A "How-to" on Designing and Analyzing a 5G 28-GHz Phased-Array Transmit Chain p27

The Wireless Product Explosion Drives Up Demand for PCB Antennas p51

This New Series of Oscilloscopes Takes on All Test Scenarios p56

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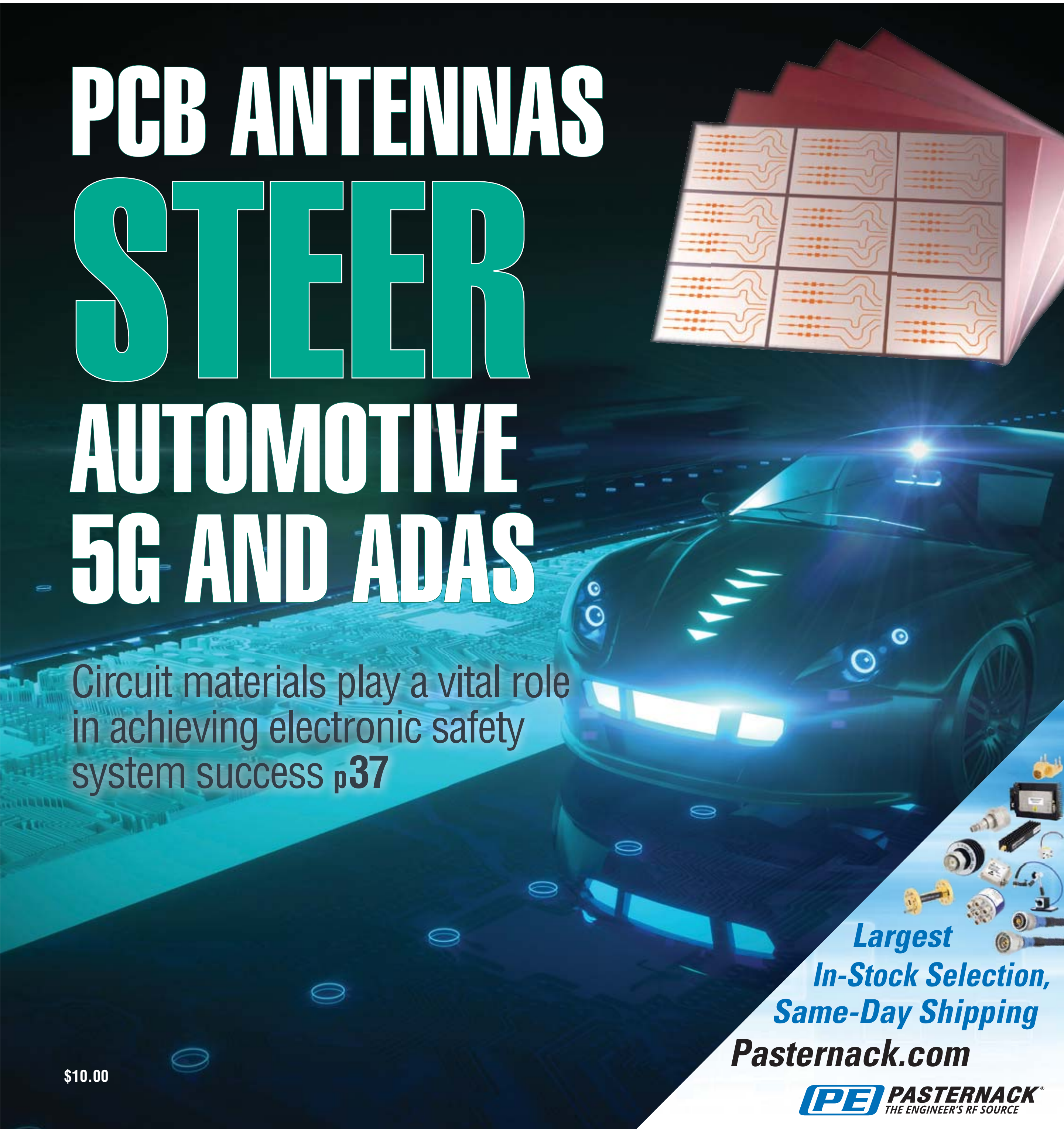

PCB ANTENNAS STEER AUTOMOTIVE 5G AND ADAS

Circuit materials play a vital role in achieving electronic safety system success p37

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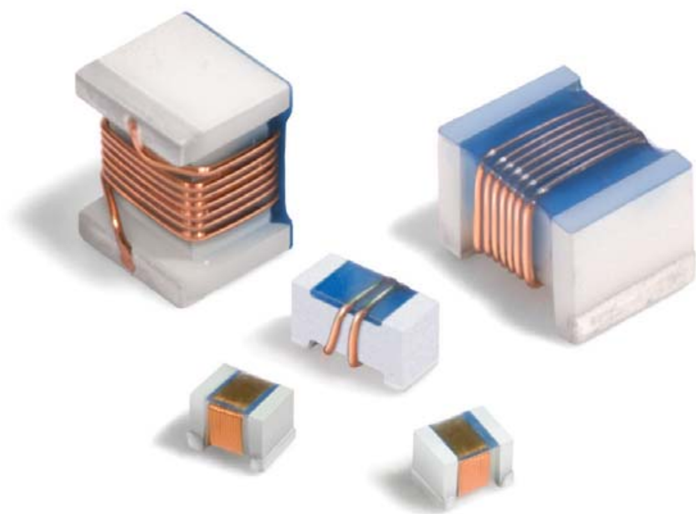

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IN THIS ISSUE

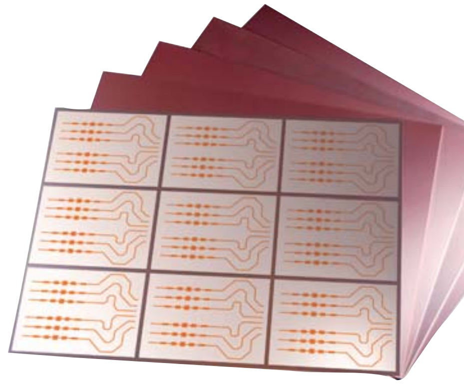
FEATURES

27 **Dissecting a 5G 28-GHz Phased-Array Transmit Chain**
This article presents the design, simulation, and analysis of a 5G 28-GHz phased-array transmit chain, implementing electromagnetic circuit excitation and co-simulation.

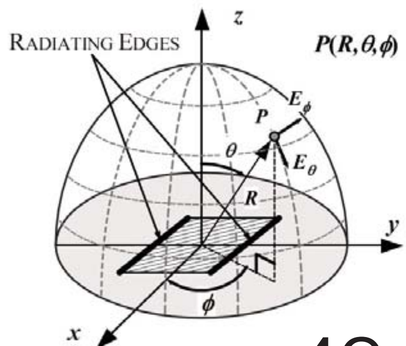
37 **Circuit Materials Secure Automotive Safety Systems**
Future automotive electronic safety systems based on radar and wireless communications will rely heavily on printed antennas, and circuit materials will play a key role in their creation.

40 **A Brief Tutorial on Microstrip Antennas (Part 1)**
This article, the first of a multi-part series on microstrip antennas, discusses antenna characterization—from antenna parameters to key attributes.

47 **Interconnect Quality, Phase Stability Can Make or Break 5G Future**
It seems like 5G communications grabs lots of headlines, while interconnects often fade into the background. Junkosha's Joe Rowan reverses that trend, answering questions on the crucial roles they play in the 5G era.



37



40

NEWS & COLUMNS

10 **ON MWRF.COM**

13 **EDITORIAL**
Harris and L3 Merge into Top 10 Contractor

18 **NEWS**

24 **R&D ROUNDUP**

44 **APPLICATION NOTES**

62 **NEW PRODUCTS**

64 **ADVERTISERS INDEX**

PRODUCTS & TECHNOLOGY

51 PCB Antenna Demand Skyrockets in Wireless Design

53 Downconverter Tackles 12 mmWave Channels

54 Arbitrary Function Generators Redefined

56 These Oscilloscopes Don't Leave Any Application Behind

58 Average Power Sensors Don't Settle for Average Performance

47

54

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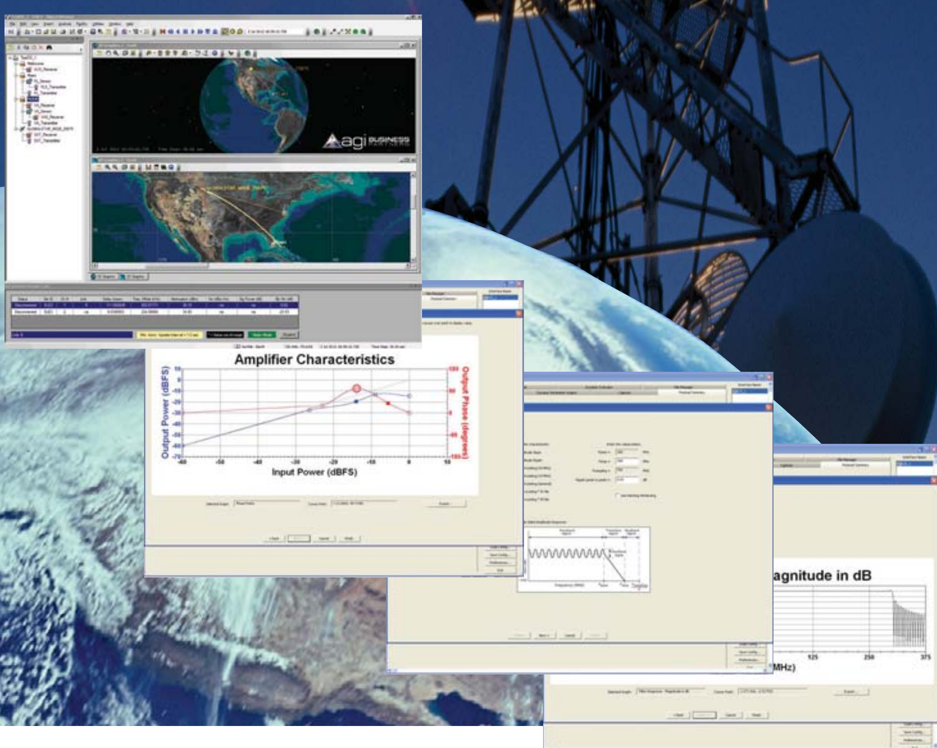

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From Farm to Fork: A Wireless-Sensor Approach to Food Safety

How can restaurants take advantage of wireless sensors based on LoRa technology to monitor food temperature? Laird's Jonathan Kaye offers his comprehensive take on this rising trend.

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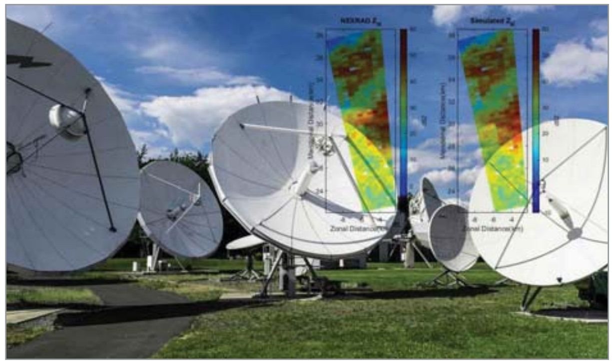
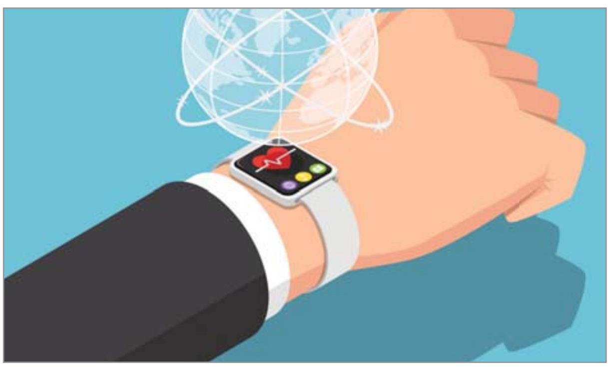


Modeling Polarization in Radar and Wireless Systems

How do you analyze polarization? This latest "Algorithms to Antennas" post from MathWorks' Rick Gentile examines polarized antennas and polarization signatures, and then presents a weather radar example to illustrate the analysis process.

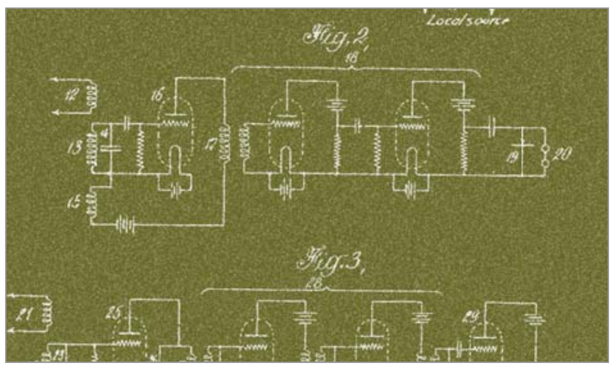
https://www.mwrf.com/systems/algorithms-antenna-modeling-polarization-radar-and-wireless-systems



Wearable Wireless is Becoming Fashionable

Combining function with fashion: Wireless technology extends well beyond cell phones to a host of often interconnected wearable wireless devices in support of personal healthcare and location tracking.

https://www.mwrf.com/systems/wearable-wireless-becoming-fashionable



A Selected History of Receiver Innovations Over the Past 100 Years (Part 2)

Wrapping up the two-part series on receiver technology, this second article picks up where the first one left off by examining the superheterodyne architecture and more.

https://www.mwrf.com/systems/selected-history-receiver-innovations-over-last-100-years-part-2

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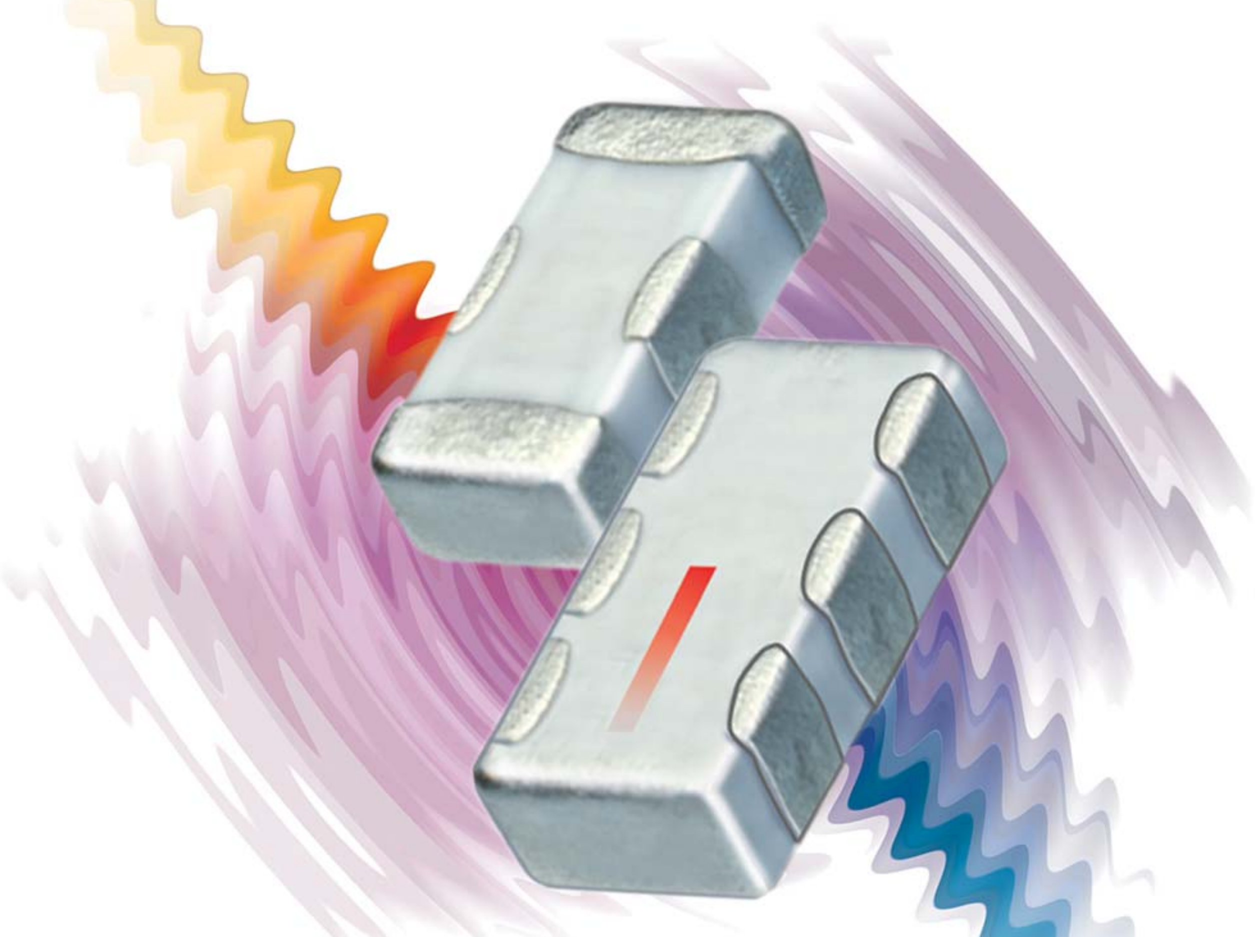

