences in conductor length or the velocity of propagation (VOP) of the individual conductors. VOP is defined as the speed at which a signal propagates through a path and is often expressed as a percentage of the free space value of the speed of light. While this definition sheds light on skew-matched high frequency cable counterparts, it does not take into account phase instabilities that can cause minor shifts in skew for coaxial assemblies.




▲ Fig. 1 Group delay ($\tau_g$) vs. phase delay ($\tau_p$) of a modulated signal.

Often, time delay is equated to group delay; while they are related, they are not identical. Group delay is the derivative of phase versus frequency. For some, group delay is more intuitive, as it can be roughly equated to the time for a pulse to arrive at a receiver or a rough estimation of the transmit time of a signal through a path. Group delay flatness, a measure of the variation in the group delay, is an important measurement in some systems, as it makes clear any abrupt changes in delay at the output of the device under test.

Not the same as group delay, time delay can be more accurately measured with phase delay (see ***Figure 1***). For a signal propagating as a sine wave with an amplitude envelope, the group delay is analogous to the time delay of the amplitude envelope ($\tau_g$ in the figure), while the phase delay is the amount of time delay for each frequency component of the signal ($\tau_p$). A coaxial pair with high delay accuracy needs the wave patterns to match at the output, as well as matching each frequency component.

Group delay is a helpful measurement for dispersive media such as a waveguide, where several modes can exist simultaneously. It is not particularly helpful for non-dispersive media, such as TEM-mode coaxial cable, as non-dispersive media remain pretty consistent across the bandwidth. Phase delay, however, can vary, as it is the integral of group delay with respect to frequency. For an ideal coaxial cable, group delay is not a function of frequency. It is constant.

Phase is a linear function of frequency, shown by the equation

$$\varphi(f) = -360^\circ f\tau \qquad (1)$$

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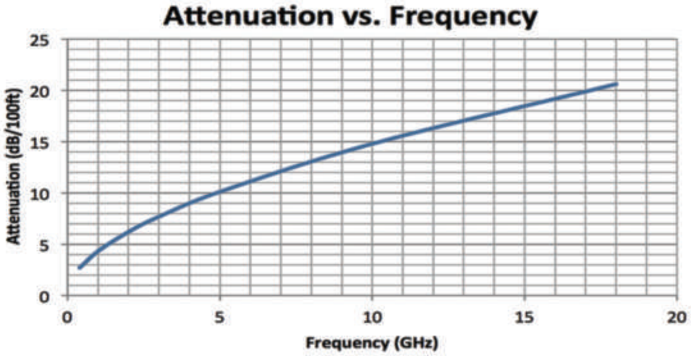


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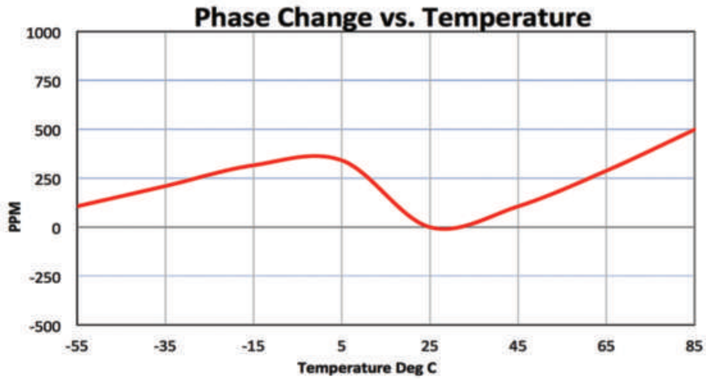


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Harbour Industries LLC • 4744 Shelburne Road • Shelburne, VT 05482 USA • 802-985-3311 where $\tau$ is the time delay. The time delay of a coax cable is directly proportional to the mechanical length and permittivity of the dielectric, shown by the equation

$$\tau = \frac{L_{MECH}\sqrt{\varepsilon}}{c} \quad (2)$$

where $L_{MECH}$ is the mechanical length of the cable, $\varepsilon$ is the relative permittivity of the dielectric material and c is the velocity of light. Phase stable coaxial cables depend on matched electrical lengths of their transmission lines, where the electrical length is related to the mechanical length by

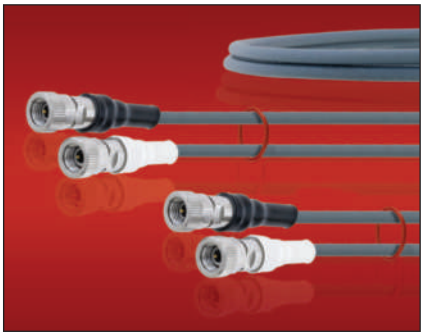
$$L_{ELEC} = L_{MECH}\sqrt{\varepsilon} \quad (3)$$

This equation takes into account the permittivity of the dielectric material and, therefore, the effective phase length the signal must travel through the dielectric material. In addition to physical length, changes in the electrical length can occur through temperature variations, frequency and mechanical stress (e.g., flexing, vibration). Phase stable coaxial cables are typically produced using extensive temperature conditioning or specialized dielectrics. These cables are particularly important in systems using multiple coax lines to feed signals from a common source or to collect signals from scattered sources. A good example is a phased array system, where intentional phase shifts are used to create constructive and destructive signal interference.

Skew takes into account two or more signal paths and is defined as the difference in time delay (also known as propagation delay) between the signal paths. Skew matching a pair of coaxial cables involves phase matching them to control the time delay. It is important for skew-matched cables to be phase stable to reliability and maintain low skew despite flexure and temperature variation. Typically, the skew between a coax pair is proportional to the channel-to-channel delay match, often measured in picoseconds. The VOP is also a value measured in cables and, ideally, will be consistent between two cables, whether or not the cables have a matching physical length or phase angle.

## SKEW-MATCHED COAXIAL CABLE CONSTRUCTION

As stated earlier, delay-matched coaxial cables, by nature, must be phase matched and are individually phase stable to consistently maintain a delay match on the order of picoseconds (ps), despite frequency, temperature or flexure. Phase changes during flexure cannot entirely be eliminated due to the change in cross-sectional area—the bend radius of the outer region is larger than the inner conductor. These minute inconsistencies in inner geometry change the electrical length. As shown by the previous equations, the time delay is directly proportional to mechanical length and the dielectric constant, so a phase stable coax necessarily has both mechanical and temperature stability. Extreme flexibility in both the shielding and dielectric are needed to maintain mechanical stability despite flexure. Seemingly benign solutions such as a cable restraint can prevent cable flexure from causing inconsistent changes in electrical length and larger than expected delays (see ***Figure 2***).



▲ Fig. 2 To minimize skew, matched coax cable assemblies should be constructed of the same materials and have the same mechanical orientation in use.

Changes in electrical length will inevitably occur due to the inner and outer conductor coefficients of thermal expansion, which indicates the growth or shrinkage of a material versus temperature. The metallic materials used for the inner conductor and shielding will grow and contract with temperature, causing a change in electrical length. This is often offset with dielectric cores such as expanded (microporous) polytetrafluoroethylene (ePTFE), where the dielectric constant decreases with an increase in temperature. This limits the change in phase that occurs with changing temperature. For these subtle reasons, simply purchasing two off-the-shelf coaxial cables of the same physical length and materials does not necessarily offer high delay match accuracies below 5 ps. The materials may not be phase stable, and the physical lengths may not be "identical." A 1 mm difference between cable lengths with an identical VOP of 74 percent equates to almost 5 ps difference in propagation delay between two lines, as shown by

$$\Delta\tau = \frac{L_{MECH1}\sqrt{\varepsilon_1}}{c} - \frac{L_{MECH2}\sqrt{\varepsilon_2}}{c} \quad (4)$$

Given this sensitivity, the electrical delay of the coaxial cables is not only a function of the cut of the transmission line, also the precision with which the connectors are attached.

## WHY PICOSECOND ACCURACIES

Parallel bus architectures have been sufficient for transferring data at medium data rates. These topologies, however, become far less economical when transferring greater data rates, i.e., Gbps, as designers have to add signal lines or increase clock frequency. Increasing the width of the parallel bus or adding lines increases the size of the system: I/O cells, pins and their respective interconnections. Increasing the clock frequency is not feasible, as all transmitted data needs to arrive at the receiver simultaneously. While this can be accomplished over short distances, crosstalk, inductive and capacitive noise coupling, and parallel data skew become unmanageable as the distance increases. Because of this, high speed serial buses using serializer/deserializer (SerDes) circuits are typically

**TABLE 1**

**OPTICAL TRANSCEIVERS**

| Form Factor | Data Rate (Gbps) | Line Rates |
|---|---|---|
| QSFP+ | 40 | 4 x 10G |
| CFP | 40, 100 | 10 × 10G or 4 × 25G |
| CFP2 | 40, 100 | 10 × 10G, 4 × 25G, 8 × 25G or 8×50G |
| CFP4 | 40, 100 | 4 × 10G or 4 × 25G Lanes |
| QSFP28 | 100 | 4 x 25 – 28G |
| CDFP | 400 | 16 x 25G |
| CFP8 | 400 | 16 × 25G Lanes or 8 × 50G Lanes or 4 x 100G |
| uQSFP | 100, 200 | 4 x 25 (NRZ), 4 x 50 (PAM4) |
| QSFP-DD | 200, 400 | 16 × 25G Lanes or 8 × 50G Lanes |

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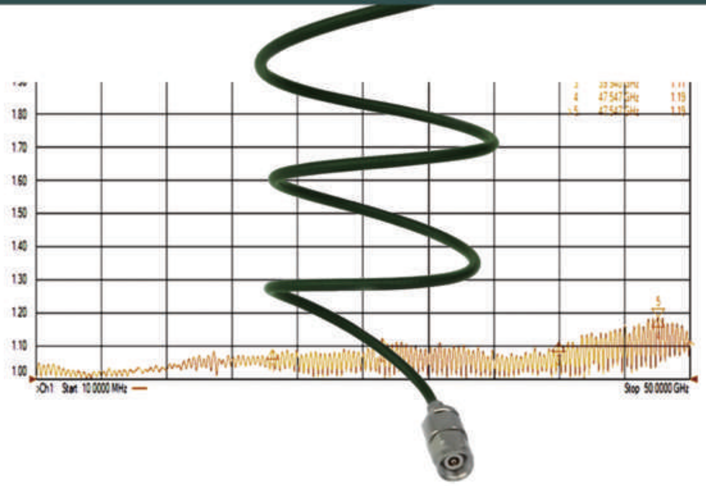

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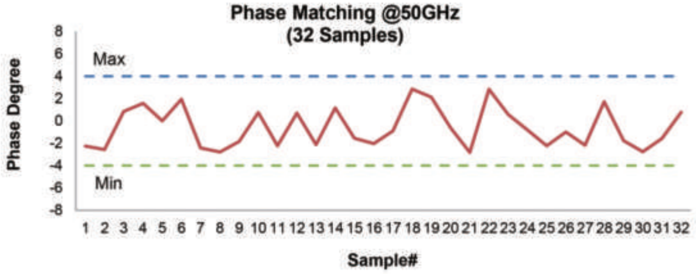


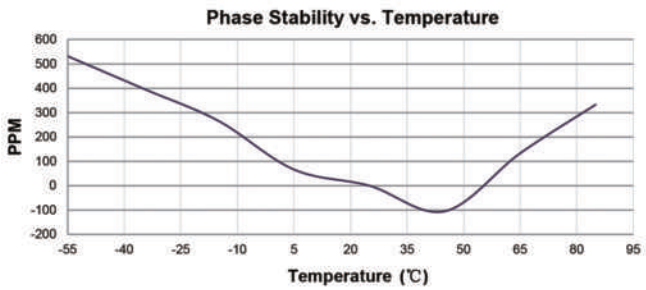


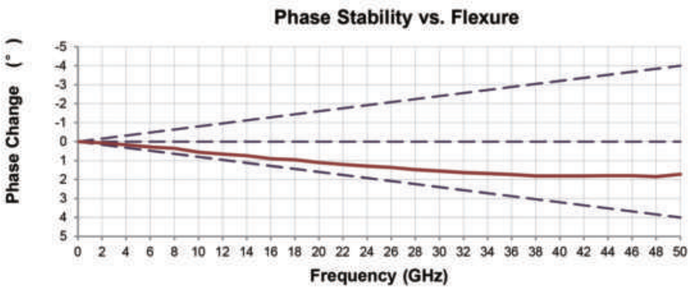


| Part Number | Frequency (GHz) | VSWR (Typ.) | Connector A (Male) | Connect B (Male) | Unit Price (EXW, 1~24pcs) |
|---|---|---|---|---|---|
| C29F-39-39-1M | 50 | 1.25 | 2.4mm | 2.4mm | $145 |
| C29F-40-40-1M | 40 | 1.25 | 2.92mm | 2.92mm | $119 |

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implemented for VLSI/LSI applications. In practice, it is simpler to synchronize one clock to the transmitted data versus synchronizing multiple lines of data.

Thus, it is critical to synchronize the serial data stream with the clock, known as clock and data recovery. The pulse waveform at the output of the differential receiver needs to maintain the high timing resolution of the original pulse signal, aligned with the rising and falling edges of the waveform. In any system, there is always inherent jitter contributed from the transmitter, making it increasingly important to discern jitter from the PCB or link (i.e., cable).

Embedded clocks have a frequency inversely proportional to the unit interval (UI), defined as the time duration of a pulse and measured in picoseconds. Eye diagrams are a useful tool for understanding the jitter of a differential signal, as the eye displays waveforms from multiple UIs, with either the embedded clock or a reconstructed one. As digital logic advances to support increasing switching rates, UIs become smaller. For example, a 12.5 Gbps clock frequency corresponds to an 80 ps UI (or bit length), and a 50 Gbps clock frequency corresponds to a 20 ps UI. Relevant performance metrics such as jitter can be difficult to discern in a test system with a relatively high differential skew. This is especially true in high data rate applications where the misalignment of rise and fall times generates a much less open eye. Electromagnetic analysis over wider bandwidths becomes important, as equipment such as oscilloscopes usually needs to capture up to the fifth harmonic to accurately reconstruct signals in the time domain. For a data link running at 28 Gbps, the analysis requires a bandwidth from DC to between 40 and 50 GHz. As CMOS technology evolves to support faster switching, it becomes increasingly important to minimize skew to enable testing over wider bandwidths without additional data-dependent jitter.

With Ethernet, current iterations of 40G and higher do not include a SerDes function; they use parallel, multi-lane architectures. The alignment of the parallel channels is accomplished through a striping function. The receiver physical coding sublayer performs skew compensation with alignment markers to reassemble 40G and higher aggregate datastreams. In theory, any lane can be used for clock recovery. As shown in ***Table 1***, optical transceivers for 40G, 100G and 400G contain four to 16 lanes, each offering 10 to 50 Gbps speeds. A minor offset in synchronicity between each lane can ultimately reduce waveform quality, making it increasingly necessary to measure parameters such as bit error rate and jitter with multichannel test equipment and obtain transmission media that adds minimal skew.

## CONCLUSION

The increased use of differential signal communication calls for reliable, delay-matched transmission lines with less than 1 ps skew. When coaxial assemblies are used as the medium, the cables must be very close to the same physical length and constructed of the same materials to ensure tight skew accuracy. Skew in a test system can limit the reception of a differential signal, adding deterministic jitter such as data-dependent jitter and causing errors in the received data. ■

# 40 GHz PCB Interconnect Validation: Expectations vs. Reality

**Marko Marin**
*Infinera*
**Yuriy Shlepnev**
*Simberian Inc.*

*The frequency content of digital signals in printed circuit board (PCB) interconnects increased up to 40 to 50 GHz in recent years. To ensure that interconnects work as expected over this bandwidth, we have to build validation boards. This article reports lessons learned from validation projects with the goal to build a formal procedure for systematic prediction of interconnect behavior up to 40 GHz.*

What does it take to design PCB interconnects with good analysis-to-measurement correlation up to 40 GHz? Is it doable with typical low-cost PCB materials and fabrication process, typical trace width, via back-drilling, and the shortage of space to place the stitching vias? Your EDA vendor shows excellent correlation of the analysis tools to measurements even up to 50 GHz, your PCB fabricator ensures that the board will be built as designed and provides all possible information on stackup and materials. Measurements with the easy-to-use TDNA or VNA should be also a "piece of cake." There is nothing to worry about and the designed interconnects should behave as expected.

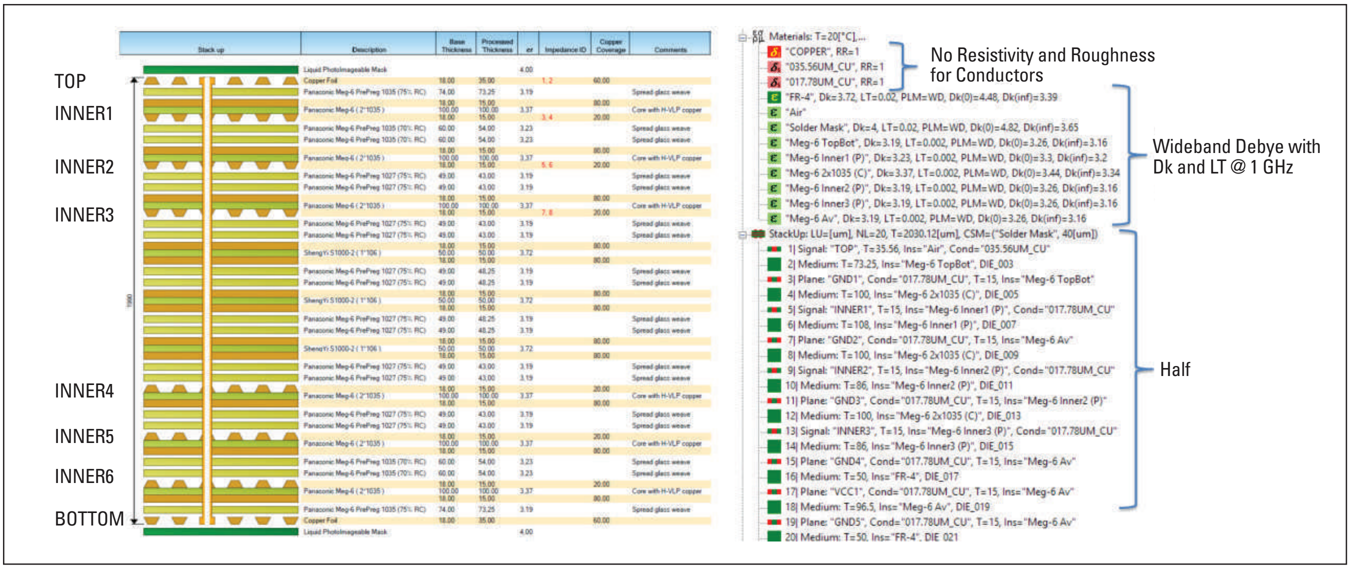
Unfortunately, many SI engineers quickly learn that this is not the case and the reality can be far from our expectations. To verify practically everything that goes into the design-to-manufacturing flow at this frequency bandwidth, we are actually forced to build validation boards. Moreover, re-validation has to be done every time when a new material or fabricator is used. The outcome of such validation should be a formal process, which allows us to reduce the gap between expectations and reality, reliably predicting the behavior of the interconnects on production boards over this bandwidth. In this article, we do not just show the final analysis-to-measurement correlation on a case-by-case basis, but instead report a formal procedure based on the material model and manufacturing adjustments identification.

## "SINK OR SWIM" VALIDATION

A key element of design success is the systematic benchmarking of manufacturing, measurements, and modelling. Systematic means analysis-to-measurement correlation observed not just for one or two structures (test coupons for instance), but rather for a broad range of typical interconnects—single-ended (SE) and differential (diff.), stripline and microstrip, simple planar and with the vertical transitions or vias, etc. Such comparisons should be done consistently both in frequency (magnitude and phase of S-parameters) and time (TDR and optionally eye diagram) domains. In other words, systematic validation or benchmarking is needed to make sure that the board is manufactured as designed, measurements are taken properly and, finally, that the interconnect analysis software provides acceptable accuracy. It is a huge project. Fortunately, there are a number of reports about similar projects to follow.[1-4] Here we will use the "sink or swim" approach.[4] It can be divided into seven steps:

1. Select materials and define PCB stackup with the manufacturer.


Maximize Coverage
Minimize Costs




▲ **Fig. 1 Validation board stackup (left) and the initial material models in Simbeor software (right).**

2. Design test structures with an EM analysis tool (simple links, launches, vias, etc.).
3. Manufacture the board and mount the connectors.
4. Measure S-parameters and validate quality of the measurements with formal quality metrics and visual inspection.
5. Do a cross-section of the board and identify the manufacturing adjustments, if any.
6. Identify broadband dielectric and conductor roughness models with GMS-parameters or Short Pulse Propagation (SPP) light techniques.
7. Simulate all structures with the identified or validated material models and confirmed adjustments. Compare consistently S-parameters and TDR with the measurements (no further manipulations with the data or “calibration” are allowed at this step).

The next sections of this paper outline the selection of the materials and board design with the stackup structure close to a typical production board. We then describe the measurement process, board cross-sectioning material parameters identification, and, finally, see how close to the reality we can get by following the process.