Editorial

JACK BROWNE | Technical Contributor
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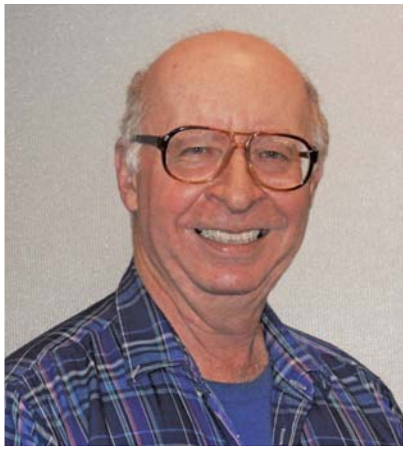
Harris and L3 Merge into Top 10 Contractor



In what will be one of the largest mergers in defense electronics history, Harris Corp. and L3 Technologies have agreed to a transformational all-stock merger of equals. The resulting combined company, L3 Harris Technologies, will be the sixth largest U.S. defense contractor, with 48,000 employees worldwide and about $16 billion in annual revenues.

With customers in more than 100 countries around the world, the new combined company—to be headquartered in Melbourne, Fla.—would be ranked about 180th on the latest Fortune 500 list of top worldwide companies. The two businesses are largely complementary, merging into a global defense technology leader with a wide range of capabilities.

The merger agreement was unanimously approved by the boards of directors of both companies. L3 shareholders will receive a fixed exchange ratio of 1.30 shares of Harris common stock for each share of L3 common stock, consistent with the 60-trading-day average exchange ratio of the two companies. Upon completion of the merger, Harris shareholders will own approximately 54% and L3 shareholders will own approximately 46% of the combined company on a fully diluted basis. The combined company is expected to generate earnings before interest and taxes (EBIT) of $2.4 billion and free cash flow of $1.9 billion.

"This transaction extends our position as a premier global defense technology company that unlocks additional growth opportunities and generates value," said William M. Brown, president and CEO of Harris Corp.

"This merger creates greater benefits and growth opportunities than either company could have achieved alone," concurred Christopher E. Kubasik, chairman, president, and CEO of L3. "The companies were on similar growth trajectories, and this combination accelerates the journey to becoming a more agile, integrated and innovative non-traditional 6th Prime focused on investing in important, next-generation technologies.

"L3 Harris Technologies will possess a wealth of technologies and a talented and engaged workforce," he continued. "By unleashing this potential, we will strengthen our core franchises, expand into new and adjacent markets and enhance our global presence."

The combined company will have a 12-member board of directors, drawing six board members from each of the formerly separate companies. Brown will serve as chairman and CEO, while Kubasik will serve as the vice chairman, president, and COO for the first two years following the closing of the transaction. For the third year following the merger, Brown will transition to executive chairman and Kubasik to CEO, after which Kubasik will become chairman and CEO. mw

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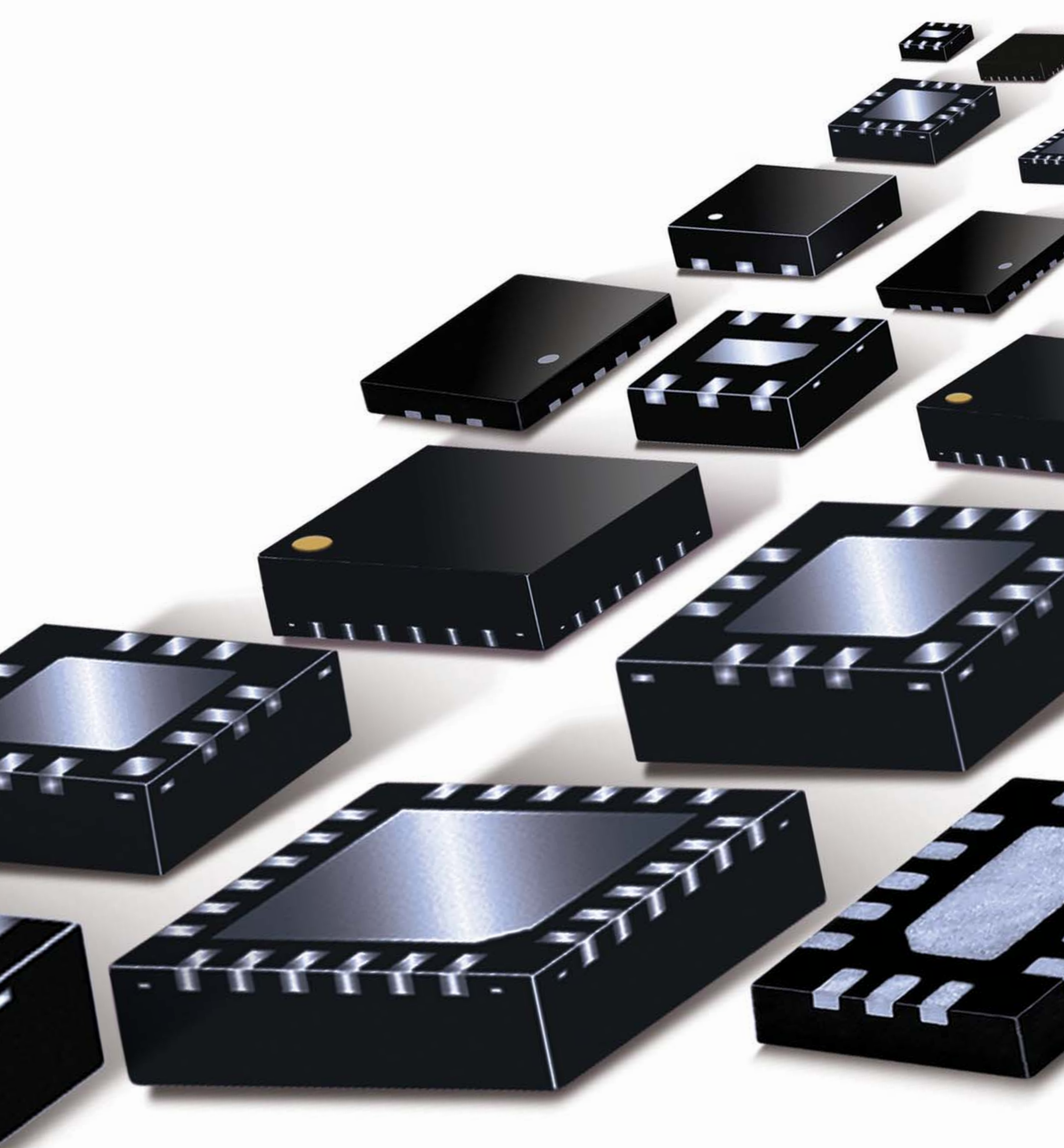

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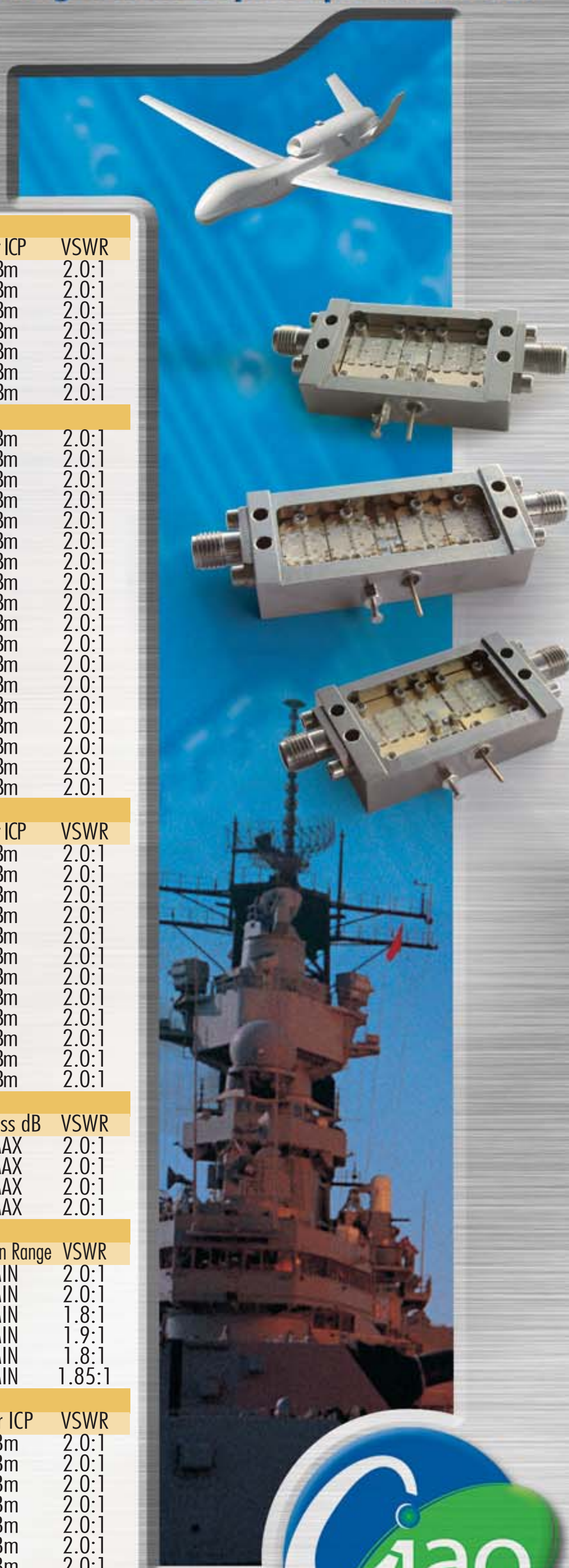

OCTAVE BAND LOW NOISE AMPLIFIERS

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

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

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

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

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

LIMITING AMPLIFIERS

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

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

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

LOW FREQUENCY AMPLIFIERS

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

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News

THIS ONE-STOP SHOP

Has the Ingredients for Your Wireless Recipe

The seventh annual TDK Developers Conference was held this past September in Santa Clara, Calif. *(Fig. 1)*. Among the various sessions at the event was “TDK RF Components for Wireless Applications,” presented by Harvey Espinoza, director of product marketing of the communication devices business group at TDK Corporation of America *(www.global.tdk.com)*. Focusing in on the company’s line of RF components, the presentation offered case studies and much more.

1. The theme of this year’s TDK Developers Conference was “Humanizing the Digital Experience.”

Any discussion surrounding TDK’s RF components typically centers on low-temperature co-fired ceramics (LTCC)—the company is at the forefront of this technology. These components are based on the same LTCC technology used in TDK’s multi-layer ceramic capacitors and inductors. More than 10 layers (as many as 35) are stacked to integrate passive circuit elements using LTCC processes.

Thin-film technology is also one of TDK’s core competencies. It enables the company to develop compact, low-profile components for applications like smartphones.

Espinoza recently spoke about some of the activity taking place within his group. “The main part of our communication products group is represented by all our components for RF applications—our LTCC-based and thin-film-based products,” he says. “These products include our filters, diplexers, triplexers, baluns, and couplers *(Fig. 2)*.”

Specific products include the DEA and TFS Series filters, as well as the DPX Series diplexers and the TPX Series triplexers. TDK also offers baluns such as the HHM1 and TFS Series. And the company’s circulators and isolators are key components for small-cell applications.

Another major focus is antennas. Espinoza notes that TDK now offers an online antenna design tool. “We have a tool online right now,” he says. “Let’s say you’re designing a product that uses a standard 2.4- or 5-GHz antenna. You have small chip antennas with very small keep-out areas. But changing that keep-out area is going to affect antenna efficiency and voltage standing wave ratio (VSWR).

“We have a tool online that lets you vary the keep-out area and see how that’s going to impact performance. Designers can use this tool to optimize their boards. There are some external components that are used for matching, and we actually recommend the value of them based on the keep-out area size on the printed-circuit-board (PCB).”

SURMOUNTING TODAY’S CHALLENGES

There’s no question that today’s requirements have created additional challenges in the RF world. For instance, there’s the ever-present demand for smaller products. According to Espinoza, TDK is helping to meet these small-size requirements. "We're working with RF front-end module makers. These companies are asking us for very low-profile components. For this, we're utilizing many of our thin-film solutions. We offer a variety of thin-film products that can be used in module-type applications. Many of these components are size 0605, or even smaller."

Espinoza believes that issues surrounding PCB layouts represent another common theme due to today's higher densities. "The other area we're getting into is layouts," he adds. "Layouts in RF were always important. But when you didn't have a high density of components on a PCB, you had a little bit more leeway in terms of how you could execute board layouts."

Today, higher densities have created additional challenges. Espinoza notes, "Now, as everything is getting closer and closer, we're starting to see a lot more issues with ground layers—people are using ground structures that are different than what we recommend on our datasheets. They're putting a lot more via holes in different locations. So, with more integration, the result is often a little bit of shifting in the performance of a product. The attenuation poles tend to shift up when you change some of the ground structures."

Shielding is a significant factor, too. Espinoza uses the case of a diplexer as an example. "Most diplexers have the inductors in the top layers of the structure," he says. "If the diplexer is too close to or right below a metal shield, the diplexer could detune a little bit—the attenuation poles could shift up. What we're doing is providing shielded diplexers. These are internally shielded, and you can just lay them out on a design and not have to worry so much about where it's going to be used. Another issue is that if you put a diplexer right next to a very noisy inductor, there will be coupling into the diplexer. Using a shielded diplexer will mitigate that effect." ■

2. Among TDK's selection of RF components is the TPX Series triplexers, which measure 2.0 × 1.25 × 0.9 mm.

KEEP AN EYE ON THESE NEW PRODUCTS for Your Next Project

AT THE RECENT European Microwave Week (EuMW), MACOM *(www.macom.com)* was among the companies that made its presence felt with the unveiling of three new products. These are the latest in a series of launches by the company.

"In the recently completed fiscal year, we released 64 new products," says Graham Board, senior director of product marketing at MACOM. "They span everything from traveling-wave amplifiers (dc-to-28 GHz and dc-to-50 GHz amplifiers) to voltage-variable attenuators (VVAs), digital step attenuators (DSAs), and detectors. What we've really been focused on are all the key building blocks that you need in the RF signal chain. We're developing parts for markets like millimeter-wave (mmWave) connectivity, aerospace and defense, test and measurement, and satellite-communications (satcom)."

One of the announcements made by MACOM during EuMW is the MAAL-011141 wideband low-noise amplifier (LNA). The MAAL-011141 is a packaged version of the previously released MAAL-011141-DIE amplifier. "A strategy that allows us to engage in disparate markets has been to offer different packaging concepts," explains Board. "There are customers who prefer packaged devices because of the ease of manufacturing. But for others in the aerospace-and-defense space, bare die formats are very important because they're building modules. So, we offer both.

"In the case of the MAAL-011141 LNA, we released it in a bare die format. The response to that was such that it made sense for us to also release it as a packaged part because there was so much interest."

Covering a frequency range of dc to 28 GHz, the MAAL-011141 has a typical gain of 17.5 dB across most of the band. At 8 GHz, it achieves a typical noise figure of 1.4 dB. Housed in a 5-mm, 32-lead AQFN package, the MAAL-011141 is well-suited for test-and-measurement, electronic-warfare (EW), electronic-countermeasures (ECM), and radar applications.

Also announced was the MASW-011102, a new single-pole/double-throw (SPDT) switch that operates from dc to 30 GHz *(Fig. 1)*. At 30 GHz, the MASW-011102 achieves an insertion loss of 1.8 dB along with an isolation of 40 dB. Furthermore, MACOM emphasizes the component's fast switching speed of 40 ns. Housed in a 3-mm, 14-lead PQFN package, the MASW-011102 is intended for applications like test and measurement, EW, and broadband communication systems.

Lastly, MACOM announced its new MACP Series of power detectors, comprised of the MACP-010571, MACP-010572, and MACP-010573. Each of the MACP Series detectors feature an integrated directional coupler along with built-in temperature compensation. The detectors are intended for power monitoring and leveling for a wide range of applications, such as point-to-point radios, radar systems, EW systems, and more.

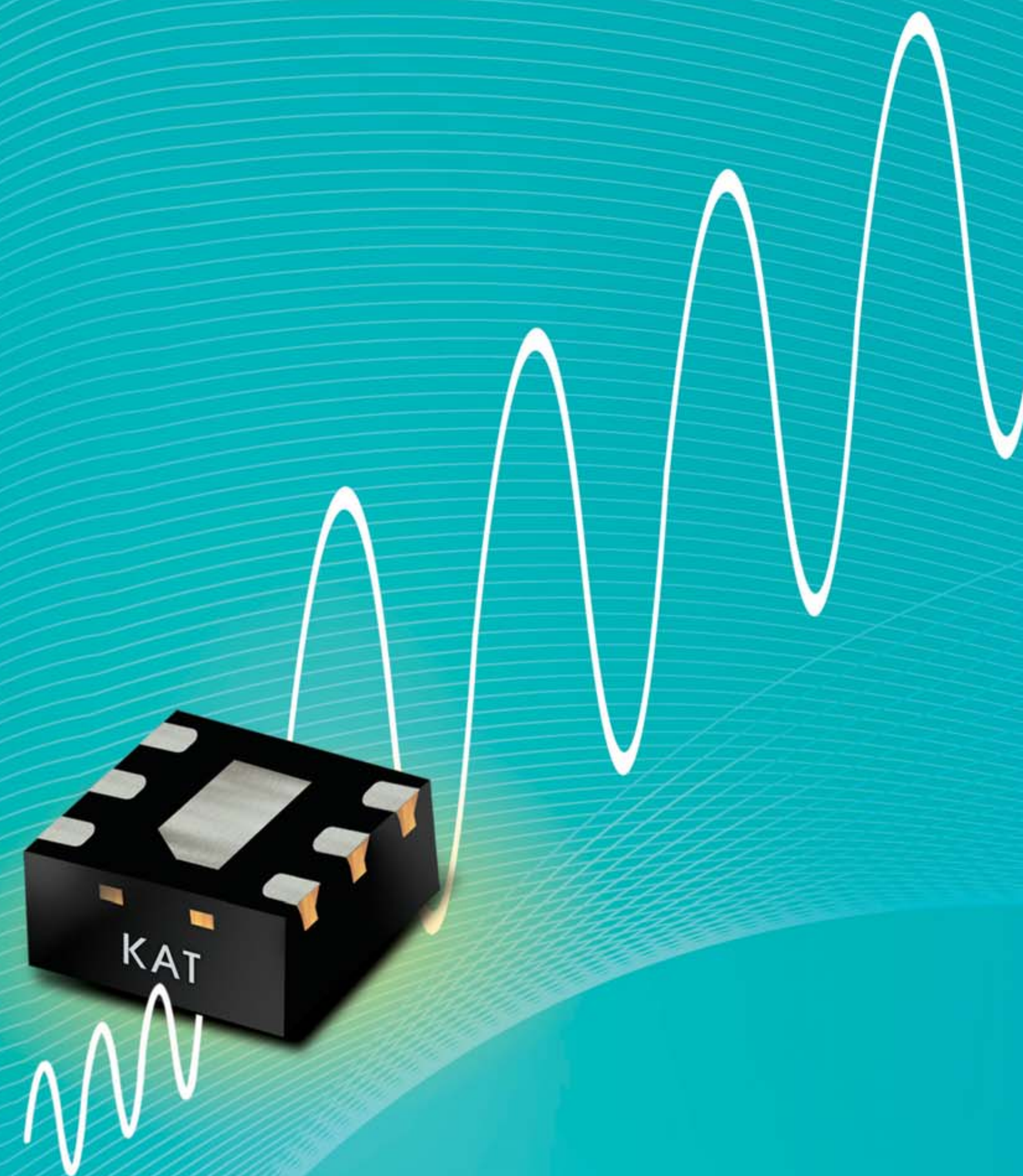
The MACP-010571 covers a frequency range of 2 to 6 GHz, and the MACP-010572 operates from 6 to 18 GHz. The MACP-010573 handles frequencies ranging from 10 to 30 GHz. The minimum detectable power level of the MACP-010571 is –15 dBm at 4 GHz; for the MACP-010572, it's –16 dBm at 12 GHz; and for the MACP-010573, the minimum is –18 dBm at 20 GHz. Each detector is housed in a 1.5- × 1.2-mm 6-lead TDFN plastic package.

BEYOND EuMW

As Board mentioned, MACOM released a number of new products during the last fiscal year. One new product portfolio to be aware of is the MLPNC Series of comb generators announced during IMS 2018 *(Fig. 2)*. The MLPNC Series is based on nonlinear-transmission-line (NLTL) technology.

Board says, "The comb generator is addressing the market's need for very-low-phase-noise sources. Our NLTL-based combs can be paired with ovenized crystal oscillators at low frequencies. There are many aerospace-and-defense applications in which a sys-

1. The MASW-011102 SPDT switch, which operates from dc to 30 GHz and maintains 1.8 dB of insertion loss across the entire band, comes in a PQFN package as shown here.


KAT

2. The MLPNC Series of comb generators is based on nonlinear-transmission-line technology.

tem may have multiple local oscillators (LOs). One of our combs would potentially address the requirement for multiple LOs. In fact, there's an application that has 20 individual LOs in a system. One of our combs addresses that requirement, providing a very clean multiplied signal with higher output power than a step-recovery diode (SRD) along with really low phase noise."

MACOM offers both surface-mount technology (SMT) and connectorized versions of the MLPNC Series comb generators. The series consists of several variants, such as the MLPNC-7100. This model, available as either an SMT or connectorized component, has an input frequency range of 100 to 400 MHz. The specified input power level ranges from +18 to +24 dBm. Furthermore, the MLPNC-7100 is rated for output harmonics at frequencies as high as 20 GHz. Visit MACOM's website for more information on the remaining MLPNC models. ■

AMRAAM PART OF Strong Missile Market Growth

RAYTHEON COMPANY'S RTN Missile Systems (MS) business division recently secured a $62-million cost-plus-incentive-fee option contract for the Advanced Medium Range Air-to-Air Missile (AMRAAM) program. The contract, which was awarded by the Air Force Life Cycle Management Center, Eglin Air Force Base, FL, calls for the form, fit, and function refresh of the AMRAAM guidance section per the exercise of options about Phase 5 activities and foreign military sales (FMS) drawings. The contract is expected to be completed by December 21, 2020, with work performed primarily in Tucson, AZ. It will involve FMS to Norway, Turkey, Japan, Romania, and Australia.

The AMRAAM system, with its AIM-120 Advanced Medium-Range-Air-to-Air missiles, features beyond-visual-range air-to-air missiles (BVRAAMs) capable of all-weather day-and-night operation which is highly dependent upon its sophisticated active guidance subsystem. The AMRAAM system has been demonstrated in more than 4,200 test shots and 10 air-to-air combat victories and has been procured by 37 nations including the U.S. It has been installed in the best known and trusted military aircraft, including F-16, F-15, F/A-18, F-22, Typhoon, Tornado, and Harrier jets.

Raytheon has enjoyed strong growth as the demand for military missile systems has grown across the international market. The company has experienced sizable recent FMS contracts more than $1 billion for its PATRIOT missile systems, from Sweden and Poland, because of growing international political tensions, establishing Raytheon as an international market leader in military missile systems, an international market that is expected to rise steadily through 2022. ■

The latest version of the AMRAAM Extended Range missile is a ground-launched weapon with enhanced target interception capabilities over longer distances and at higher altitudes in support of AMRAAM systems installed on some of the best-known military aircraft, including the F-35 fighter. *(Courtesy of Raytheon Co.)*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COUNTING CRANBERRIES with Radar Signals

Radar is a mature microwave technology typically associated with counting enemy aircraft or, in commercial applications, counting speeding motorists on roadways. But radar systems have also been recruited by farmers for counting fruits often associated with healthy beverages—namely, cranberries.

For years, farmers have relied on somewhat old-fashioned methods of estimating crop yields: They harvest the plants in one square foot of a cranberry bog or marsh and counting the number of cranberries by hand. Even by repeating the process several times and averaging the results of the different counts, this method of calculating crop yields is imprecise and time-consuming, especially when compared with doing it by radar.

Most of the world's cranberries are grown by Ocean Spray, which is a cooperative of more than 700 farms. Ben Tilberg, an Ocean Spray agricultural scientist, felt that there had to be a better way to estimate crop yields than the laborious counting methods used by the company and its farmers. He reached out to IEEE Fellow and researcher Susan Hagness and her associate researchers at the University of Wisconsin in Madison, and they felt that microwaves could be used in counting the cranberries.

Cranberries typically grow in beds of sand, peat, and gravel flooded with water, known as bogs. Because of the high water content of the fruit, the dielectric constant of each cranberry is much different than the dielectric constants of the surrounding vines and leaves, and the cranberries can be detected through the application of electromagnetic (EM) energy.

Using a prototype microwave sensing system that's able to scan a small part of a cranberry bog at one time, cranberry farmers can scan about a square foot of a cranberry bog and receive an estimation of the number of cranberries in that section. The prototype transmits radar pulses towards the ground and receives the reflections from the bog, measuring the different plants and fruits according to their dielectric-constant differences.

The prototype cranberry-counting radar system consists of metal waveguide mounted on a PVC support structure that's mounted over an area to be measured. The research team is already at work on a second-generation system that will be suspended from a boom and transported by truck, allowing farmers to measure spatial variations in a cranberry field for more accurate yields of the entire field.

See "Radar to the Rescue," *The Institute*, September 2018, p. 6.

BRINGING SAFER LEVEL CROSSINGS with mmWave Antennas

AUTOMOTIVE TRAFFIC AT level crossings can be hazardous because of the openness of the intersection and multiple vehicles often attempting to make the crossing at the same time. However, teaming millimeter-wave (mmWave) radar signals at 77 GHz with the right types of industrial-grade antennas can greatly increase the safety of pedestrians and cyclists at these level crossings. Such is the finding of researchers from Siena and Florence, Italy, as they attempt to apply mmWave radar-monitoring systems at 77 GHz to help enhance the safety of wide-open level-crossing traffic intersections.

Because of the sophisticated, commercial railway systems used for travel and transport throughout Italy, rail crossings are critical parts of the Italian (and throughout Europe) roadway systems. A rapidly growing population has underlined the needs for some form of automatic traffic-monitoring technology, such as mmWave, frequency-modulated-continuous-wave (FMCW) radar at 77 GHz, to maintain safe traffic/pedestrian flow at level crossings.

The high frequency of these radar systems has spurred the development of suitable antennas that meet the specific requirements of the systems under all operating conditions. These antennas also are capable of performance levels at 77 GHz based on a certain mounting distance above the ground and from the railway tracks.

Furthermore, the antennas are designed to monitor roadway crossings of a certain maximum road width (12 m), assuming a certain maximum detection distance to the target. Additional requirements consider maximum antenna size and target costs. Initial requirements included containing the monitoring antennas within a box measuring 16 cm on a side. Those initial requirements were quickly redefined as a result of experience from operating in the field.

The first antennas were designed for a bandwidth of 1 GHz centered at 76.5 GHz, providing more than 25 dBi gain and more than 70% efficiency. Early antenna designs were based on horn antennas, with further developments leading to lens horn antennas to decrease the beamwidth.

The researchers pursued many different mmWave antenna designs and their simulations, comparing the performance levels of the different configurations at 76.5 GHz, including reflectors, horns, and horn arrays. Tradeoffs in size, complexity, and manufacturing costs were evaluated to guide the choice of 77-GHz antennas for the safest railway level crossings possible.

See "Industrial Antenna Development for 77-GHz Level-Crossing Monitoring Radar," *IEEE Antennas & Propagation Magazine,* Vol. 60, No. 5, October 2018, pp. 95-106.

JACK SIFRI | MMIC/Module Design-Flow Specialist and Product Manager, Keysight Technologies
www.keysight.com

Dissecting a 5G 28-GHz Phased-Array Transmit Chain

This article presents the design, simulation, and analysis of a 5G 28-GHz phased-array transmit chain, implementing electromagnetic circuit excitation and co-simulation.

5G is expected to offer extremely fast rates with extremely low latency. To achieve these tough specifications, the operating frequency must be in a region where high bandwidth and high speed is available. That means a move toward the millimeter-wave (mmWave) band.

The mmWave band had always been viewed as unsuitable for mobile communications, mainly due to high loss and propagation issues. However, research has shown that these propagation issues can be addressed and overcome with phased arrays and beamsteering antennas.

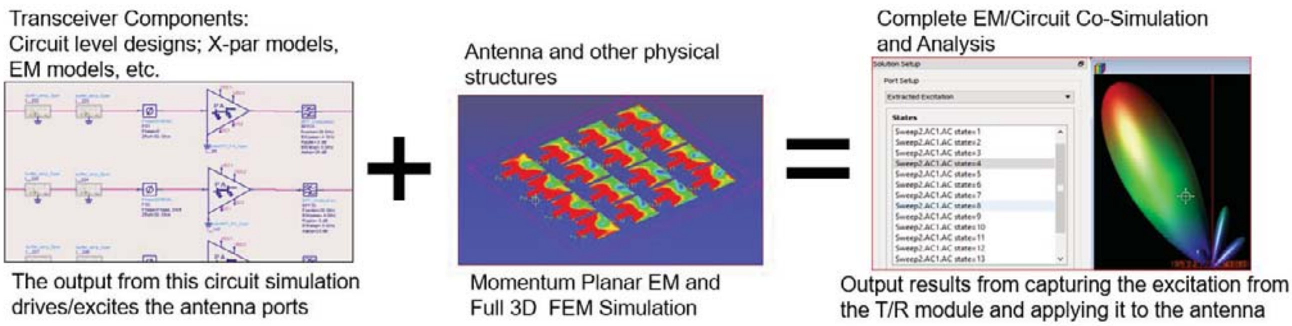
A phased-array antenna is composed of multiple radiating elements. Each element is connected to a phase shifter, which forms the beam that steers the antenna via constructive or destructive interference. Phased-array antennas allow engineers to enter the mmWave spectrum and achieve the high bandwidth and high speeds that 5G promises. Within the mmWave spectrum, the 28-GHz band has been chosen as one of the candidate bands to quantify 5G.

This article discusses the process involved in the design and simulation of a 5G 28-GHz phased-array transmit chain, as well as the theory behind each step in the process. Starting with electromagnetic (EM) circuit co-simulation, results and analysis that were uncovered during the design phase are detailed.