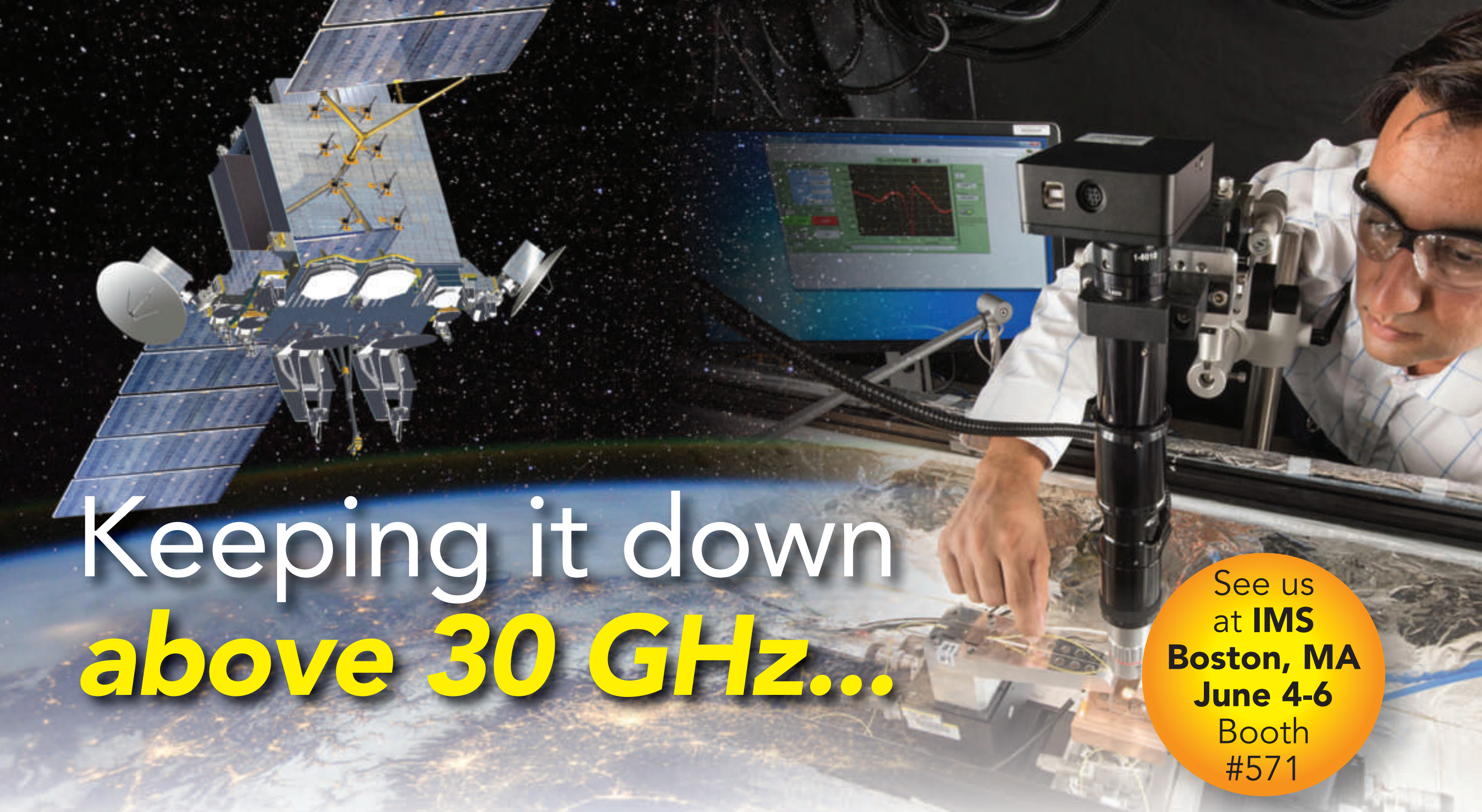
## VALIDATION BOARD

A validation platform, whether developed in house or purchased, is very important to pre-qualify a manufacturer, benchmark signal integrity software or learn how to do measurements in the microwave to mmWave bandwidths. The accuracy and limitations of the software can be easily identified with analysis-to-measurement comparisons on a typical set of interconnect structures. One of the first validation platforms was the physical layer reference design board (PLRD-1) from Teraspeed Consulting Group.[1] An example of a readily available validation platform is the CMP-28/32 channel modelling platform from Wild River Technology.[3]

Off-the-shelf validation platforms are convenient, but their stackup and interconnect geometry may not be representative for a production board. So, custom validation platforms with a stackup structure similar to a production board have to be used, as is done in this project. The board design starts from the material selection and stackup definition. We selected Panasonic Megtron6 material for the high speed routing layers. The board has 20 layers with eight layers assigned for high speed signals (see ***Figure 1***). The target impedance has been specified for the PCB manufacturer who has to fulfill it with eight percent tolerance. That is too large variation to expect good correlation even up to 40 GHz, but this is the typical choice for a production board. The manufacturer also provided expected trace widths and spacing adjustment. The stackup for the pre-layout analysis was defined (see right side of Figure 1). Megtron6 specs provide dielectric constant and loss tangent at multiple frequencies. It is expected that the Wideband Debye (aka Djordjevic-Sarkar) model (defined using the specs) provides a good approximation over the target frequency bandwidth.

In Figure 1, the values for Dk are the ones used by PCB manufacturer based upon their experience with this material. The major problem is with the conductor roughness model: the copper foil roughness is specified as H-VLP and no other data. PCB manufacturers also roughen the shiny side of the copper foil during board manufacturing, without any parameters for the electrical modelling. So, even if we had data for the matte side of the copper foil, the PCB manufacturer treatment of the shiny side would make it practically useless. Thus, we start without the conductor roughness model and with the trace adjustments provided by the PCB manufacturer. The structures on the validation board, then, should be useful for material model identification/validation. For identification with GMS-parameters[5] or SPP Light[6], we used two segments (5 and 10 cm) of differential or SE transmission lines for each unique layer. We also used the Beatty standard (series resonator) to confirm that the extracted models work for traces with different widths. The line segments used for material identification can also be used as tests for simple diff. and SE links (they are similar to the traces used on production boards). In addition, we decided to use structures typically used in interconnects for the serial and parallel interfaces: diff. and SE via-holes for each routing layer; AC coupling capacitors similar to used on SERDES links; meandering line segment similar to used on DDR links; and diff. link skew compensation structures. All are routed at an angle to the edge of the board to avoid the fiber weave effect. The final board layout with all structures is shown in ***Figure 2***.

The launches are the most impor-



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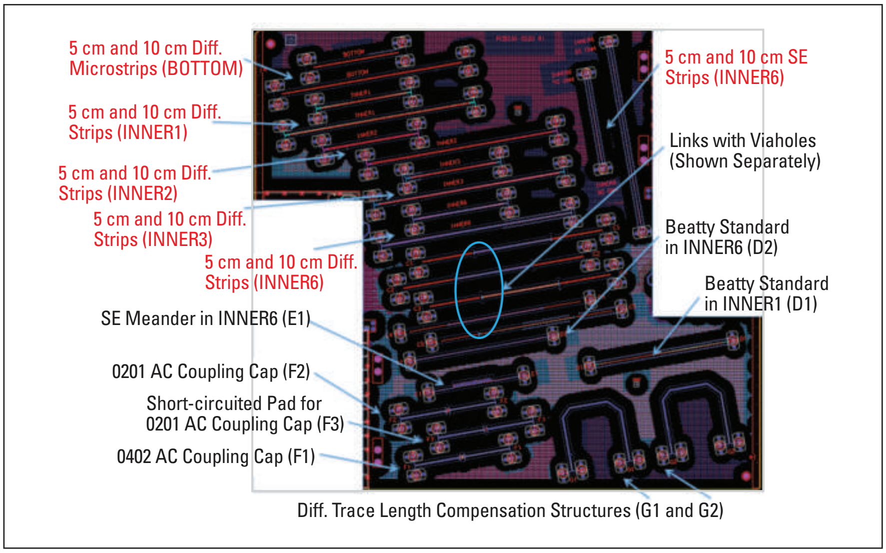
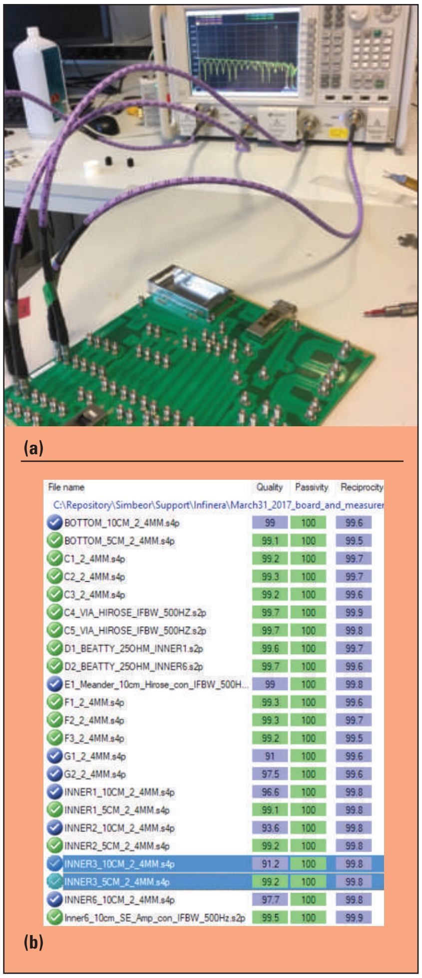



**Fig. 2** Layout of 20 layer validation board. Red legends are for the material identification structures.




| File name | Quality | Passivity | Reciprocity |
|---|---|---|---|
| C:\Repository\Simbeor\Support\Infinera\March31_2017_board_and_measurer | | | |
| BOTTOM_10CM_2_4MM.s4p | 99 | 100 | 99.6 |
| BOTTOM_5CM_2_4MM.s4p | 99.1 | 100 | 99.5 |
| C1_2_4MM.s4p | 99.2 | 100 | 99.7 |
| C2_2_4MM.s4p | 99.3 | 100 | 99.7 |
| C3_2_4MM.s4p | 99.2 | 100 | 99.6 |
| C4_VIA_HIROSE_IFBW_500HZ.s2p | 99.7 | 100 | 99.9 |
| C5_VIA_HIROSE_IFBW_500HZ.s2p | 99.7 | 100 | 99.8 |
| D1_BEATTY_25OHM_INNER1.s2p | 99.6 | 100 | 99.7 |
| D2_BEATTY_25OHM_INNER6.s2p | 99.7 | 100 | 99.6 |
| E1_Meander_10cm_Hirose_con_IFBW_500H... | 99 | 100 | 99.8 |
| F1_2_4MM.s4p | 99.3 | 100 | 99.6 |
| F2_2_4MM.s4p | 99.3 | 100 | 99.7 |
| F3_2_4MM.s4p | 99.2 | 100 | 99.5 |
| G1_2_4MM.s4p | 91 | 100 | 99.6 |
| G2_2_4MM.s4p | 97.5 | 100 | 99.6 |
| INNER1_10CM_2_4MM.s4p | 96.6 | 100 | 99.8 |
| INNER1_5CM_2_4MM.s4p | 99.1 | 100 | 99.8 |
| INNER2_10CM_2_4MM.s4p | 93.6 | 100 | 99.8 |
| INNER2_5CM_2_4MM.s4p | 99.2 | 100 | 99.8 |
| INNER3_10CM_2_4MM.s4p | 91.2 | 100 | 99.8 |
| INNER3_5CM_2_4MM.s4p | 99.2 | 100 | 99.8 |
| INNER6_10CM_2_4MM.s4p | 97.7 | 100 | 99.8 |
| Inner6_10cm_SE_Amp_con_IFBW_500Hz.s2p | 99.5 | 100 | 99.9 |

**Fig. 3** S-parameters measurement setup with 50 GHz VNA (a) and final Simbeor quality metrics (b), the metrics are in the process of standardization by IEEE T370 PG3.

tant elements of the validation board design, and they have to be optimized. If they reflect too much, they will likely be more susceptible to manufacturing variations and more difficult to de-embed for the material identification. The validation board was designed to have either 2.92 or 2.40 mm compression-mount connectors mounted on the TOP layer. We used connectors from two vendors. Five low-reflection launches were designed to connect the TOP and BOTTOM for structures with microstrip lines, TOP to INNER1, 2, 3 (with back-drilling), and TOP to INNER6 (with small stubs). Stackup/materials obtained from the manufacturer were used to simulate and optimize the launches, and they were designed to be functional up to 30 GHz.