EM/CIRCUIT EXCITATION AND CO-SIMULATION

5G presents considerable design and simulation challenges, especially when combining high-frequency circuit design elements of multiple manufacturing technologies with different model abstractions including physical EM models. All of this must be combined and co-simulated simultaneously.

EM coupling from the physical designs and their interactions with other components in the system needs to be modeled and accurately accounted for. For this reason, 5G designers desperately need good tools that can integrate and co-simulate these models and technologies together and account for all their interactions, or else the simulation



1. Shown is the EM/circuit excitation process in ADS.

results will be off and result in product failure.

The EM/circuit excitation and co-simulation process in Keysight Technologies' Advanced Design System (ADS) delivers such simulation and analysis criteria. It also plays an important role in delivering accurate simultaneous simulation and analysis of the whole transmit chain with all of its components, including the antenna.

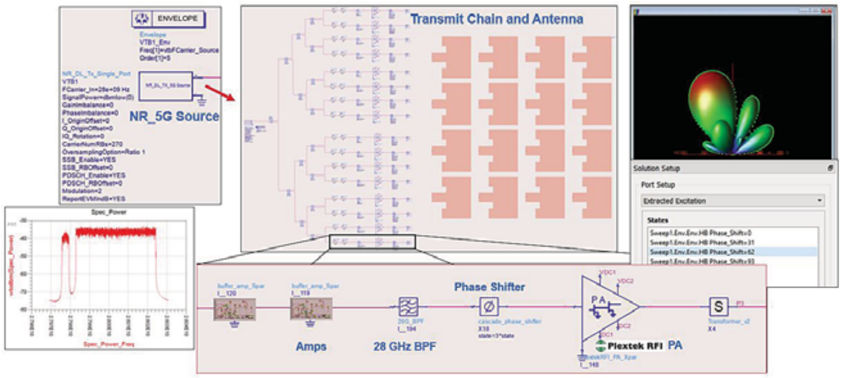
Figure 1 illustrates the EM/circuit excitation technique. The transceiver components on the schematic page are designed at the circuit level using foundry design kit models, or they're represented by their S-parameter models, nonlinear X-parameter models, and EM models.

The output of such circuit simulation on the transmit chain drives and excites the physical antenna structure that's being simultaneously co-simulated with Momentum Planar EM solver or Full 3D FEM solver in ADS. The output response at the far right of *Fig. 1* comprises the complete EM/circuit co-simulated results produced by capturing the excitation from the transmitter module and applying it directly to the antenna.

All simulated states of the phase shifter are exported to the output far-field results as shown at the far right of *Fig. 1*. The output beam and its side lobes and nulls can then be displayed and steered for any selected phase-shifter state. Thus, it contains the complete EM/circuit co-simulation and analysis results.

EM/CIRCUIT CO-SIMULATION WITH CIRCUIT ENVELOPE

EM/circuit excitation and co-simulation work with all circuit simulators in ADS.[1] However, using a circuit-envelope simulator in this process is essential because it allows for realistic 5G modulated sources to be applied at the input of the transmit chain and accurately outputs the results at the antenna.



2. This simulation features EM/circuit excitation on the entire transmit chain using a 5G New Radio source with circuit envelope.

5G signals by nature are time-varying complex modulated signals. Circuit envelope is a hybrid time- and frequency-domain simulator that can effectively handle and simulate these types of signals. When these signals drive the power amplifiers (PAs), the output at certain times consists of peak power values, while at other times consists of lower power values.

The peak-to-average ratio would compress the PAs in a complex fashion as compared to traditional steady-state harmonic balance with simplistic sinusoidal power sources. This helps designers uncover how much power must be backed off from the input of the PA to maintain the required linearity and meet the specifications. Circuit envelope is also much more efficient in memory when simulating modulated signals; it captures memory effects of the amplifiers and their effect on the spectrum power, error vector magnitude (EVM), and other measures.

In this EM/circuit co-simulation process with circuit envelope using 5G modulated sources, we are not abstracting models to co-simulate. Rather we are truly co-simulating the actual circuits with memory effects. The EM/circuit excitation truly captures the excitation from the TR module output and applies it to the antenna to get true and complete EM circuit simulation results.

Figure 2 shows the simulation setup of the transmit chain using a 5G New Radio (NR) source with circuit-envelope simulation on the entire transmit chain. The output beam far-field plot is shown on the right for the phase shifter angle of 62° that corresponds to a 20° beam look-up angle.[2]

TRANSMIT-CHAIN COMPONENTS AND ANTENNA

Figure 2 also illustrates the transmit-chain components of the 16 channels, all designed in ADS[1] and connected to the patch antenna:

- The mmWave PA was designed by Plextek RFI *(www.plextekrfi.com)*. It was implemented using Global Communication Semiconductors' (GCS; *www.gcsincorp.com)* indium-phosphide (InP) dual heterojunction bipolar transistor (HBT) process. The PA provides 20 dB of gain at 28 GHz and achieves a 1-dB compression (P1dB) of +27 dBm. Its input and output voltage standing wave ratio (VSWR) is better than 1.2:1.
- The small signal amplifier was also designed by Plextek RFI. It was implemented using Qorvo's *(www.qorvo.com)* pHEMT process. It provides 14 dB of gain with input and output VSWR better than 1.2:1.
- The power dividers and the mmWave four-bit phase shift-

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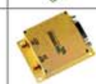
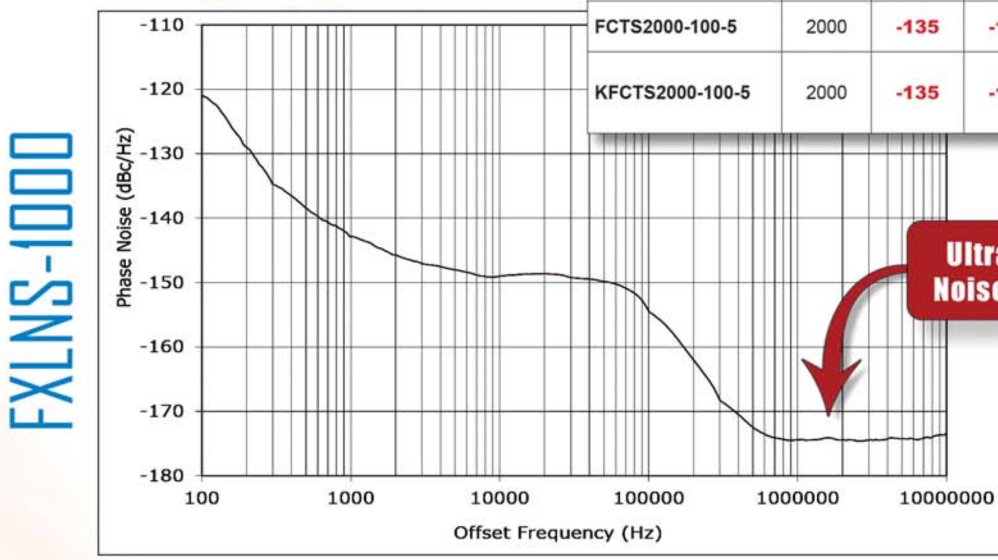
Model	Frequency (MHz)	Phase Noise (dBc/Hz) [Typ.]		Package
		@10 kHz	@100 kHz	
FCTS800-10-5	800	-144	-158	
KFCTS800-10-5	800	-144	-158	
FSA1000-100	1000	-145	-160	
KFSA1000-100	1000	-145	-160	
FXLNS-1000	1000	-149	-154	
KFXLNS-1000	1000	-149	-154	
FCTS1000-10-5	1000	-141	-158	
KFCTS1000-10-5	1000	-141	-158	
FCTS1000-100-5	1000	-141	-158	
FCTS1000-100-5-H	1000	-144	-160	
FCTS2000-100-5	2000	-135	-158	
KFCTS2000-100-5	2000	-135	-158	



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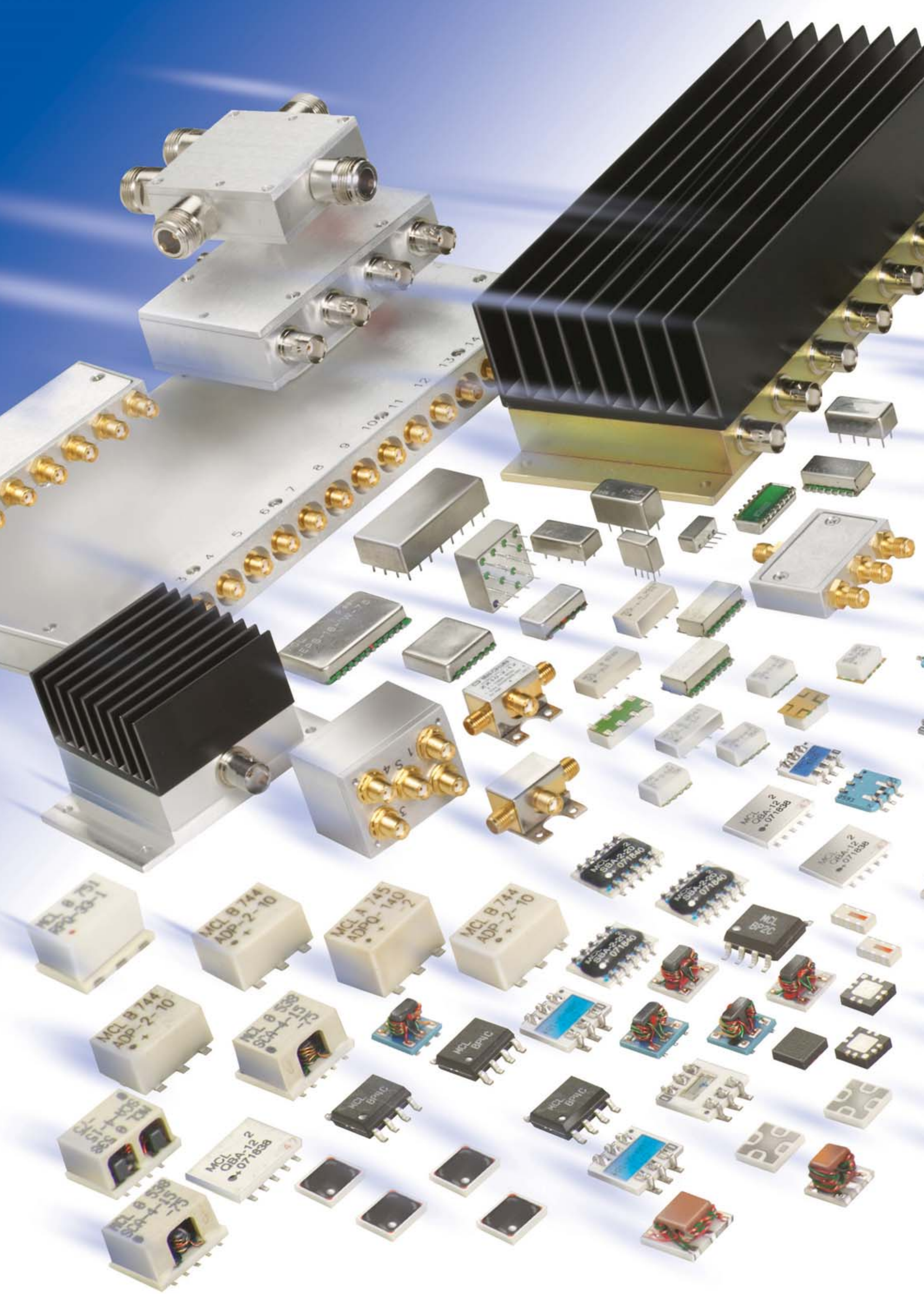
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ers (with 22.5-deg. phase increments) were designed using Qorvo's pHEMT process. The filter was implemented with lumped component models in ADS.

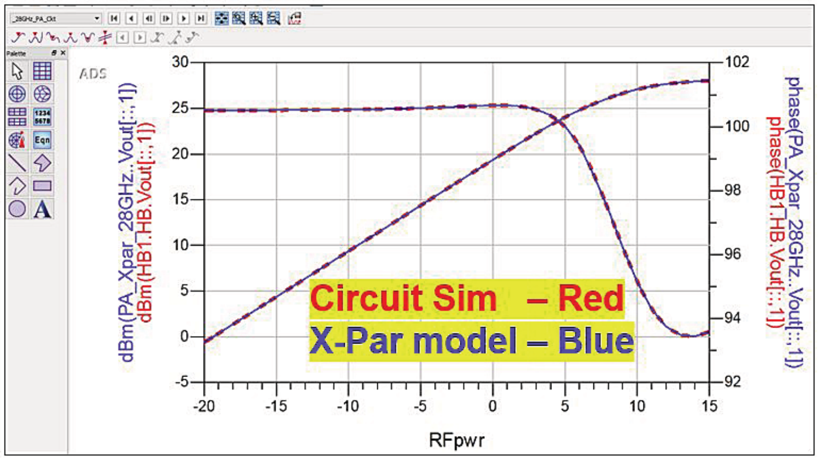
- The 28-GHz λ/2 patch antenna was designed on a Duroid substrate with VSWR better than 1.4:1.

More information concerning these component's design and performance is provided in the referenced webcast.[6]

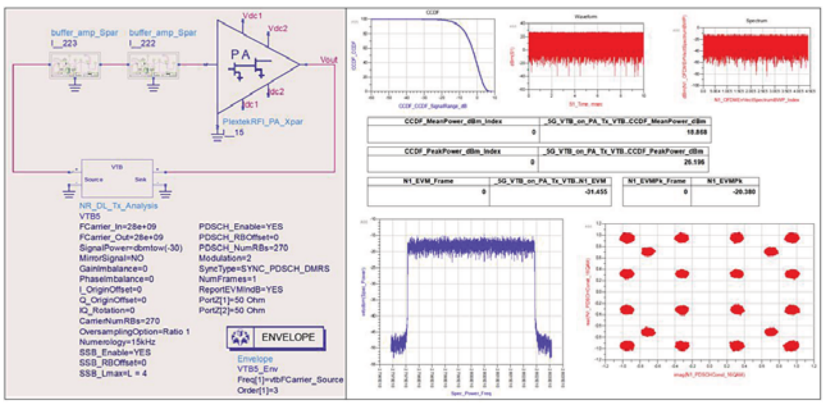
X-PARAMETER MODELS AND 5G SYSTEM SIMULATION

When designing and simulating 5G modules, X-parameters become extremely beneficial.[3] Since its pioneering introduction in 2008, X-parameter technology has developed rapidly. While S-parameters provide a solution to small-signal linear devices, X-parameters solve nonlinear problems with higher input power. They can accurately capture all nonlinearities in nonlinear circuits such as the PA, including the fundamental, the harmonics, the intermodulation distortion, amplitudes, and phase. They accurately replicate the actual circuit design, resulting in much faster simulation time—especially during tradeoff analysis.

For example, *Figure 3* clearly shows how the PA's circuit-simulation results are identical to the X-parameter model simulation results in both amplitude and phase. Therefore, it's advantageous to use X-parameter models during "what if" and "tradeoff" analysis. It runs much faster and provides protection to your IP if you prefer not to expose or share the topology of your circuit designs.



3. In this circuit simulation versus X-parameter model simulation, P_{in}/P_{out} and phase response of the PA is revealed.



4. VTB simulation setup and output results in ADS are given for the pre-amplifiers and PA in the transmit chain.

5G VERIFICATION TEST BENCHES IN ADS

A verification test bench (VTB) is a regular component in the ADS simulation environment, which is linked to the VTB in SystemVue.[4] VTBs enable circuit designers to make use of sources and measurement setups from SystemVue and verify the performance of a circuit using real-world complex modulated signals that conform to advanced wireless standards like 2G, 3G, 4G, and 5G.

Placing a 5G VTB onto a schematic allows you to verify the transmit-chain components or the PA by itself with respect to 5G standards. The example in *Figure 4* displays a VTB simulation setup for the two pre-amplifiers followed by the output PA in the transmit chain. The output display contains the complementary cumulative distribution function (CCDF) curve, the input and output spectrums, the mean and peak powers, EVM, constellation plot, and other measures.

EXPERIMENTATION AND ANALYSIS

Several experiments were performed using the EM/circuit excitation and co-simulation method to investigate the effect on the quality of the beam and its side lobes and nulls. Below is a summary of each analysis and its findings.

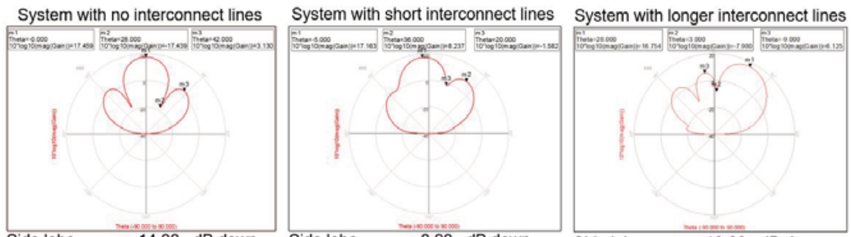
Effect of the Feed Network and Line Lengths

Feed network lines connect the PA integrated circuits (ICs) to the antenna ports. When all PAs are implemented on one IC, the outputs connect to the antenna patches with unequal line lengths and result in different and higher path losses and require calibration.

Described below is the effect of these unequal line lengths between the IC and the antenna patches prior to any calibration. This is something a design engineer would experience in the lab while prototyping and testing a system in its development stage.

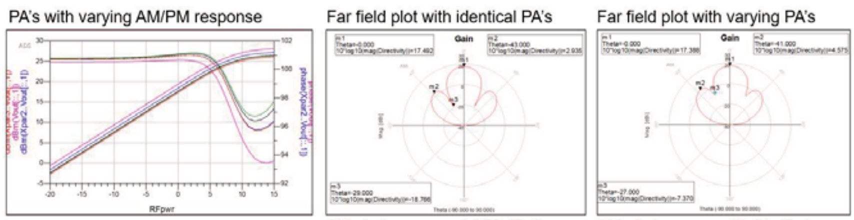
To get a baseline reference, a simulation with no interconnect lines was initially performed. *Figure 5* shows the result. The main lobe is perfectly centered at 0 deg. phase shift along the y-axis. The side lobes are 14.33 dB down and the nulls are 34.9 dB down.

Next, feed lines of different lengths between the IC and the antenna patches were used to determine their effect on the beam. Using short lines (0.5 to 2 mm) resulted in shifting the beam by 5 deg., as shown in *Fig. 5.* The side lobes degraded and increased from −14.33 dB down to −8.9 dB down. The nulls degraded and went up from −34.9 dB down to −18.75 dB down.



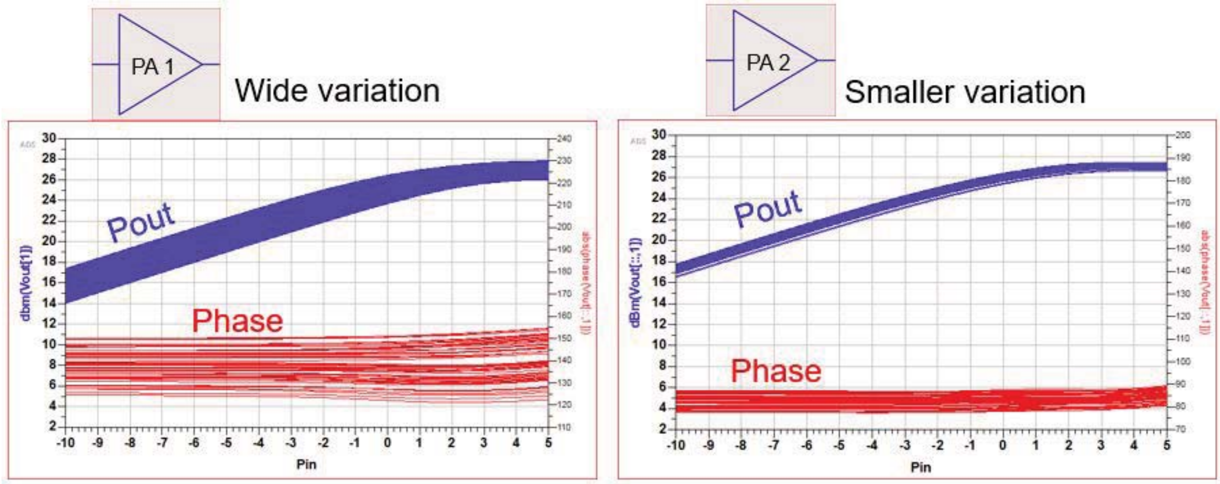
	System with no interconnect lines	System with short interconnect lines	System with longer interconnect lines
Side lobe	14.33 dB down	8.93 dB down	10.63 dB down
Null	34.90 dB down	18.75 dB down	24.73 dB down
Phase Shift	0 deg	5 deg	28 deg

5. This analysis uncovers the effect of the feed network and line lengths on the quality of the beam.

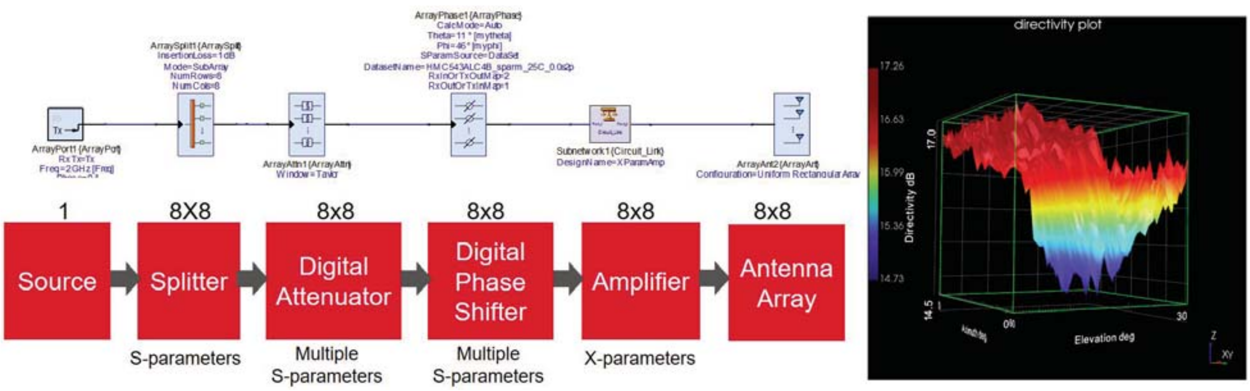


	Far field plot with identical PA's	Far field plot with varying PA's
Side Lobe	14.56 dB down	12.81 dB down
Null	36.26 dB down	24.76 dB down
Phase Shift	0 degrees	0 degrees

6. When various PAs with variation in AM/PM response are used in this experiment, side lobes are 2 dB higher and nulls are at least 10 dB higher.



7. The DOE methodology transformed a PA with wide variation into one with smaller variation in both amplitude and phase.



8. This SystemVue test case on dynamic impedance shows blind spots at certain azimuth and elevation scanned angles.

A second experimental trial using longer lines (3 to 9 mm) was performed, resulting in drastic degradation in beam quality with a larger phase shift of 28 deg. The nulls and the lobes also went up. *Fig. 5* tabulates the results.

This analysis clearly show that the lines can cause problems in the system. When working on a prototype, this issue comes up often. To avoid it, you must simulate and correct for it before building the system.

Effect of Varying the PA's AM/PM Response

This experiment investigates the effect of having variation in amplitude and phase among all PAs used in the system. First, a simulation was performed with identical PAs to get a reference baseline of the beam quality with no variation. Next, several PAs with variation in their AM/PM response were utilized. The beam angle was not affected, but the influence on the lobes and nulls was prevalent.

The left side of *Figure 6* displays the response of the PAs used in the experiment. Notice when the input RF power is +10 dBm, the corresponding P_{out} of the PAs varies by 3 dB and their phase varies by 3 deg. This variation in amplitude and phase has caused the distortion and degradation in the side lobes and nulls. *Fig. 6* shows that the side lobes degraded and went up by 2 dB, while the nulls degraded and became at least 10 dB higher.

Therefore, it's very important to design the nonlinear components, such as the PAs, with small variation. Otherwise, unwanted results occur and cause problems in the overall system.

This leads to a discussion of a valuable statistical design technique that uses the "Design of Experiments" (DOE)[5] to produce robust designs with minimum variation. I encourage the reader to learn more about this technique by watching the YouTube video, "How to Use Design of Experiments to Create Robust Designs with High Yield." *Figure 7* illustrates how the DOE methodology has transformed a PA with wide variation into one with smaller variation in both amplitude and phase.

Effect of Coupling, Crosstalk, and Isolation

Coupling and crosstalk can occur between components in adjacent channels, either from adjacent PAs or from the antenna elements (usually accounted for by the EM simulation on the antenna). Coupling also appears on feed lines that connect the PAs to the antenna.

Similarly, crosstalk between two adjacent channels could occur, potentially leading to noticeable degradation in output signal quality. An RF signal in one channel would appear in an adjacent channel and cause interference and distortion.

An experiment on coupling effects was performed, first with no coupling between the channels in the transmit chain and then with coupling. The results showed similar degradation in the side lobes and nulls. The side lobes degraded and went up from −14.53 dB to −11.7 dB down from the main beam. The nulls degraded and went up from −36 dB to −19 dB down from the main beam.

Isolation is another key matter to consider. It's crucial to design for good isolation between channels and avoid leakage from one channel to another as this could significantly affect the antenna element impedance. Designing for good isolation starts with making sure that all split-components in the system are designed well from the beginning. 5G systems contain several switches and splitters. It's crucial to design these splitters, switches, and couplers with high isolation at the component level. It would eliminate many headaches at the end.

Effect of the PA Dynamic Impedance with the Antenna

As phase shifters control and change the beam-scan angle, the effective cross-section area of the array decreases because there's less power to the main lobe and less directivity due to the wider beam. The PA loading and impedance changes, also referred to as "Active or Dynamic Impedance," and can affect the final beam shape, and in extreme cases, may create blind spots as well.

In the April 15, 2011 technical note by Neill Tucker titled "An Introduction to Phased Array Design," Tucker explains that the importance of active input impedance should not be underestimated. Its effects can be dramatic because they directly impact the amplitude and phase excitations of the array elements, and these are the very parameters you are using to control the array.

To explore this phenomenon, an 8-×-8 transmit chain was constructed and simulated in SystemVue *(Fig. 8)*.[4] Mild

In the April 15, 2011 technical note by Neill Tucker titled "An Introduction to Phased Array Design," Tucker explains that the importance of active input impedance should not be underestimated.

blind spots can be seen at certain azimuth and elevation scanned angles. The main beam is seen to drop down by 3 dB at these specific angles. Under different conditions, different active impedance between the PAs and the antenna could result in full blind spots of the beam. Designers, therefore, should not underestimate it and must give it considerable attention.

CONCLUSION

The design, simulation, and analysis of a 5G 28-GHz phased-array transmit chain was demonstrated. The EM circuit excitation and co-simulation process in ADS using realistic 5G NR input sources and X-parameter models was thoroughly described. It was shown to be practical, powerful, and efficient, especially during the system design, analysis, and development phase. Various design-related analyses were performed with interesting and useful results to the design engineers. For more information, readers are encouraged to check out the live webcast recording that was given on this topic.[6] mw

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Circuit Materials Secure Automotive Safety Systems

Future automotive electronic safety systems based on radar and wireless communications will rely heavily on printed antennas, and circuit materials will play a key role in their creation.

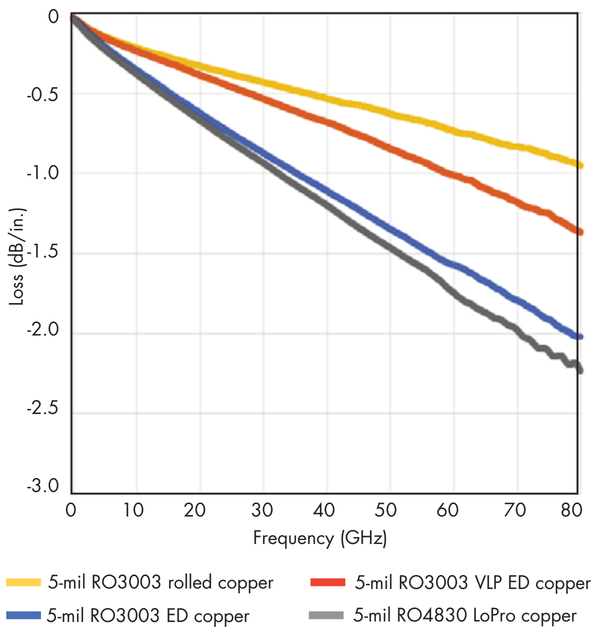
Electronic safety systems are rapidly becoming major parts of modern automotive vehicles, steering toward a future of roadways filled with autonomous vehicles. Advanced driver-assistance systems (ADAS) based on radar and electronic communications circuits are promising safer future roadways. Crafting these systems requires high-frequency electronic components, such as RF/microwave printed-circuit-board (PCB) antennas for automotive radar sensors and for various forms of communications between vehicles. In turn, fabricating effective components requires suitable circuit materials.

Increased reliance on high-frequency electronics can help pave safer roadways for the future. At present, more than 1.25 million automobile-related deaths occur each year globally, with another 50 million people injured. Improving traffic safety is a key motivation for expanding the ADAS functions of vehicles.

New Car Assessment Program (NCAP) organizations in several countries and regions have established car safety roadmaps, challenging automobile manufacturers to improve safety functions to earn NCAP top vehicle safety ratings. Mobility as a Service (MaaS) is also emerging as a market to provide consumers affordable transportation options versus personal vehicle ownership, which also frees passengers to convert their driving time to higher value activities.

ADAS systems such as millimeter-wave (mmWave) radar sensors help to improve the safety of commercial automotive vehicles and, as such, are graded by the Society of Automotive Engineers (SAE) in terms of six levels of vehicle autonomy, from Level 0 (no automation) to Level 5 (full automation). Many organizations focused on increasing vehicle safety approach vehicle automation from the ground (Level 0) up, while organizations interested in developing autonomous vehicles have great interest in Level 4 or 5 automation, where a driver becomes more of a passenger.

Whatever the level of vehicle safety required, multiple sensors are needed for a reliable, full 360-deg. view of a vehicle's environment. Electronic devices contributing to that full view include light detection and ranging (LiDAR) sensors, cameras, radar, Global Positioning System (GPS) receivers, and vehicle-to-everything (V2X) communications systems. Radar sensors are important ADAS components since they can measure the distance, velocity, and angular position of targets near a vehicle.



1. The plots of insertion loss versus frequency compare RO3003 and RO4830 circuit laminates with different copper-foil options.

Automotive radar sensors are currently designed at two operating frequencies: 24 and 77 GHz. While the ultrawide-band 24-GHz allocation (21.65 to 26.65 GHz) will no longer be available in the U. S. and Europe by 2022, narrowband 24-GHz (24.05 to 24.25 GHz) vehicle radar will continue to be available. The 77-GHz band extends from 76 to 81 GHz.

Radar sensors at 24 GHz are typically used for short- and mid-range functions such as rear blind-spot detection and rear cross-traffic alert. Shorter-wavelength 77-GHz radar sensors can be employed for short-, mid-, and long-range target detection. Some long-range functions include adaptive cruise control and automatic emergency breaking. To achieve higher levels of safety and autonomous functions, 77-GHz radar requirements will increase and evolve from their current uses for object detection to object discrimination and imaging. Greater reliance on 77-GHz radar systems will require increased distance detection, distance resolution, and elevation measurements.