At the end of the board layout phase we noted the following issues, which make the post-layout analysis inaccurate and practically useless for the target bandwidth:

- The PCB is manufactured with the "impedance control" process—all trace width and spacing adjusted by the PCB manufacturer must be accounted for in the post-layout analysis.
- No information on trace shape (etching).
- Ask shape/parameters.
- No information on conductor roughness model.
- No information on actual backdrilling.

## MEASUREMENTS AND GMS-PARAMETERS

The main goal during the measurement step is to have accurate high-quality S-parameters measured from 10 MHz to 40 GHz. Also, the S-parameters should be suitable for the extraction of the reflection-less GMS-parameters for material parameters identification[5] up to 30 GHz. Achieving this goal was the most challenging step in the project.

The board was manufactured as scheduled, and the S-parameters were measured first with TDNA. The formal quality metrics of these S-parameters was barely acceptable. Though, the visual inspection revealed a lot of noise in the S-parameters magnitudes. The GMS-parameters[5] computed with these S-parameters were also very noisy and considered not acceptable for the material identification. If we would proceed with the noisy GMS-parameters, the material identification becomes ambiguous above 10 GHz. Thus we decided to find other measurement options. For instance, we used a 26 GHz VNA, multiple 40 GHz VNAs and one 50 GHz VNA.

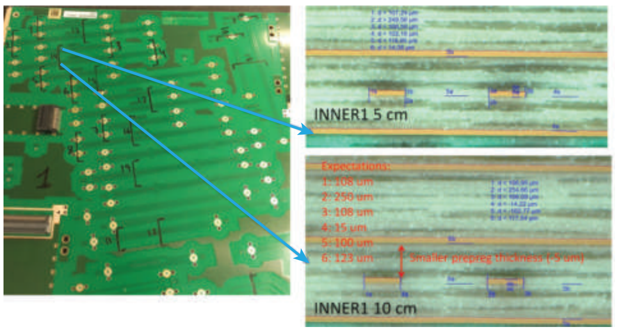
The final measurement setup with 50 GHz VNA is shown in ***Figure 3***. The measurements came out with the high formal quality metrics as shown on the bottom of the Figure 3. However, a closer look at the lower frequencies revealed a problem: the reflection parameters converge to incorrect values at frequencies below 70 MHz. The VNA vendor explained this as the defect of the electronic calibration kit. To overcome the problem and be able to identify conductor resistivity, we did additional measurements with a mechanical calibration kit, but it had lower bandwidth and was used for the resistivity identification only.

In regards to measurements, we stress that broadband measurements of S-parameters for signal integrity purposes are particularly challenging, and not all measurement equipment is suitable. SI problems require high accuracy over extremely broad bandwidth. Though at this step, the GMS-parameters are successfully extracted up to 30 GHz, which is sufficient to identify the frequency-continuous material models that are expected to work up to 40 to 50 GHz. Also, measurements down to 10 MHz are available to identify the copper resistivity.

## BOARD CROSS-SECTIONING

Before material parameters identification, we had to know the actual geometry of the traces for the material identification structures. As was observed in a similar project,[4] the actual geometry can be very far from expected, so the resulting analysis results can be unreliable.

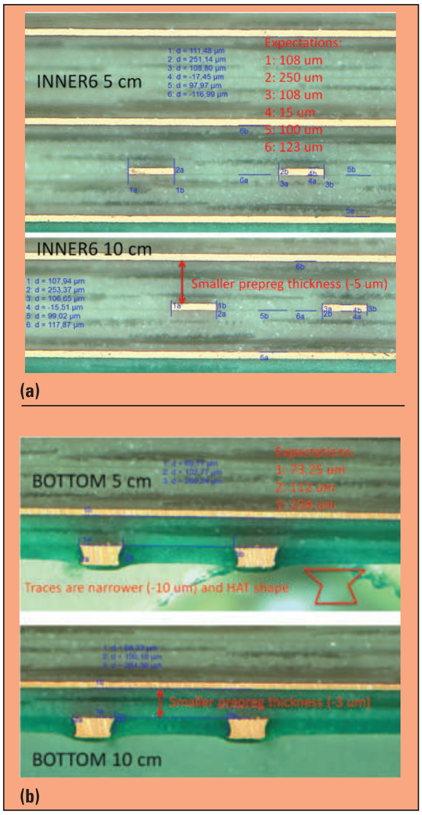





▲ **Fig. 4 Validation board cross-sectioning plan (a) and example of the cross-sectioning analysis for 5 and 10 cm links in layer INNER1 (b).**

Traces on the material identification structures, launches, Beatty in INNER6, and some viaholes have been cross-sectioned as shown in ***Figure 4***. This is not a statistical investigation but rather validation of our expectations based on the adjustments provided by the manufacturer. Analysis of the cross-sections of traces in layers INNER1 is shown in Figure 4 on the right. Analysis of the cross-sections in layer INNER6 and BOTTOM is shown in ***Figure 5***.

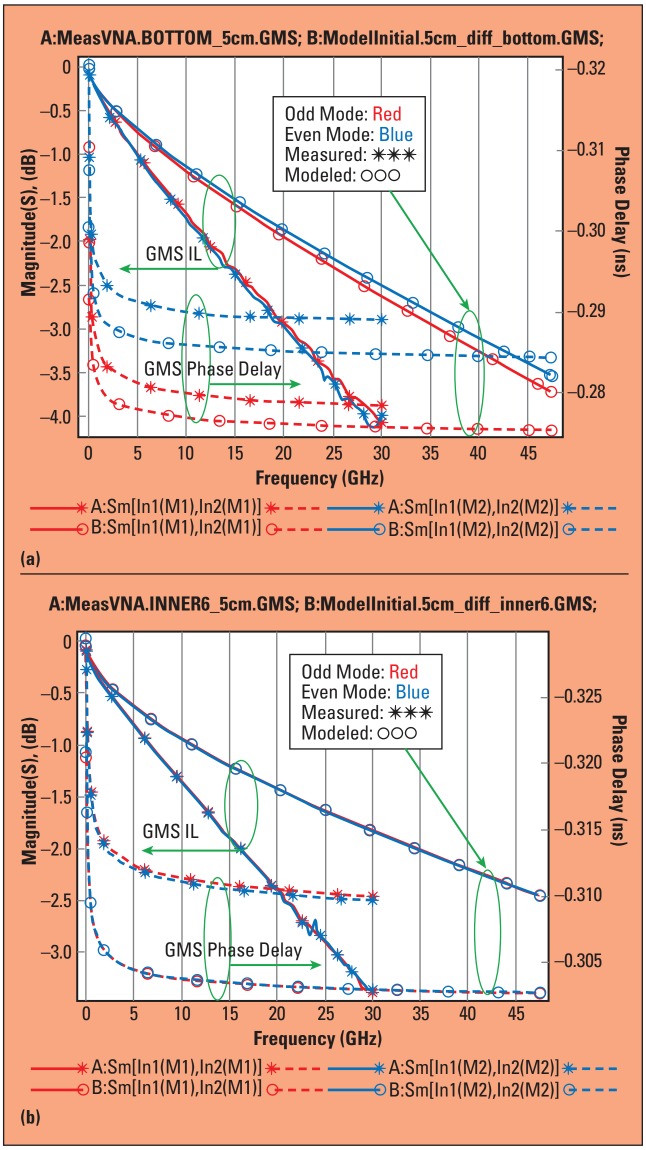
The first observation is that the prepreg layer thickness is 3 to 5 μm thinner than provided by the manufacturer (expectation column in Figures 4 and 5). With that adjustment, the thickness of the interior prepreg layers becomes closer to the thickness of the core layer. The second observation is that the geometry of the stripline traces are very close to the expectations. Even without the cross-sectioning, the material identification and analysis results would be very close. Though, it is totally different for the microstrips as we can see in Figure 5. The final trace width and distance adjustments are summarized in ***Figure 6***. The most critical adjustments for the microstrips are highlighted in red. The microstrip metal layer thickness is 48 μm instead of the expected 35 μm, and the solder mask layer has a thickness of 10 μm over the strips and 38 μm between the strips (that was not known in advance). The analysis with the microstrip geometry from the board layout or even with the adjustments obtained from the manufacturer would lead to characteristic impedance mismatch, about 3 ohm for the SE and about 6 ohm for the diff. microstrip traces. We can state that the analysis with the trace width and spacing specified in the original layout are not acceptable to provide good accuracy even below 10 GHz due to considerable impedance mismatch. The microstrip trace adjustments cannot be predicted and properly accounted for without the cross-sectioning. Though, the adjustments provided by the board manufacturer for stripline layers can be safely used. In addition to traces, some viaholes marked in Figure 4 were cross-sectioned and compared with the expectations: the results are available in the complete report.[7] At this point, everything is ready for the material models identification.




▲ **Fig. 5** Cross-sectioning analysis for 5 and 10 cm links in layer INNER6 (a) and in layer BOTTOM (b), large differences.

| Designed Trace Dimensions: | Dimensions From Manufacturer: | Dimensions After Cross-Sectioning: |
|---|---|---|
| BOTTOM: 120-250-120 [um] | BOTTOM: 112-258-112 [um] | BOTTOM: HAT (89/97)-260-HAT (89/97) [um] |
| INNER1/6: 110-250-110 [um] | INNER1/6: 107-250-107 [um] | IINNER1/6: 107-255-107 [um] |
| INNER2/3: 100-250-100 [um] | INNER2/3: 99-245-99 [um] | IINNER2/3: 96-254-96 [um] |
| INNER6 SE: 110 [um] | INNER6 SE: 109 [um] | IINNER6 SE: 109 [um] |
| Beatty Inner 1 and Inner 6: 110 um 2.5 cm, 330 um 2.5 cm | | Beatty Inner 6: 109 um 2.5 cm, 326 um 2.5 cm |

▲ **Fig. 6** Width-distance-width adjustments for the differential traces and width adjustment for SE traces (can be applied only for the impedance controlled segments).