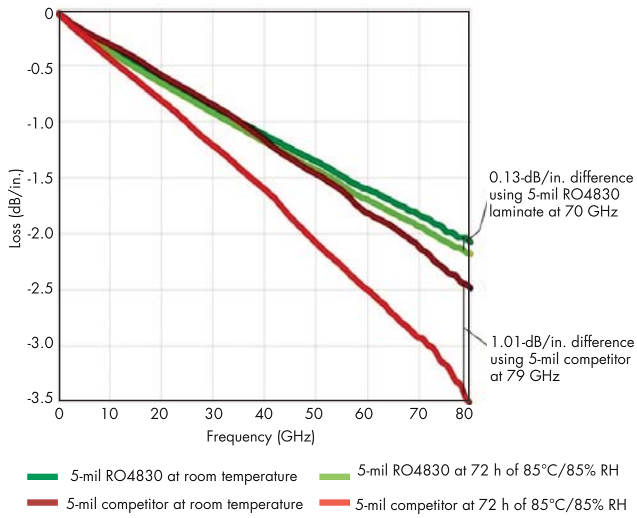
CIRCUIT MATERIALS

Automotive radar sensors at 24 and 77 GHz rely on high-performance circuit laminates for reliable PCB antennas at such high frequencies. Antenna frequencies and specific performance goals will determine the circuit material requirements. An RF/microwave circuit designer must balance the tradeoffs of circuit material properties with other antenna components to find the most cost-effective circuit material solution for a PCB antenna design. For example, there are four key circuit material properties to consider for a 77-GHz automotive radar antenna: the dielectric constant and its tolerance, the insertion loss, the electrical stability of the material, and the homogeneity of the substrate material.

Signal wavelengths decrease with increasing frequencies, requiring very fine circuit features for 77-GHz PCB antennas. Because circuit substrate materials with higher dielectric-constant (Dk) values can also result in smaller circuit features for a given frequency/wavelength, circuit materials with lower Dk values, such as 3.0 (based on measurements using IPC TM-650 2.5.5.5 at 10 GHz), are often used for circuits at mmWave frequencies. Stable Dk performance is necessary, both for good performance from an individual PCB antenna and for consistent antenna-to-antenna performance over the typical time of a 10- to 15-year program. Therefore, circuit material with carefully controlled dielectric constant within a tolerance of ±0.05 or better (based on IPC TM-650 2.5.5.5 at 10 GHz) is desired.

High PCB radar antenna gain aids in distance detection, and PCB radar antenna gain is optimized using circuit materials with low insertion loss. The insertion loss of a circuit laminate consists of the material's dissipation factor (Df) and copper foil surface roughness. The Df depends on the substrate material; PTFE-based laminates tend to have a lower Df compared to other substrate resin systems, such as hydrocarbon thermosets.

At mmWave frequencies, thin RF laminate core thicknesses of 0.010 in. or less are often used, and the copper-foil surface roughness will have a more significant impact on the overall insertion loss as compared to thicker (for example, greater than 0.030 in. thick) RF laminates. Rolled copper foil has the lowest copper-foil root-mean-square (RMS) roughness (R_q) at 0.4 μm.



2. The insertion loss of microstrip transmission lines is compared (by differential length method) for 5-mil-thick RO4830 circuit laminate and a competitive 5-mil-thick thermoset circuit material.

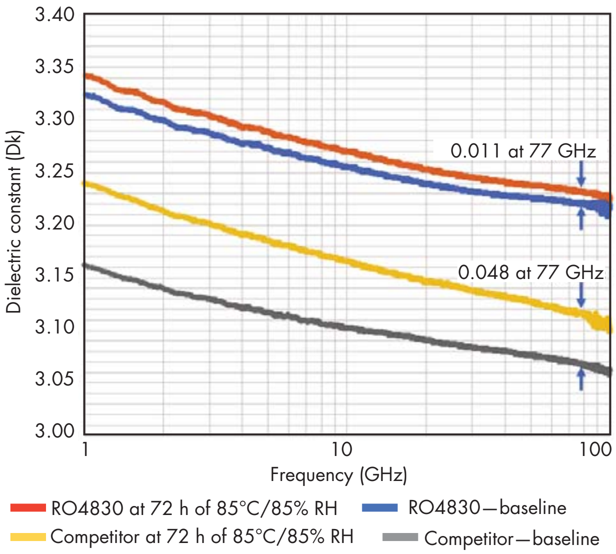
Circuit laminates are available with electrodeposited (ED) copper foils with varying levels of surface roughness, typically costing less than laminates with rolled copper. However, surface roughness and electrical performance must be balanced with other properties, such as copper adhesion strength to the dielectric substrate through thermal exposures.

RO3003 and RO4830 circuit laminates from Rogers Corp. *(www.rogerscorp.com)* represent examples of how circuit laminate Df and copper surface roughness can be selected for low overall circuit laminate insertion loss. As a ceramic-filled PTFE resin system, RO3003 laminates have a low Df of 0.0010 at 10 GHz. Pairing 5-mil-thick RO3003 substrate with different copper foils that have different copper-foil surface roughnesses will result in different insertion loss values *(see Fig. 1 and the table)*.

For example, with rolled copper, RO3003 laminates exhibit microstrip transmission-line insertion loss of 0.9 dB/in. at 77 GHz (using a microstrip differential phase length test method). When using very-low-profile (VLP) ED copper foil with a copper surface roughness of 0.7 μm, RO3003 laminate has insertion loss of 1.3 dB/in.

In contrast, RO4830 circuit laminates, which are based on a hydrocarbon thermoset resin system, have a Df of 0.033 (at 10 GHz), significantly higher than the Df of RO3003 laminate. However, when paired with a reverse-treated ED copper foil with R_q roughness of 0.9 μm, the insertion loss of a 5-mil-thick RO4830 laminate is 2.2 dB/in., which is quite close to the insertion loss value of RO3003 laminate with a standard ED copper foil that has roughness of 2.0 μm *(Fig. 2)*.

In use, automotive radar sensors will encounter a wide range of environmental conditions that can impact antenna



3. The Dk versus frequency is plotted for RO4830 circuit laminate and a competitive circuit material under different operating environments.

performance. For stability, an antenna can be protected by a suitable enclosure, which will add to cost, or be fabricated on a circuit laminate that provides high stability under the expected operating conditions.

The environmental stability of a circuit laminate can be gauged by checking its thermal coefficient of dielectric constant (TCDK), which is how much the dielectric constant varies over a wide temperature range, and by measuring Dk and Df in a hot, humid environment. One rule of thumb is that a TCDK target of | 50 | ppm/°C or better for TCDK is appropriate for RF laminates used for automotive radar applications. *Figure 3* plots insertion loss and Dk for two circuit laminates after the materials spent 72 hours at +85°C and 85% relative humidity (RH).

For insertion loss, the two green trend lines compare measurements of 5-mil-thick RO4830 circuit laminates taken at room temperature and taken after environmental exposure. The difference in loss is small for the RO4830 circuit material under different conditions, especially when compared to another thermoset circuit laminate (the red lines), which reveal a difference of 1 dB/in. at 77 GHz.

For Dk, as *Fig. 3* shows, the Dk of RO4830 circuit laminate increases by about 0.011 after exposure to the +85°C/85% RH conditions. This is not as significant as the 0.048 increase in Dk exhibited by the alternative thermoset circuit material for those same +85°C/85% RH conditions. Considering that the Dk is held to a tolerance of ±0.05 for these materials, a change of 0.048 in Dk is one-half of the expected Dk tolerance, and it may be a variation in Dk value that is not accounted for in an antenna design.

HOMOGENEOUS SUBSTRATES

Stable electrical performance is an important circuit material property whether evaluating one antenna or many. Circuit laminates with homogeneous composition support uniform electrical properties on a small scale, especially at short wavelengths at 77 GHz.

RO3003 laminate is an example of a homogeneous circuit material. It's comprised of a uniform layer of ceramic-filled PTFE, with no glass fabric. Sometimes RF circuit laminates containing woven glass fabric are desired for their mechanical properties through PCB fabrication. For those cases, it's helpful to use a ceramic-filled RF circuit laminate that contains a spread-weave woven-glass fabric.

A standard weave glass has "windows" between the warp and weave bundles (like a loosely knit sweater). As a transmission line moves across the laminate, it will alternate between being above a glass bundle (in which glass has a Dk of about 6) and a resin-rich, glass-poor bundle (where the resin has a Dk between 2 and 3). The glass fibers in each direction of a spread-weave glass fabric are modified to minimize that window effect and create a more uniform consistency of glass fabric in the x-y plane. RO4830 laminate is one example of a ceramic-filled RF circuit laminate with Dk of 3 and spread glass.

COMMUNICATIONS ANTENNAS

To facilitate ADAS and autonomous vehicle functions, a vehicle's electronic systems must also gather information about its exact position, about the locations and velocities of vehicles outside its line of site (LOS), and about pertinent road conditions. Global Navigation Satellite System (GNSS) antennas and V2X antennas help achieve these goals. However, integrating an increasing number of communications antennas within a vehicle poses numerous challenges, since space is limited and aesthetics may favor antennas concealed behind fascia rather than combined in a traditional shark fin.

GNSS antennas are already commonly used in modern vehicles, but they will become increasingly important for ADAS and autonomous-vehicle functions to determine more precisely the position of the vehicle. Various GNSS systems around the world employ frequency bands from about 1.1 to 1.6 GHz, with ceramic and FR-4-based circuit materials commonly used for GNSS PCB antennas.

But as GNSS antennas with greater accuracy are required, circuit materials with much more stable material properties, such as lower insertion loss, tighter dielectric thickness tolerance, and tighter control of Dk, will become more critical. Such enhanced-performance GNSS antennas may be candidates for circuit materials like high-performance FR-4 or Kappa 438 circuit laminates from Rogers Corp.

As part of electronic safety systems, vehicles are expected to communicate with each other by means of vehicle-to-vehicle

(Continued on page 61)

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A Brief Tutorial on Microstrip Antennas (Part 1)

This article, the first of a multi-part series on microstrip antennas, discusses antenna characterization—from antenna parameters to key attributes.

A significant performance element in communication and radar systems—as well as wireless devices—is the antenna. It may be defined as a transducer between a guided electromagnetic (EM) wave propagating along a transmission line, and an EM wave propagating in an unbounded medium (usually free space) or vice versa.[1] The antenna is required to transmit or receive EM energy with directional and polarization properties suitable for the intended application.

This multi-part tutorial explores the radiation properties of rectangular microstrip antennas—specifically, the radiation method, coupling of the feed structure to the microstrip radiating element (or elements in the case of array structures), and the simple transmission-line model utilized for design and performance estimates. Parts 1 and 2 of the series explore the single-element, rectangular microstrip antenna. Later installments will examine the properties of antenna arrays constructed from the ensemble of single microstrip elements.

ANTENNA PARAMETERS AND DEFINITION[2]

Parameter	Definition
Radiation Pattern	A mathematical function or graphical representation of the radiation properties of an antenna as a function of geometric, typically spherical, coordinates.
Radiation Pattern Beamwidth	The angular separation between two identical points on opposite sides of the radiation pattern maximum – generally, the value definition is the half-power point..
Sidelobe Level	The portion of the radiation pattern bounded by relatively weak radiation intensity.
Directivity – D	The ratio of the radiation intensity in a given direction to the radiation intensity averaged over all directions – maximum radiation is the implied direction; a measure of the ability of the antenna to focus radiated power in a given direction.
Gain – G	The ratio of the radiation intensity in a given direction to the radiation intensity of an isotropic antenna with the same input power – unlike directivity, gain also accounts for antenna efficiency.
Efficiency –η	A numerical term that accounts for losses of the antenna from the input terminals and all elements of the antenna structure.
Effective Area – A_e	The ratio of the available power at the terminals of an antenna to the power flux density from a plane wave incident normal to the antenna.
Aperture Efficiency	The ratio of the effective area, A_e, of an antenna to the physical area, A_{ph}, of the antenna – mathematically.: $G = \frac{4\pi}{\lambda^2} \cdot A_e$ and $G = \frac{4\pi}{\lambda^2} \cdot \eta \cdot A_{ph}$
Polarization	Indicates the time-varying direction of the electric field vector – vertical, horizontal, and circular polarization are typical.
Input Impedance	The ratio of voltage to current at the input terminals of the antenna.

ANTENNA CHARACTERIZATION

Antennas are characterized and described by classification and descriptive parameters. In addition to microstrip or printed antennas, other classes of antennas are wire (e.g., dipole or loop); aperture (e.g., horns); reflector (e.g., parabolic); and lenses. The microstrip antenna may be considered a wire antenna due to the associated property of current on the radiating element. However, microstrip antennas are commonly granted the distinction of a separate antenna classification.

The most notable antenna parameters and definitions are summarized within *Table 1*.

In addition to the antenna definitions, understanding descriptive antenna parameters requires a graphical and geometric reference. That reference is

MICROSTRIP ANTENNA ATTRIBUTES[3, 4]	
Positive Attribute	**Negative Attribute**
Low cost fabrication – printed circuit manufacturing methods	Narrow bandwidth – bandwidth increase generally requires increasing volume
Surface conformable – facilitated by flexible substrate materials	Sensitive to temperature and humidity – low-loss substrates utilize PTFE in composite
Mechanically stable – dielectric substrates may use composite ceramic filled construction	Limitation on maximum gain
Polarization diversity – readily achieved using alternate feed methods	Poor cross-polarization – limited element and feed isolation
Flexible gain and pattern options – readily achieved using alternate feed methods and array techniques	Spurious radiation – surface and other propagation modes
Ease of integration with other passive and active functions – achieved via compatibility with passive and active components	Low efficiency due to dielectric and conductor losses
Low profile – low-profile planar construction	Modest power handling

provided by the spherical coordinate system as defined in *Figure 1*.

In the following discussion, geometric planes are referenced with respect to the graphic of *Fig. 1*. Specifically, the *E*-plane *(y-z)* refers to the conditions:

$$\phi = \pi/2 \text{ and } -\pi/2 < \theta < \pi/2$$

while the *H*-plane *(x-z)* refers to the conditions:

$$\phi = 0 \text{ and } -\pi/2 < \theta < \pi/2$$

The *E*-field and *H*-field of the radiated signal lie in the respective planes. Polarization of the radiated signal is defined with respect to the *E*-field.

For a microstrip antenna, radiation intensity is typically confined to the upper half hemisphere, i.e. above the *x-y* plane with radiation intensity in the positive *z*-direction.

MICROSTRIP ANTENNA DESCRIPTION

The microstrip, or patch, antenna is a relatively new development that was originally patented in 1955 but did not find broad application for almost two decades. Construction of a microstrip antenna embodies a dielectric substrate with a ground-plane conductor on one side and a thin, radiating conductor element on the opposite side *(Fig. 2)* in which the radiating element is a rectangular conductor attached directly to a microstrip feed line.

The principal attributes of microstrip antennas are summarized in *Table 2*.

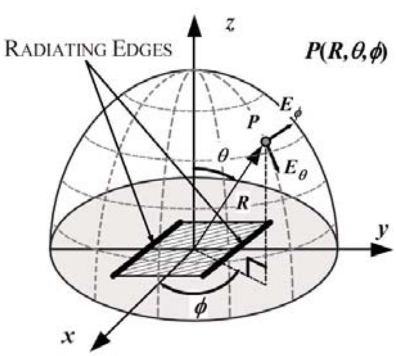
In a properly designed microstrip antenna, the radiation intensity is in a direction normal to the radiating element (i.e., broadside). For the rectangular microstrip antenna, the length, *L*, is typically one-third to one-half wavelength long, depending on the substrate relative dielectric constant, which is commonly 2.0 to 10.0. The lower values of dielectric constant yield higher efficiency.

The substrate height, *h*, is another a critical parameter with respect to efficiency and bandwidth. It's also important in terms of reducing undesired propagation modes at the conductor edges and within the substrate.

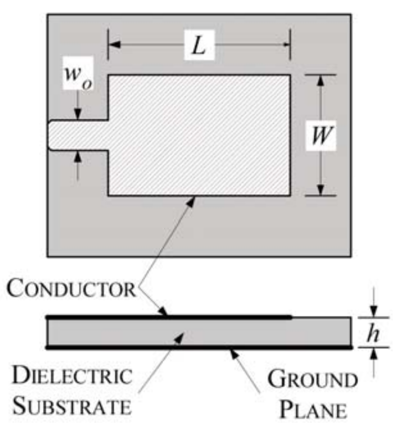
Several techniques are available for the introduction of RF energy to the radiating microstrip via the feed-line structure. In some cases, alterations in the feed-line structure have the potential for attendant changes to the efficiency, gain, and bandwidth of the microstrip antenna. The most common feed structure for the rectangular microstrip antenna is direct attachment at the radiating edge as illustrated in *Fig. 2.*

The rectangular microstrip antenna geometry is most popular. However, alternate shapes (e.g., circular and triangular), provide utility in certain applications. Thin strips for the implementation of half-wavelength dipoles are attractive for increasing the operational bandwidth. To maintain brevity, the emphasis within this tutorial is restricted to microstrip antennas of rectangular geometry.

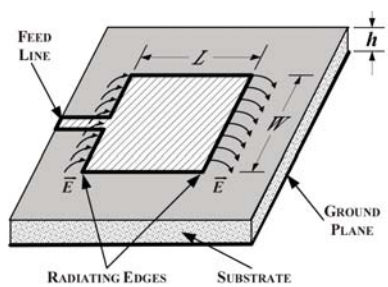
The graphic of *Figure 3* represents the rectangular microstrip antenna with the various parameters identified. Note specifically the radiating electric-field con-



1. Spherical coordinate system.



2. Microstrip antenna construction.



3. Rectangular microstrip antenna—radiating edges.

figuration at each edge of the microstrip conductor. Because the effective length of the microstrip conductor is a half-wavelength, the electric field is at maximum at the left and right edges due to the effective open circuit and the repeating field pattern at half-wavelength intervals.

The radiation intensity is significantly influenced by the conductor length, L, and width, W, and to a lesser extent the substrate height, h.

The microstrip conductor is located at the boundary of two dielectric materials: the substrate below the conductor and the air above. Since part of the electric field is located within the substrate material and part in the air, the relative dielectric constant of the substrate must be modified to accommodate the influence of the dielectric boundary. The accommodation is represented by the mathematical definition of the *effective* dielectric constant.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \frac{1}{\sqrt{1 + \frac{12h}{W}}} \quad \text{for } \frac{W}{h} > 1$$

In addition to the influence of the dielectric substrate and air boundary, the impact of fringing of the electric field at the edges of the conductor must be accommodated. Electric field fringing at conductor edges may be accurately modeled by lumped-element capacitors that effectively increase the electrical length of the conductor at each edge by an incremental length, ΔL. The incremental length is represented mathematically:[5]

$$\Delta L = 0.412 \cdot \frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.80\right)} \cdot h$$

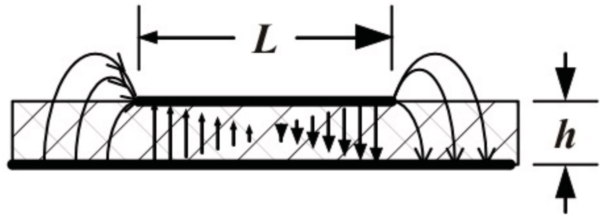
Thus, the effective electrical length of the conductor may be written:

$$L_{eff} = L + 2\Delta L$$

As mentioned earlier, the electrical length of the microstrip conductor at resonance is λ/2. Therefore, accounting for the fringing, the resonant frequency, f_o, or corrected operating frequency, f_{rc}, may now be written:

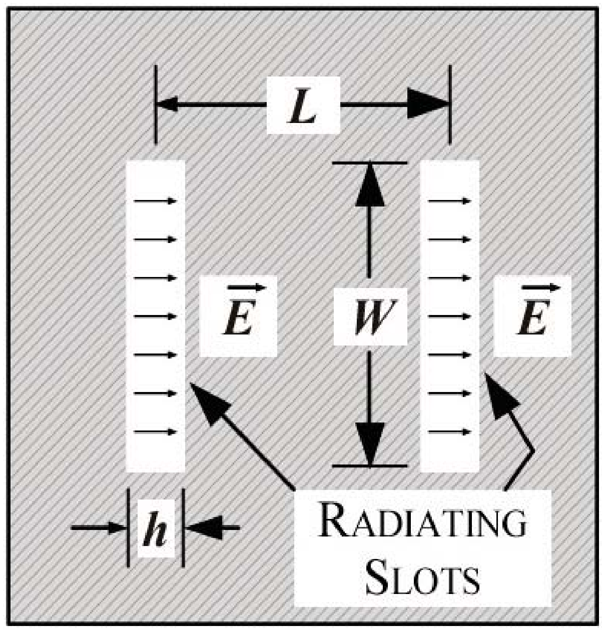
$$f_o = \frac{c}{2\lambda} = \frac{c}{2 \cdot L_{eff} \cdot \sqrt{\varepsilon_{eff}}} = f_{rc} = \frac{c}{2(L + 2\Delta L)\sqrt{\varepsilon_{eff}}}$$

The rectangular microstrip antenna is uniquely represented by the transmission-line model, which provides a simple analysis method as well as an intuitive understanding of the radiation mechanics and other operational parameters. It's also instructive to examine the relative magnitude of the E-field below the conductor to gain additional physical insight. That brings us to *Figure 4*. Note specifically the E-field fringing at each end of the microstrip line, as well as the dual dielectric occupancy mentioned earlier.



4. Electric field distribution of rectangular microstrip antenna.

The transmission-line model of the rectangular microstrip antenna utilizes an equivalent radiating slot of width W, and height h, to represent each of the radiating edges *(Fig. 5)*.



5. Radiating slot equivalence to microstrip edges.

Each slot may be represented by an equivalent admittance consisting of a conductance and susceptance:

$$Y = G + jB$$

The admittances are separated by a transmission line of length, L, and characteristic impedance, $Z_o = 1/Y_o$, thereby forming the equivalent network of the microstrip antenna *(Fig. 6)*. The equivalent circuit provides a convenient method of input impedance calculation upon numeric evaluation of the conductance and susceptance.[6]

(Continued on page 62)

DON'T BYPASS the Right Capacitors for Your Design

Any engineer knows that capacitors are a fundamental building block in RF/microwave systems. Bypass networks are one example—they require capacitors to bypass ac signals to ground. For such cases, rules-of-thumb or approximate equations can be used to select the best capacitor for the job. However, those approaches may not always be valid. In the technical paper, "Choosing blocking capacitors - it's more than just values," Knowles Precision Devices discusses real-world capacitor performance and then presents measurement results of various capacitor bypass networks.

For bypass applications, the paper explains that capacitor values are chosen to provide a low-resistance ground path for unwanted noise signals. It then presents the familiar mathematical expression of capacitor reactance. This equation allows one to determine the theoretical capacitor values needed to provide a low-resistance path to ground for a signal at a given frequency.

In practice, actual capacitors are modeled as a combination of capacitors, inductors, and resistors. A low impedance is realized at a capacitor's first self-resonant frequency. Above the resonant frequency, the impedance rises as the frequency increases. The paper illustrates this by presenting impedance plots of several capacitors with different values. Furthermore, a common approach to enable broadband RF isolation involves shunting three or four capacitors, each with different values, to ground. Oftentimes, designers employ this method by simply following the recommendations from a manufacturer's datasheet.

Knowles Precision Devices, 277 Hwy 20, Cazenovia, NY 13035; (315) 655-8710; www.knowlescapacitors.com

The paper continues by breaking down the parasitic inductance that's present in a capacitor. It's noted that increasing a capacitor's contact pad size can reduce the parasitic inductance. Mention is made of a new manufacturing process that allows for larger pad areas in capacitor footprints without compromising the voltage rating.

Real measurements are shown of the V-Series capacitors, demonstrating how one of them can offer broadband performance that's typically achieved by bypass networks with multiple capacitors. Additional measurement results compare the performance of a traditional capacitor bypass network with a V-Series capacitor by itself, as well as with a UX-Series capacitor in combination with a V-Series capacitor.

MEASURE DISTORTION with Confidence

TESTING UNWANTED AND nonlinear spectral distortion is critical—distortion not only degrades transmitter performance, but also receiver sensitivity. For signal generators, distortion performance is an important attribute that can significantly impact device characterization. In the white paper, "Tactics for Improving Distortion Measurements," Keysight Technologies explains the different types of distortion along with effective measurement techniques.

The white paper begins by providing a basic definition of distortion, explaining that it's the alteration of an original waveform. While a linear device does not create distortion, applying an input signal to a nonlinear device can result in an output with a frequency shift or additional frequencies.

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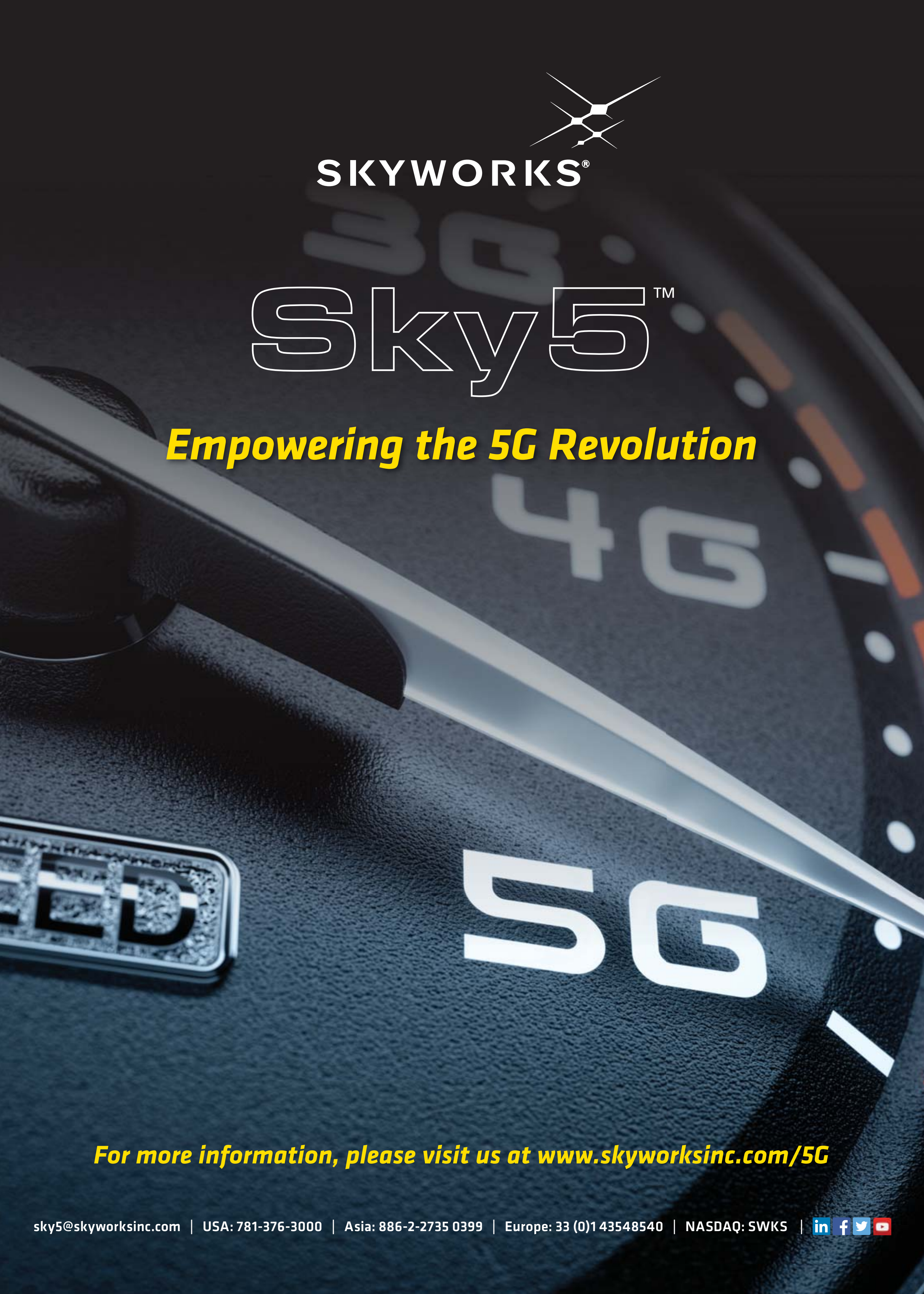
Harmonic distortion and intermodulation distortion (IMD) are two major types of nonlinear distortion. Harmonic distortion results in an output with frequency components at integer multiples of the input frequency. IMD is a result of mixing of two or more signals at different frequencies—whether these signals are created in the system or not.

Using a continuous-wave (CW) tone is the most straightforward approach to measuring harmonic distortion, according to the white paper. In such scenarios, the device under test (DUT) could be an amplifier or mixer. A signal generator can be used to provide the input signal to the DUT. The document points out that it's important to use a generator with low harmonic distortion. Another crucial step is to include a lowpass filter between the signal generator and DUT to ensure that measured harmonics come from the DUT and not the generator. Furthermore, the common two-tone technique for IMD measurements is described. Block diagrams of both harmonic distortion and IMD measurement setups are presented.

The paper notes that the two-tone third-order IMD technique does not completely characterize the behavior of wideband components. Specifically, digital modulation techniques can generate what's known as spectral regrowth. Examining this type of distortion requires adjacent-channel-power-ratio (ACPR) measurements, which are key for meeting most cellular conformance specifications. For ACPR measurements, the document notes that generating a specific standard-compliant test waveform requires a signal generator with ultra-low-distortion performance.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JOE ROWAN | President and CEO of USA and Europe, Junkosha
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Interconnect Quality, Phase Stability Can Make or Break 5G Future

It seems like 5G communications grabs lots of headlines, while interconnects often fade into the background. Junkosha's Joe Rowan reverses that trend, answering questions on the crucial roles they play in the 5G era.

1. The MWX061 cable can be used at frequencies as high as 67 GHz.

Is the performance of cables and interconnects one of the greatest barriers to delivering a 5G world?

Fifth-generation wireless, or 5G as it's more commonly known, is the latest iteration of cellular technology, engineered to greatly increase the speed and utility of wireless technology. 5G isn't just an incremental improvement over 4G—it's the next major evolution of mobile communication technology with performance improvements of an order of magnitude over today's networks. 5G does not replace 4G—it simply enables a wider diversity of tasks that 4G alone cannot perform. 4G will continue to advance in parallel with 5G as the network to support more routine tasks. The new high-frequency network will enable services that are yet to be imagined as connected technologies touch every aspect of our lives.

Beyond the fundamental but highly technological challenges of ensuring that the 5G network will work, a number of significant hurdles will need to be overcome by operators. For example, spectrum availability is not limitless. With the radio frequencies of 3G and 4G becoming increasingly crowded, 5G will have to operate at even higher frequencies to deliver the faster data speeds. This brings into play the millimeter-wave (mmWave) band, which has its own unique challenges with issues of reliability and ruggedness of cabling.

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 rigors of higher frequencies and environments with high temperature and flexure. The challenge of companies like Junkosha that deliver these solutions is: How do we change engineers' perceptions of cabling and interconnects into the future?

To meet the higher speed and capacity demands, 5G will have to turn to mmWave frequencies to be successful. With capacities of up to 1.4 Gb/s at a median speed of 28 GHz, 5G will be as much as 10 times faster than the previous incumbent (4G). This step change in speed brings with it demands and complications never witnessed before.

What are the demands of this mmWave world?

To meet the higher speed and capacity demands, 5G will have to turn to mmWave frequencies to be successful. With capacities of up to 1.4 Gb/s at a median speed of 28 GHz, 5G will be as much as 10 times faster than the previous incumbent (4G). This step change in speed brings with it demands and complications never witnessed before.