▲ **Fig. 7** Measured (stars) and modelled without roughness (circles) GMS insertion loss and phase delay for 5 cm differential segment in layers BOTTOM (a plot, microstrips) and INNER6 (b plot, striplines).

## MATERIAL MODEL IDENTIFICATION

For material parameters identification, we used measurements obtained with 50 GHz VNA and electronic calibration kit. The measurements with the mechanical calibration kit are used to identify the copper resistivity for INNER6 layer only (used for all conductors).

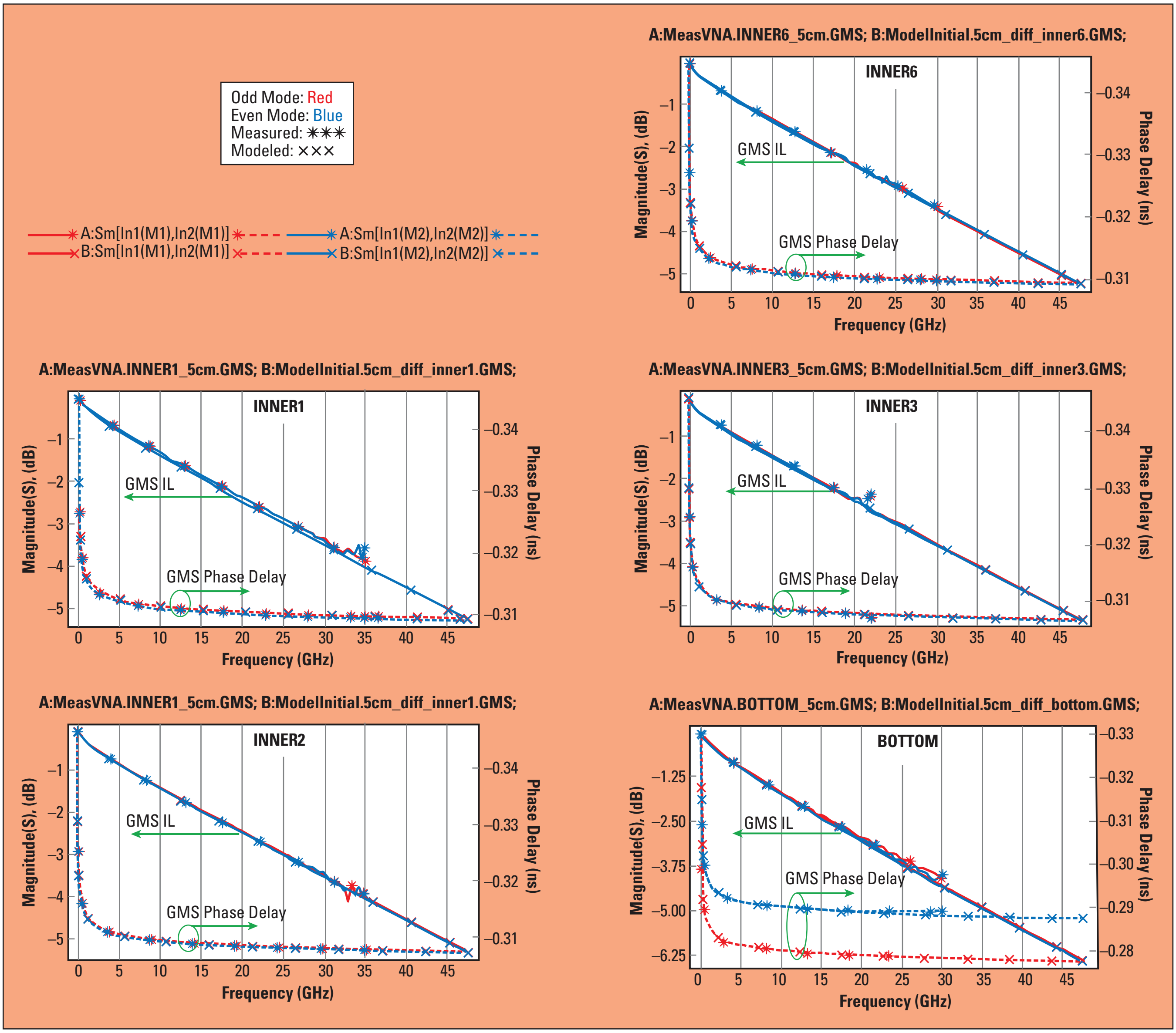
Generalized modal insertion loss and phase delay for differential microstrip and striplines are shown in ***Figure 7*** as an example of the initial measurement to simulation comparison. We can observe some differences in the modal phase delays—the model with manufacturer data predicts lower delays. More importantly, the measured and simulated modal insertion losses are dramatically different. Such difference makes any analysis with the spreadsheet or manufacturer data completely useless above about 3 GHz. This is due to the absence of data for the roughness model.

There are multiple ways to proceed with the material models identification[4,5]. Typically, raw or de-embedded S-parameters are used to "tune" a corresponding model (sometimes called "model calibration"). This is an acceptable technique, but it is too complicated due to the large number of non-zero S-parameters in the case of differential traces. The simplest way is to use just two GMS-parameters and the following formal process (identification with dielectric and conductor loss separation):

1. Identify copper resistivity by matching measured and simulated GMS insertion loss (GMS IL) at the lowest frequencies.
2. Identify dielectric constant (Dk) by matching measured and simulated GMS phase delay (GMS PD).
3. Identify loss tangent by matching GMS IL at lower frequencies (below 1 to 2 GHz) and re-adjust Dk to match GMS PD (changes in LT can affect the delay).
4. Identify the roughness model parameters by matching GMS IL at high frequencies (above 2 to 3 GHz) and re-adjust Dk to match GMS PD (roughness can also affect the delay).
5. Do it for all unique dielectrics in the stackup.

There are multiple ways to proceed with the material identification for this stackup. One option is to stick with the core/prepreg stackup structure and identify one model for the core dielectric and three models for the stripline prepreg layers. The table lists identified Wideband Debye models with Dk and LT at 1 GHz (the PCB manufacturer's spreadsheet data are in the brackets for comparison):

Causal Huray-Bracken models[8] with parameters SR = 0.098 μm, RF = 12.5 are used for all stripline layers. A non-causal model would produce about 2 ohm differ-




▲ **Fig. 8** Measured (stars) and simulated (x-s) GMS insertion loss (IL) and phase delay (PD) for diff. transmission lines in all unique layers.

| *Layer* | *Dk* | *LT* |
|---|---|---|
| Core (all layers 2x1035 weave) | 3.37 (3.37) | 0.003 (0.002) |
| Prepreg INNER1/6 (2x1035 weave, 70% RC) | 3.37 (3.23) | 0.003 (0.002) |
| Prepreg INNER2 (2x1027 weave, 75% RC) | 3.27 (3.19) | 0.002 (0.002) |
| Prepreg INNER3 (2x1027 weave, 70% RC) | 3.25 (3.19) | 0.002 (0.002) |

ence between the measured and modelled TDR impedance.[8] Conductor resistivity was adjusted to 1.2 of the resistivity of the annealed copper. Note that the "prepreg" and "core dielectric" parameters came relatively close to the spreadsheet data. This model would be perfect, except for one limitation. There will be too small a difference in the propagation velocity for the odd and even modes in the differential striplines to account for the far-end cross-talk observed in the measurements.

To account for the inhomogeneity of the layered dielectric, additional resin-rich layers around the strips are defined. "Resin-rich" in this context does not mean that this is a resin layer. It may contain different components that make properties of this composite material different from the layer with the fabric. The table on page 29 lists identified Wideband Debye models with Dk and LT at 1 GHz (PCB manufacturer spreadsheet values are in the brackets).

The conductor and conductor roughness models are the same as for the previous case. The material parameters for the microstrip layer were the same for the two cases with Dk = 3.40 (3.19), LT= 0.006 (0.002) for prepreg and Dk= 3.2 (4.0), LT= 0.02 for the solder mask (both Wideband Debye models at 1 GHz). Causal Huray-Bracken model parameters for the microstrip layer are SR= 0.229 μm, RF = 3.77 (rougher copper is used for the surface layers). Correspondence of the measured and identified GMS-parameters is shown in ***Figure 8***. There is a small difference in the phase delays of the even and odd modes in the strip layers (sufficient to

| Layer | Dk | LT |
|---|---|---|
| Core (all layers 2x1035 weave) | 3.37 (3.37) | 0.003 (0.002) |
| Prepreg INNER1/6 (2x1035 weave, 70% RC) | 3.17 (3.23) | 0.003 (0.002) |
| Resin INNER1/INNER6 | 3.562 | 0.003 |
| Prepreg INNER2 2-ply (2x1027 weave, 75% RC) | 3.124 (3.19) | 0.002 (0.002) |
| Prepreg INNER3 2-ply (2x1027 weave, 75% RC) | 3.09 (3.19) | 0.002 (0.002) |
| Resin INNER2/INNER3 | 3.425 | 0.002 |

account for the observed far-end cross-talk at about –30 dB). Everything finally looks good, and we are ready to proceed with the validation step.

## VALIDATION

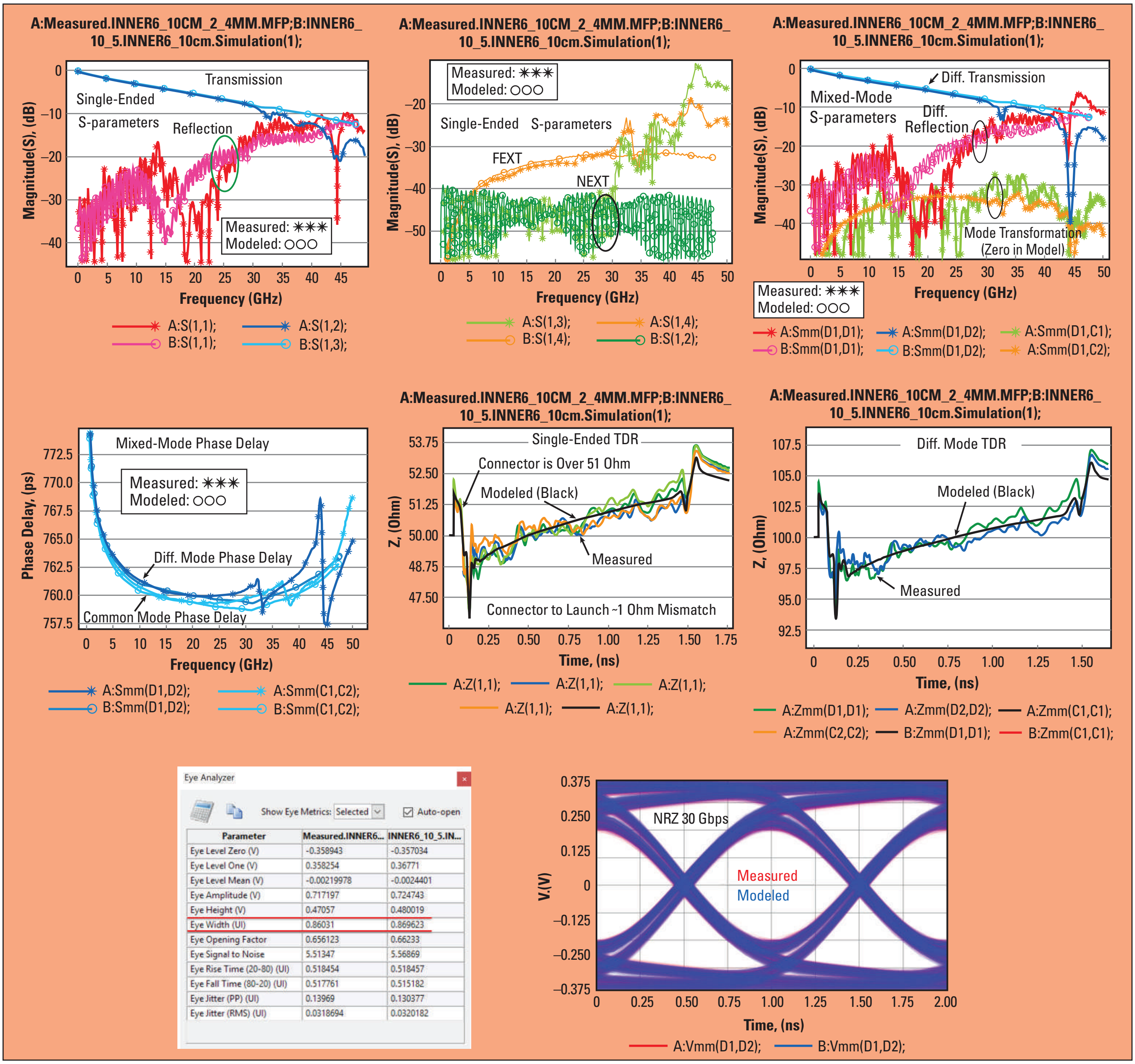
At the validation step, we simulated all structures on the board using the trace width and shape adjustments as well as the dielectric and conductor roughness models identified earlier. The layered dielectric structure with the "resin-rich" layer was used for all transmission line segments. No further adjustments were performed. The goal here is not getting a good fit between the measurements and models by tuning the model parameters and showing that we can achieve excellent correlation, but rather to see what accuracy can be achieved based on the formal material identification and limited number of cross-sections. This is the most important step to have confidence in the manufacturing, measurements, and modelling to reveal the potential problems.

To start the validation, we had to decide what was going to be modelled. We could either de-embed the connectors and launches from the measured data (simpler models) or create models of the measured links with the coaxial connectors and launches. De-embedding on PCBs is notoriously difficult due to the manufacturing variations.[1] We used it only for high-reflective structures, such as Beatty standard. The low-reflective structures are simulated with the connectors and launches. The model of the connector was simply synthesized from S-parameters measured for two connectors connected symmetrically back-to-back. In addition, models for all launches (PCB part) and discontinuities were built with 3D electromagnetic analysis as a part of the post-layout electromagnetic de-compositional analysis in Simbeor.

Comparing the magnitudes and phases of S-parameters is sufficient to make a decision on the accuracy or spot a problem. However, comparison in the time domain is usually also needed, and may help clarify problems. Comparison with a TDR/TDT response that is measured directly with a TDR scope requires modelling with the step function with the shape and spectrum matching the one used in the experiment. That approach has some uncertainties. Here the measured and modelled S-parameters could be used to do all time domain computations with exactly the same stimuli matching the bandwidth of the model. After all decisions on the modelling were made, we ran the post-layout analysis for all structures on the validation board and compared the magnitudes of S-parameters, phase delays, TDR computed with Gaussian step with 20 ps, 10 to 90 percent rise-time, and eye diagrams computed with 30 Gbps NRZ PRBS signal with 25 ps rise and fall time generated with LFSR with order 32.

An example of a detailed report for 10 cm differential stripline link in layer INNER6 is provided in ***Figure 9***. We observed acceptable correspondence in the SE as well as in the mixed-mode S-parameters, to have less than 2 percent difference in the modelled and simulated 30 Gbps eyes. Substantial discrepancies above 30 GHz on all structures are caused by break out of the launch localization. The main reason for discrepancies in the reflections below 30 GHz is the variation of the impedance along the transmission line that is not accounted for in the model. We do not know what caused these variations, perhaps non-homogeneity of the materials or non-uniformity of the trace cross-sections or both. If so, it would be practically impossible to include all of those variations in the analysis because of a lack of the statistical distributions of the geometry and material parameters. A summary report for 10 structures is provided in ***Table 1***.

The first three columns of the table list acceptable correlation bandwidth for the insertion loss (IL), reflection loss (RL) and far- and near-end crosstalk (FEXT and NEXT). Column TDR shows the approximate absolute difference in computed and measured TDRs for SE and diff. modes. The TDR excludes the connector-to-launch transition area, where a 1.5/3 ohm difference was observed on all structures. The eye column shows the difference between the simulated and measured 30 Gbps NRZ eyes. Additional observations are listed in the "Notes" column. A complete report for all structures on the validation board is available on request.[7]




| Parameter | Measured.INNER6... | INNER6_10_5.IN... |
|---|---|---|
| Eye Level Zero (V) | -0.358943 | -0.357034 |
| Eye Level One (V) | 0.358254 | 0.36771 |
| Eye Level Mean (V) | -0.00219978 | -0.0024401 |
| Eye Amplitude (V) | 0.717197 | 0.724743 |
| Eye Height (V) | 0.47057 | 0.480019 |
| Eye Width (UI) | 0.86031 | 0.869623 |
| Eye Opening Factor | 0.656123 | 0.66233 |
| Eye Signal to Noise | 5.51347 | 5.56869 |
| Eye Rise Time (20-80) (UI) | 0.518454 | 0.518457 |
| Eye Fall Time (80-20) (UI) | 0.517761 | 0.515182 |
| Eye Jitter (PP) (UI) | 0.13969 | 0.130377 |
| Eye Jitter (RMS) (UI) | 0.0318694 | 0.0320182 |

**Fig. 9** Example of detailed analysis to measurement correlation for 10 cm differential link in INNER6—acceptable correlation up to 30 GHz, about 2 percent difference in modelled and measured eye diagrams.

## TABLE 1
### ANALYSIS TO MEASUREMENT CORRELATION REPORT FOR 10 STRUCTURES

| Structure | IL (GHz) SE & MM | RL (GHz) SE & MM | FEXT & NEXT (GHz) | TDR (Ω)~ SE/MM | Eye (30 Gpbs, diff.) | Notes |
|---|---|---|---|---|---|---|
| ***INNER1***<br>***5 cm***<br>***10 cm*** | 25<br>25 | 15<br>15 | 30 | 1/2<br>1/2 | 1% EH & EW | There is uncertainty in the epoxy filling after the backdrilling, the launches is more inductive then predicted. DM/CM phase delay correlate up to 25 GHz. |
| ***INNER2***<br>***5cm***<br>***10cm*** | 30<br>30 | 25<br>25 | 30 | 1/2<br>1/2 | 1% EH & EW | Trace width seems to be 95 µm instead of 99 µm. Launch more inductive then predicted, PCB trace width variation. DM/CM phase delay correlate up 30 GHz. |
| ***INNER3***<br>***5cm***<br>***10cm*** | 30<br>30 | 30<br>30 | 30 | 1/2<br>1/2 | 3.6% EH, 1% EW | Core/prepreg dielectric models–layered anisotropy. Resonance frequency little lower than predicted. Launches have long stubs (not back-drilled). |
| ***D2 Beatty INNER6*** | 30 | 30 | N/A | 1/N/A | N/A | Loss and dispersion models work for much wider strips. Good correspondence in phase delay and TDR. |
| ***BOTTOM***<br>***5cm***<br>***10cm*** | 30<br>30 | 10-15<br>10-15 | 30<br>30 | 2/4<br>2.5/5 | 6% EH, 1.5% EW | More reflections from 10 to 30 GHz (investigate). Large variations of impedance (investigate). |
| ***C2 Diff. via INNER6 (backdr.)*** | 30 | 15 | 25 | 1/2 | 5% EH, 1% EW | Reality: differences in diff. reflection from 10 to 25 GHz and in transmission above 30 GHz. Made conversations in measurement up to -30 dB. |

## CONCLUSION

A systematic PCB interconnect analysis-to-measurement validation process is suggested and successfully used in this article. We outlined the minimal number of steps to have acceptable analysis-to-measurement correlation up to 30 GHz on most of the structures on the validation board. Technically, this is sufficient for the reliable analysis of 28 to 32 Gbps links. The design of launches and reference plane stitching localization degrades the correlation above 30 GHz. To extend the predictability up to 40 to 50 GHz, the launches have to be redesigned and manufacturing tolerances should be reduced.

The specificity of signal integrity problems also dictates very strict requirements for the measurement equipment—accuracy at low and high frequencies is equally important. The reality is that not all measurement equipment satisfies such requirements, and this is not common knowledge. Anyone with plans to purchase the equipment (or EDA tools) should try it first and evaluate S-parameters quality and validity, regardless of vendor. Validation boards are an excellent tool to do that. The selection of the measurement equipment and components caused substantial delay in this project.

We found that the identified dielectric parameters were very close to the vendor specs. Conductor roughness was the major contributor to signal degradation, no models were available in advance and analysis without proper conductor roughness models is useless. The Causal Huray-Bracken conductor roughness model provided good correlation in the losses and in the TDR impedance.

In conclusion, we should state that this is an ongoing project and we continue to investigate obtained data in preparation for the next validation board. We expect it will be actually predictable up to 40 GHz.■

**Acknowledgments:** The authors gratefully acknowledge Ingvar Karlsson, Kunia Aihara, Davood Khoda, Kenneth Jonsson, Matti Nuutinen, Andreas Agerstig and Magnus Svevar for their valuable help during this lengthy project.

*More detailed version of this article is available at www.signalintegrityjournal.com and this work was the basis of a Best Paper Award at DesignCon 2018. [www.signalintegrityjournal.com/articles/1002]*

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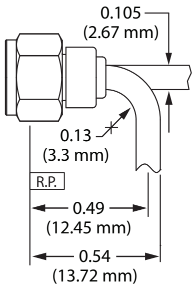
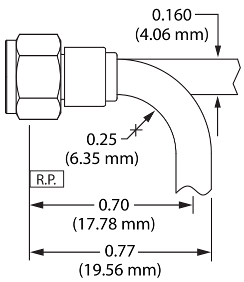



**ArcTite 141**

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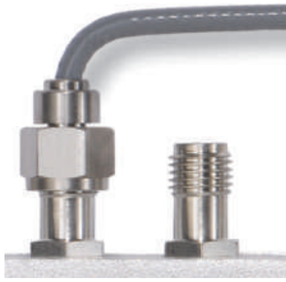

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single path to optimal performance

# 70 GHz Cabling Solutions for 5G and Beyond

**Junkosha**
*Irvine, Calif.*

Beyond the fundamental but highly technological challenges of ensuring the upcoming 5G network will work, there are several significant hurdles that will need to be overcome by operators. For example, spectrum availability is not limitless, with the radio frequencies of 3G and 4G increasingly crowded; 5G will have to operate at even higher frequencies to deliver the faster data speeds. This brings into play the mmWave band, which has its own unique challenges including the issues of reliability and ruggedness of cabling as a key hurdle. With median speeds of up to 1.4 Gbps at 28 GHz, 5G will be as much as 1000× faster than the previous incumbent (4G) in terms of download speeds. This step change in speed brings with it demands and complications never witnessed before in the wireless telecom segment.

Over the years, interconnects have gained a reputation as the weakest link in a system, especially when operating at the limit of performance. A new generation of cables has been developed that will stand up to the rigours of higher frequencies and in environments with high temperature and flexure. The challenge to companies like Junkosha who deliver these solutions—how to change engineers' perceptions of cabling and interconnects into the future?

## PHASE PERFORMANCE THAT ENDURES

At the higher mmWave frequency, "phase performance that endures" is a statement that cabling and interconnects must live up to, especially in the test and measurement environment. At these frequencies, interconnects are very small, meaning that connector design is a complicated activity. In addition, the amount of bending and stress the cabling is placed under is significant, resulting in an environment that requires phase stable cables to be installed. If the cabling is the first thing to let the engineer down, it remains the most system critical element in terms of reliability. This is why it is so important that engineers use cabling and interconnects that have been built for a 5G world.

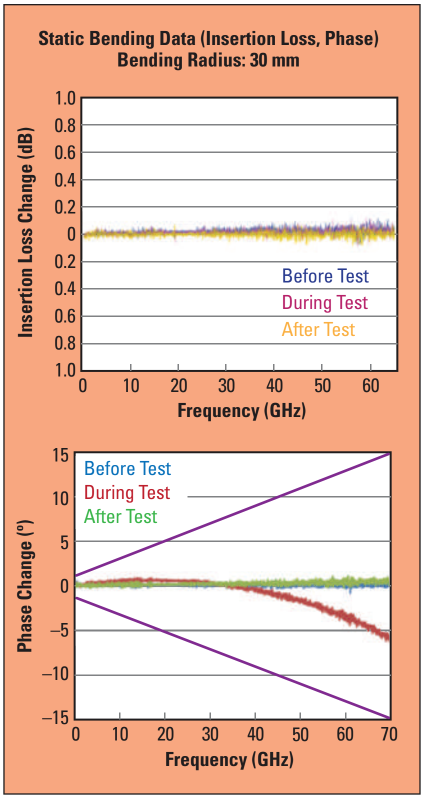
## HIGH PERFORMANCE CABLING INTERCONNECTS

As the move to 5G accelerates the requirement for more advanced "phase stable" interconnects, Junkosha has developed its latest mmWave cabling solution, the MWX071 (see ***Figure 1***), in a bid to go beyond the 70 GHz barrier. Designed for applications including faster wireless communications and military radar, Junkosha's latest interconnect provides Vector Network Analyzer (VNA) manufacturers with the capability to test very high frequency components that are at the heart of today's highly sophisticated systems.

With this latest mmWave interconnect, Junkosha is continuing its move to design solutions that will meet the higher frequency demands of tomorrow's 5G networks. Available with ruggedized NMD connector assemblies to deliver reliable and robust connections to the VNA, this new interconnect solution adds further breadth to the 5G oriented MWX0 series. The new MWX071 can be fitted with 1.85 mm M/F connectors making it the ideal system for precision measurements. It also features characteristics including a low dielectric constant and high flex life thanks to Junkosha's precision engineered expanded-PTFE tape wrapping technology, meaning this new interconnect meets the need for a future proof, highest quality, cabling solution.

***Figure 2*** shows the insertion loss and phase change of the MWX071 for bend testing. The cable was wrapped 360° around a 60 mm round mandrel. These cables are guaranteed within ±15 degrees at 70 GHz when delivered to the customer, though as can be seen typical deviation is around 5 degrees. ***Figure 3*** shows the phase change versus temperature for various frequencies ranging from 10 to 70 GHz. The cable was measured in a chamber every 20°C from –30°C to 90°C after one hour of stabilization at each point. The

▲ Fig. 1 MWX071 70 GHz mmWave cable.




▲ Fig. 2 Insertion loss and phase change vs. frequency for 360° bending test over 60 mm round mandrel.

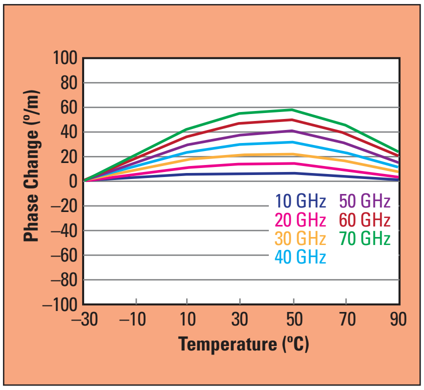
graph shows excellent phase stability over the different temperatures.

Junkosha's MWX071 adds breadth to its wide range of mmWave interconnects, which also includes the MWX051 and MWX061, both of which have also been designed for the 5G environment. Reaching up to 67 GHz, these mmWave cabling solutions have been created to withstand the most rigorous of testing environments for periods of approximately three and a half years (based on an internal Tick Tock test of 30,000 cycles, which equates to 30 tests per day, five days per week for 3.8 years).

## EXPANDED PTFE WRAPPING EXPERTISE

Expanded PTFE is the key material needed to deliver a low dielectric constant, high flexure and phase stability in flexure and temperature deviation, all the desired attributes that are vital for mmWave data communications. At the core of Junkosha's innovations are the company's legacy fluoropolymer expertise and precision engineering which enables this unique expanded PTFE tape wrapping technique.

It is this technique, uniquely implemented by only two manufacturers in




▲ Fig. 3 Phase stability over temperature for frequencies from 10 to 70 GHz.

this sector, that allows Junkosha to deliver a flexible cabling assembly at these high frequencies that provides "phase performance that endures" over time.

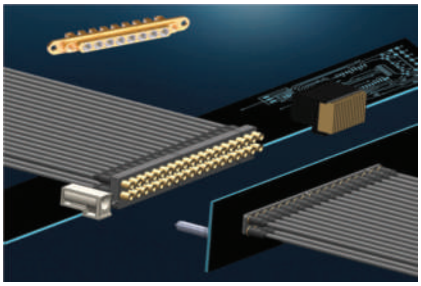
## A CONNECTED FUTURE

According to Masaru Omoto, product manager for Junkosha: "The demand for mmWave frequencies is no longer the preserve of military and research applications. 5G and high speed data applications are now driving innovation. For those familiar with the 'Secret of Junkosha,' it will be no surprise that we are continuing to push the boundaries of what is possible in the world of high frequency interconnects. A key enabler is our expertise and pedigree in expanded PTFE tape wrapping, which has allowed us to deliver flexible phase stable cables that endure."

Lassi Kuosmanen, COB, partner at Signal Solution Nordic Oy, adds: "5G is our future, and we need to embrace it. It won't stop there either. We are continually asked for cabling solutions that take us beyond current speeds and frequencies, moving us to a highly connected world in the future. However, with significant change comes significant challenges that will affect us all. The cabling and interconnects, often cited as the weakest link of many systems, is one such area that is in need of innovation. Thanks to organizations like Junkosha, interconnect innovations are at the heart of what they do, enabling future technologies for 5G that will bring about a wireless network that will change the mobile telecoms space forever."

**Junkosha**
**Irvine, Calif.**
**momoto@junkosha.com**
**www.junkosha-mwx.com**





# Microwave and mmWave Interconnects

Delta Electronics Mfg. Corp. continues to roll-out stackable Gang-Mounted RF/microwave interconnect designs. The latest design is end-to-end stackable to keep centerline distances tight and uniform. These designs are single or double row, but could accommodate additional rows, should the demand/need require the feature. The multi-port design is based around the 65 GHz rated SMPM style interconnects, with external keying features. The actual housing blocks are modular in scope, and are offered in sizes 2, 4, 8 or 16 position, with other positions available on demand. Terminations are thru-hole, surface mount, edge-launch or cable termination ready. A precision locating keying features minimal tolerance stack-up, allowing for up to four multi-port modules interlinked. Engagement/disengagement forces need to be considered, when stacking multiple modules. Typical engagement force of a single port is 1.5 lbs., while disengagement force is 1 lb. typical. The board-to-board spacing, as well as, the locating pin and receptacle, conform to the VITA 67.2 industry standard. Delta's fully vertically integrated facilities, with horizontal milling capabilities, allows for housing generation as well as the complete coaxial connector manufacturing cycle.

Gang-Mounted design efforts by Delta have incorporated a variety of RF/microwave push-on interfaces, including either hermetic or weather-sealed options for external box applications. Gang-Mount cable assemblies are available in a multitude of connector interfaces: all slide on- SMA, SMB, SMP, SMPM, among others. The assemblies utilize industry standard semi-rigid (.047, .085, .141) or flexible cable equivalents.

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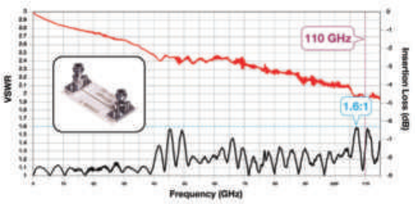
# Board-Mounted 1 mm Vertical Launch Connector




Southwest Microwave has developed the industry's first 1 mm, board-mounted, vertical launch connector, achieving low insertion loss and VSWR to 110 GHz. The maximum insertion loss of the 24359-001J connector is 0.6 dB, with VSWR better than 1.18:1 to 50 GHz and no greater than 1.25:1 across the complete 110 GHz bandwidth. The data shown in the graphic represents the measured insertion loss and VSWR of two 1 mm connectors mounted on a 5 mil thick test board fabricated with Rogers RO3003 material, connected with a thru transmission line.

The 24359-001J female connector is mode free with a stable phase response and leakage better than –100 dB through 110 GHz. The operating temperature range is –55°C to +165°C.

Providing excellent signal integrity for microstrip and grounded coplanar waveguide designs, all of Southwest Microwave's vertical launch connectors are reusable and can be installed without soldering. Southwest Microwave also offers board-mounted vertical launch connectors in 1.85 and 2.92 mm configurations, covering DC to 67 and DC to 40 GHz, respectively. These connectors feature a common two-hole flange mounting footprint, with the flange mounting holes tapped for screws to be inserted from the bottom of the PCB. The connectors can be supplied with screws sized for various board thicknesses.

Board designers are always motivated to reduce the footprint of connectors; however, the design of a right-angle launch with good performance to 110 GHz is quite challenging. The success of the 24359-001J design reflects the long experience of the Microwave Product Division of Southwest Microwave, established in 1987.

**Southwest Microwave**
**Tempe, Ariz.**
**mpd.southwestmicrowave.com**

## Anoison PLEX Series Cable

Anoison, known for not only the best solutions for your RF/microwave interconnect requirements, but also the most value with outstanding quality and fast delivery, now offers ANOISON PLEX, a high frequency flexible coaxial cable series. Using special expanded PTFE tape dielectrics and combined with their broad range of RF/microwave connectors, the PLEX series allows the creation of high performance assemblies with excellent loss, VSWR and phase stability. PLEX is the answer for many applications including VNA test cables and radar systems.

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## Cobham Phase Matched Cables

VENDORVIEW

Cobham cable assemblies are featured in military, space and high performance commercial applications. Cables range from 0.09 in. diameter FZ09, a very flexible cable, to the large 0.92 in. diameter FE92 flexible cables, with extremely low insertion loss for special ground-based applications. Cables boast excellent electrical performance, proven reliability and overall mechanical strength, providing the best cable-to-connection transitions in the industry. Designed and manufactured in a single location, customers receive full cable assemblies tested to their specific requirements.

**Cobham Advanced Electronic Solutions**
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## Receiver Products

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The power of repeatable and reliable performance! DynaTest™ series cable assemblies offer exceptionally low VSWR and insertion loss characteristics across a broad frequency range: DC to 40 GHz. These assemblies are highly flexible and are ideal for testing switch matrices or high density backplanes. Featuring spacing < 0.5 in. centerlines, SMA hex/knurl coupling nuts facilitate quick mating, stainless steel connectors, excellent strain relief at cable-connector junction and 100 percent RF tested.

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## LLS290 18 GHz Low Loss Coax

Harbour developed LLS290 to achieve the lowest possible insertion loss at 18 GHz by utilizing expanded PTFE dielectric and proprietary shielding. The expanded PTFE dielectric provides velocity of propagation greater than 80 percent. The manufacturing process ensures excellent phase stability over temperature. The LLS290 is smaller and lighter compared to solid dielectric coax. The proprietary shield design provides < –110 dB shielding effectiveness.

**Harbour Industries LLC**
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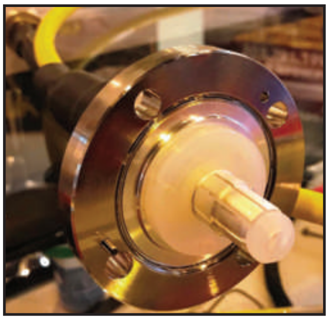

## 1-5/8 EIA Flange

IW is pleased to introduce a 1-5/8 EIA flange for use with 4806 cable. Cable attachment method is solder clamp to ensure minimal impedance variation and low VSWR, and body material is brass to provide optimum thermal performance. Flange assemblies can be supplied with the interface bullet if required. Customer testing has proven 4806 capable of handling 17 KW at 13.56 MHz for semiconductor material processing and is also widely used for EMC testing and other high-power commercial and military applications.

**IW Microwave Products Division**
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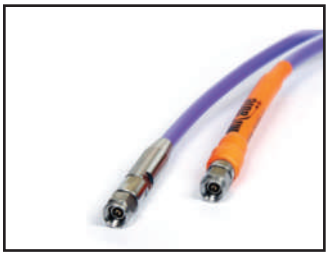
# Cables & Connectors

COMPANY SHOWCASE



## T26 Series High Performance Test Cables

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**MIcable Inc.**
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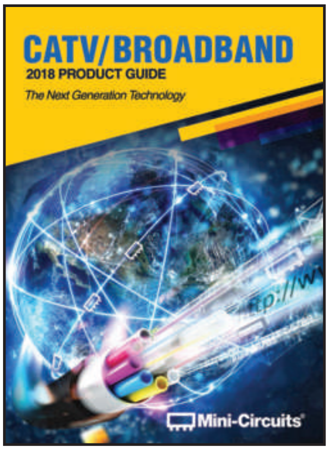


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As consumer demand for higher data capacity continues to intensify, network operators deploying optical and hybrid-fiber-cable (HFC) infrastructure continue to push the limits of their equipment under the DOCSIS® 3.1 standard. Mini-Circuits' CATV/Broadband product guide provides information on a wide range of components from passive devices including transformers, couplers and splitter/combiners to active elements including amplifiers, equalizers and more.

**Mini-Circuits**
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## RF Interconnect Products

Richardson RFPD provides a comprehensive RF Interconnect product and vendor portfolio. From high-end, space-qualified coaxial cables, connectors, attenuators and terminations to low-cost, commercial-grade solutions, they stock all major transmission line components for a range of applications, including wireless infrastructure, microwave telecommunications, military RF installations, radio tower sites, satellite Earth stations, navigation systems and broadband. Given their extensive applications engineering experience, product knowledge, technical aptitude and flexibility, Richardson RFPD is ready to supply all of your RF Interconnect product needs.

**Richardson RFPD**
**www.richardsonrfpd.com/interconnect**


## New Series RPC-1.35 Connectors

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**Rosenberger**
**www.rosenberger.com**

## Lab-Flex® T Series

Lab-Flex® T cable assemblies are mechanically robust and specifically designed to minimize phase change while maintaining excellent return loss when subjected to a wide range of operational temperatures; an ideal fit for radar, satellite and test applications. Their special foam dielectric material provides a much lower attenuation than solid PTFE. Precision Connector interfaces meet MIL-STD-348 requirements and are designed for maximum frequency capability up to 50 GHz. T cables are pretested and available in standard mechanical lengths or phase-matched electrical lengths as needed.

**Smiths Interconnect**
**www.smithsinterconnect.com**

## High-Power Adapters of Series 8058

Spectrum Elektrotechnik GmbH is introducing High-Power 18 GHz Adapters of Product Category 8058-, which shows Series and In-between Series Adapters of Types N and TNC. The units use special heat dissipating dielectric between Center Conductor and Outer Conductor, and have Cooling Fins to dissipate power to the environment. In addition, the High-Power Hermetic Sealed Adapter Series have been expanded as well, now operating to 18 GHz for N and TNC Series.

**Spectrum Elektrotechnik GmbH**
**www.spectrum-et.org/**

## COMPANY SHOWCASE

### Protecting Active In-Building Solutions

VENDORVIEW

SPINNER's Power Protector prevents sudden high-power surges from damaging low-power devices. It monitors the power carried by RF transmission lines and automatically interrupts it if it exceeds a predefined threshold. A typical application is monitoring the connection between a BTS module and an In-Building master unit. Beside protecting devices, this also lets operators achieve significant cost savings with BTS and A/C by safely operating the BTS in low-power mode.

**SPINNER**
**www.spinner-group.com**

### Clarity™ Series 40 GHz Test Cables

VENDORVIEW

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

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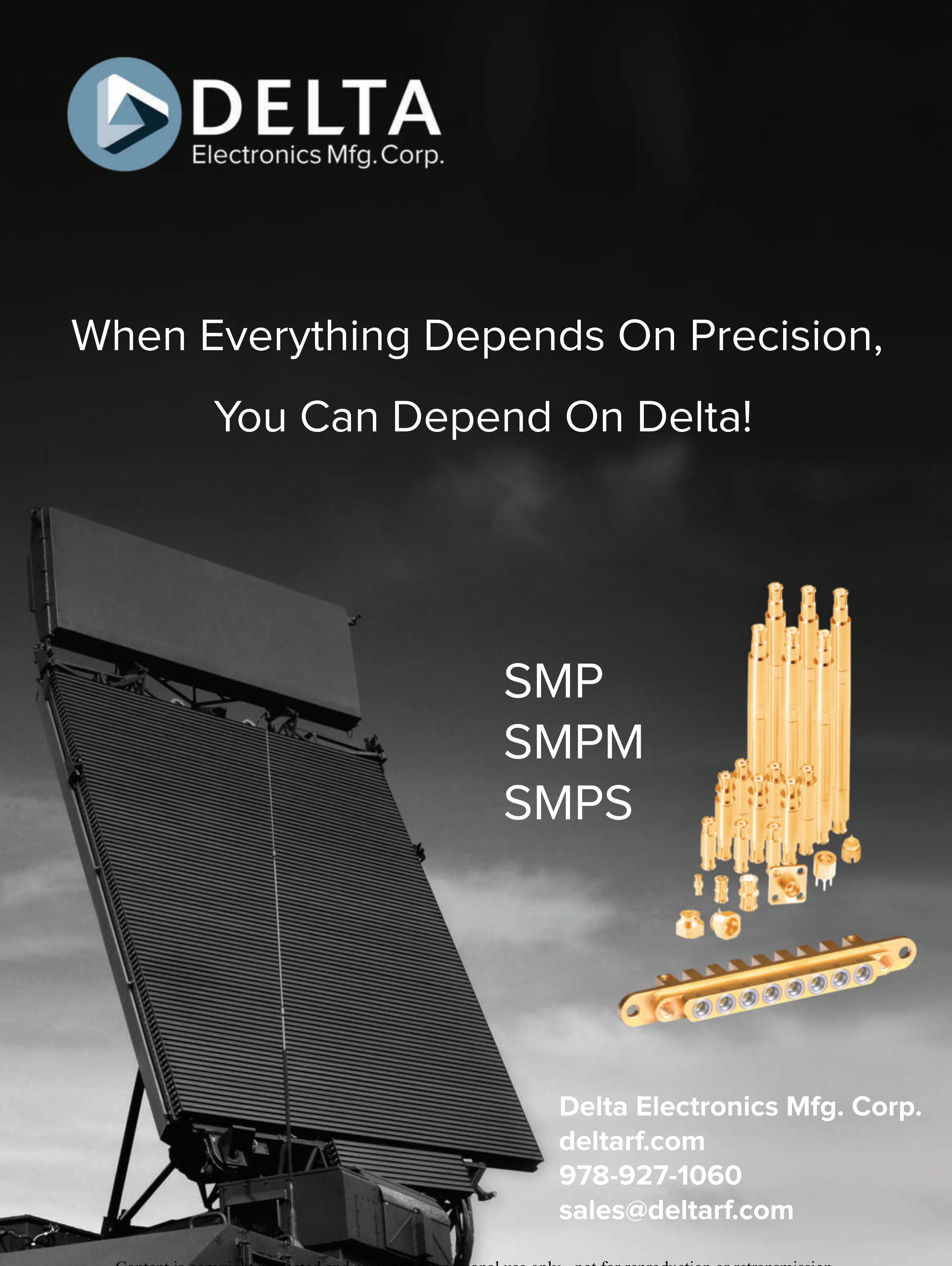
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