Today, the demand for mmWave frequencies is no longer the preserve of military and research applications; instead, it's now being demanded in mainstream technologies like 5G. The requirement for high-speed data applications are driving innovations in today's technology-driven world.

At the higher mmWave frequencies, "phase performance that endures" is a statement that the 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 not trivial. In addition, the amount of bending and stress the cabling endures is significant, resulting in an environment that requires phase-stable cables to be installed.

After all, 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's so important that engineers use cabling and interconnects built for the 5G world.

Do the characteristics of the cables required for mmWave frequencies need to be of higher quality?

The short answer to this question is yes—the interconnects used should be of the highest quality to withstand the rigor they are put through in each scenario. Examples include the system development or device characterization phases where precision and repeatability are required, as well as in the stages of commissioning the overall system and monitoring during the production test environment.

At the mmWave level, the connector designs used are very small—2.4 mm down to 1.85 mm and even 1 mm is now required. These small sizes have a considerable effect on the engineer's ability to transition from the connector to the cables, which needs the highest levels of precision and accuracy to implement. On completion of this task, the next activity is to test the assemblies in a test environment, using such equipment as a vector network analyzer (VNA). Here, instances of flexure and movement significantly impact the accuracy of results, which is accentuated as frequencies increase.

At this miniaturized, high-frequency level, the quality of the cables and the connectors used must be of the highest order. The reason is very simple: With cheaper alternatives, the cabling often lasts less than a year, meaning replacements are required on a frequent basis. With high-end cabling and interconnects, such as Junkosha's MWX051 and MWX061 *(Fig. 1)*, engineers can rigorously test for periods of approximately three and a half years.[1]

What are the key challenges to the assembly or interconnect manufacturer?

5G is foremost about enhanced mobile broadband, requiring much greater throughput than its 3G or 4G predecessors. The vision for 5G includes ultra-low-latency speeds to enable futuristic applications, such as the heralded potential benefits of connectivity across smart cities and autonomous transport. However, implementing 5G has many significant challenges, not the least of which is exploiting mmWave frequency bands, which has proved a major step.

At the mmWave frequency level, path loss presents a key issue. Obstacles such as vegetation, walls, and even glass, as well as the general interference encountered in urban environments, all have a major effect. In addition, to enable a future of machine-to-machine communications—which ultimately means far more connected devices than we have today—greatly reduced latency is required to enable real-time applications. Lastly, the requirement to generate much more power presents a considerable hurdle for the interconnect manufacturer, since a higher insertion loss is a fact of life at the mmWave level for cable assemblies.

Another consideration for everyone operating in the 5G sector is the current lack of standards. Although these are anticipated, nothing is likely until the end of 2018 at the earliest. Even then, this will only be the start; more will come as we develop the technologies required over the course of 2019 and 2020. Therefore, the operators in this market must sort out the essential 5G features and functionalities without an appreciation of what standards they will have to meet, which isn't ideal. From a cable manufacturer's perspective, we must be sensitive to the end user's need for a system that will not only operate at the mmWave frequencies, but also perform at the highest standards and remain compliant.

Interconnects for the 5G world must be flexible, repeatable, and durable to withstand an environment that will test them beyond their limits. These requirements are not easy to meet, and it takes considerable precision and expertise to create a cabling solution that engineers will be hard-pressed to improve upon.

Has Junkosha developed a solution?

Junkosha has been developing very high-frequency interconnects since the 1980s. Collaborating with Gore, the team created a mmWave dielectric waveguide. At that time, the applications were unique bespoke projects, often within the defense sector.

Earlier this year, at IMS 2018, Junkosha launched its MWX051 and MWX061 interconnects that target a new era of high-frequency communications *(Fig. 2)*. Reaching frequencies up to 70 GHz, these next-generation cabling solutions provide engineers with the highest-quality phase-stable interconnects designed to withstand the most rigorous of testing environments for periods of up to three years. Featuring high tensile strength, a low dielectric constant, and high flex life thanks to the company's precision-engineered expanded-PTFE tape-wrapping technology, these new interconnects will test engineer's resolve to stick with lower-quality, lower-cost alternatives.

With these new solutions, original equipment manufacturers (OEMs) operating in the 5G arena are better able to test their systems with confidence and longevity in mind.

How have they achieved phase stability on these high frequencies?

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

2. Junkosha's MWX051 and MWX061 cables were on display at IMS 2018.

This technique, uniquely implemented by only two manufacturers in this space, allows Junkosha to deliver a flexible cabling assembly at these high frequencies that provides "phase performance that endures" over time.

What does the future hold?

5G is set to completely transform the way we do business. Bringing enormous data capacity, rapid speeds, and incredibly low latency, 5G marks a huge step up from its 4G predecessor.

The future is a connected future, with millions more connected devices set to enter the marketplace. Not only will it boost efficiency, but it will also enable us to explore developing technologies well into the 2020s and 2030s. Anticipated technologies include connected and autonomous cars, smart cities, and the Internet of Things (IoT), all of which will bring a huge amount of devices that require connection to the wireless network for the operation of immersive entertainment (virtual and augmented reality). Furthermore, thanks to unprecedented transfer speeds, they will be able to realize the benefits of big data.

The reason for looking to the future is that, whether we like it or not, 5G is part of all our futures, and we need to embrace it. And it won't stop there. We are continually asked for cabling solutions that take us beyond current speeds and frequencies, moving us to a world we can barely imagine.

However, with significant change comes significant challenges that will affect everyone. The cabling and interconnects, often cited as the weakest link of many systems, is one such area in need of innovation. Operating at mmWave frequencies since the mid-1980s, Junkosha was one of the organizations that foresaw the need for these high-end frequencies beyond just the military. Innovating the future through technologies for 5G will bring about a wireless network that will change the mobile telecoms space forever. mw

REFERENCE

1. This is 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.

JACK BROWNE | Technical Contributor

PCB Antenna Demand Skyrockets in Wireless Design

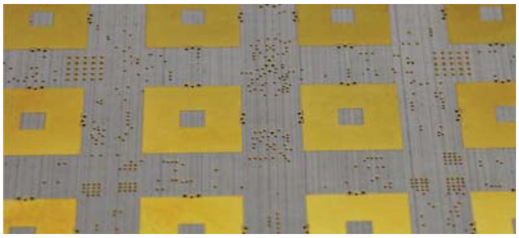
As consumers clamor for the latest and greatest in wireless, it's fueling a need for PCB antennas that can be easily mounted inside wireless communications products.

Antennas are critical components for many wireless systems, with printed-circuit-board (PCB) antennas leading the pack due to their small size and ease of integration with other high-frequency circuits. The performance and consistency of a PCB antenna depends heavily on the quality of its foundation circuit laminate, with size very much a function of the target frequency and wavelength of the antenna.

There's no doubt a voracious appetite for wireless applications—from personal communications systems (PCS) to Internet of Things (IoT) apps, to automotive electronic control and safety systems. And as operating frequencies creep higher, from the 2.4-GHz band of PCS applications to the millimeter-wave (mmWave) frequencies of automotive advanced driver-assistance systems (ADAS), the needs for antennas accompanies them. That's where PCB antennas step in—designers often turn to them as practical solutions to handle the ever-growing array of wireless applications.

High-frequency PCB antennas can be as simple as a microstrip patch fabricated on one side of a circuit laminate with a slightly larger ground plane underneath it, on the other side of a dielectric layer. The low profile of such antennas makes them attractive for mounting within systems that have any available flat surface.

Of course, the antenna radiation pattern from such a simple microstrip patch will be limited. PCB antennas working with microstrip patches often combine several patches on one PCB to achieve higher gain for a given operating frequency. The size the patch will depend on the wavelength of the target operating frequency, with one-half wavelength typically selected to optimum resonant antenna characteristics at the target frequency.



1. Some manufacturers offer extended capabilities for fabricating PCB antennas on a wide range of circuit materials and according to a customer's precise requirements. *(Courtesy of Advanced Circuitry International)*

Certainly, RF/microwave PCB antennas can be fabricated with many different transmission-line technologies, such as stripline and coplanar-waveguide transmission lines. They may even combine several different transmission lines within the same PCB antenna design.

WHAT'S OUT THERE?

PCB antennas are available from many suppliers as fabricated components that can be added to a system design; several manufacturers also offer services to construct PCB antennas according to computer-aided-engineering (CAE) design files or custom mechanical requirements. For example, Advanced Circuitry International (ACI, *www.aciatlanta.com*) can manufacture large antennas (for lower frequencies) or large volumes of smaller antennas on large circuit boards, such as 12 × 18 in. and 18 × 24 in., using single-sided, double-sided, and multilayer PCB antenna configurations *(Fig. 1)*.

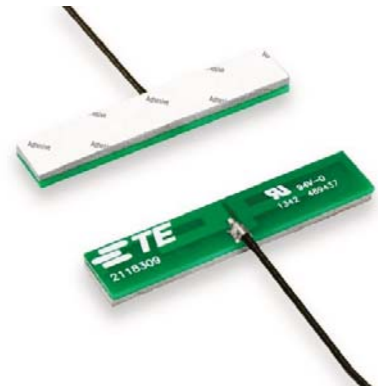
ACI fabricates antennas on a variety of different substrate materials, including high-performance flexible circuit materials from DuPont *(www.dupont.com)* as well as RF/microwave circuit laminates from leading circuit material suppliers such as Arlon *(www.arlonemd.com)*, Isola *(www.isola-group.com)*, Rogers Corp. *(www.rogerscorp.com)*, and Taconics *(www.4taconic.com)*.

The PCB antennas are often supplied with an adhesive to simplify mounting within an intended application. Choosing such a circuit material as the foundation for a PCB antenna is critical to its short- and long-term performance (see p. 37), especially as PCB antennas are being used at higher mmWave frequencies and in more hostile operating environments (e.g., ADAS applications).

GENERAL ASSEMBLIES

In some cases, PCB antennas are supplied as "assemblies," complete with a connected coaxial cable and connector for quick and easy interconnections to an internal circuit board. One such PCB antenna supplier, TE Connectivity *(www.te.com),* has developed an extensive line of PCB antennas with cables and connectors to accommodate a wide range of frequency bands for personal communications systems applications.

Specifically, there's the company's Model 2118060-1 PCB antenna assembly *(Fig. 2)*. It can be supplied for operating frequencies from approximately 2.4 to 2.5 GHz for Bluetooth, Wi-Fi, and wireless local-area networks (WLANs). The cable is 13.78 in. (350 mm) in length, with choice of different types of connectors, such as MCIS and MHF connectors; the PCB antenna includes adhesive for mounting on a flat surface.



2. This PCB antenna is considered an assembly, with interconnecting cable and connector and adhesive for ease of integration and mounting in different applications. The antenna assembly (model 2118060-1) is designed for use from 2.4 to 2.5 GHz. *(Courtesy of TE Connectivity)*

Similarly, the model FXP07.07.0100A from Taoglas Antenna Solutions *(www.taoglas.com)* is a low-profile flexible PCB antenna with short length of cable and IPEX connector and adhesive tape to facilitate stick-on mounting on flat surfaces *(Fig. 3)*. The RoHS-compliant antenna is designed for use with "Pentaband" frequencies, which include AMPS from 824 to 896 MHz, GSM from 880 to 960 MHz, DCS from 1710 to 1880 MHz, PCS from 1850 to 1990 MHz, and UMTS from 1710 to 2170 MHz. The compact 50-Ω antenna measures 41 × 24 mm with linear polarization and an omnidirectional radiation pattern.

(Continued on page 57)

JACK BROWNE | Technical Contributor

Downconverter Tackles 12 mmWave Channels

This multichannel frequency downconverter module provides frequency translation of mmWave signals through 50 GHz to lower-frequency bands for signal processing.

Millimeter-wave frequency spectra offers invaluable bandwidth for automotive, communications, research, and other applications if those frequencies can be downconverted to lower-frequency bands for analysis and study. The model A20-MCH313 frequency downconverter from AKON *(www.akoninc.com)* provides such frequency downconversion for 12 parallel channels of mmWave signals. It leverages a common local-oscillator (LO) source for the downconversion process.

The downconverter is driven by compact hybrid microwave-integrated-circuit (MIC) modules. It performs frequency conversion of 12 signal channels across any 200-MHz frequency span from 36 to 37 GHz to a lower, output intermediate-frequency (IF) band from 335 to 535 MHz for ease of signal processing.

Used at lower power levels, the 12-channel downconverter's hybrid MIC modules include a six-channel LO generator *(Fig. 1)* and six dual-channel, frequency-downconverter modules *(Fig. 2)*. The LO source module works with an external reference oscillator capable of producing 9.0625 MHz at 0 dBm. It provides LO signals to the six dual-channel, frequency-downconverter modules. Each input channel of the downconverter modules includes a low-noise amplifier (LNA), an image-reject filter, frequency mixer, IF bandpass filter, and IF amplifier. The 12 input channels are identical, and all convert the same RF input band from 36 to 37 GHz to the same output IF band from 335 to 535 MHz.

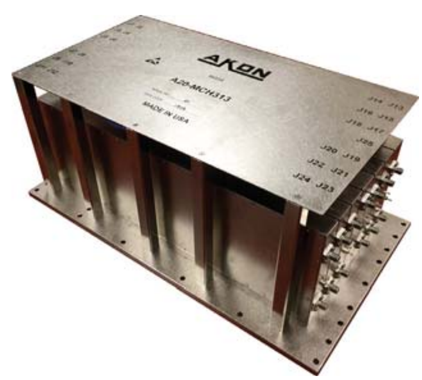
The A20-MCH313 fixed-frequency downconverter array maintains a noise figure of 4 dB or better with nominal conversion gain of 67 dB. It can process input mmWave signals across a wide dynamic range of –87 to –55 dBm while providing 25-dB image rejection for all input signal levels.

The overall downconverter assembly measures a compact 14.0 × 8.0 × 5.8 in., including baseplate and cover with 2.92-mm female RF input connectors and SMA female output IF connectors. It's designed for operating temperatures from +15 to +40°C—a test laboratory is an example of a typical operating environment. The downconverter assembly requires a +12-V dc bias source to power its active components.

Versions of the 12-channel frequency downconverter can be supplied for customer-defined bands at frequencies to 50 GHz, in sealed housings for a wide range of applications. The RF-to-IF conversion gain is nominally 67 dB for custom designs with better than 25-dB IF stopband rejection and –25 dBc minimum image rejection across the passband. The LO generation modules work with reference frequency input of 9.0625 MHz at a nominal input level of 0 dBm, and a "no damage" RF input levels to 0 dBm while generating an IF output dynamic range of –20 to +12 dBm. mw

AKON INC., 2135 Ringwood Ave., San Jose, CA 95131; (408) 432-8039, FAX: (408) 432-1089, e-mail: sales@akoninc.com, www.akoninc.com.

1. This module provides common stable LO signals for the mmWave frequency downconversion modules.



2. This hybrid MIC module contains 12 channels of frequency downconversion to translate mmWave input signals to lower-frequency IF output signals.

JACK BROWNE | Technical Contributor

Arbitrary Function Generators Redefined

The impressive command, control, and functionality of these test signal sources greatly simplifies the creation of the complex waveforms needed for testing modern systems.

Test signals are becoming more complex with the components and systems they characterize. Although such signals are needed to evaluate the performance of an expanding array of electronic devices, generating the necessary test signals—with advanced modulation—is often the most difficult part of running a device under test (DUT) through a required set of measurements.

Fortunately, the instrument developers at Tektronix are also users of test equipment, and a great deal of that personal touch can literally be found in the company's latest arbitrary function generators (AFGs), the AFG31000 series. The AFGs use a touchscreen to create almost any kind of test signal waveform or sequence of waveforms.

This line of compact one- and two-channel test signal sources with signal bandwidths to 250 MHz combine high performance, usability, and flexibility, essentially bringing complex test signal waveforms "down to earth." The AFGs show all of the details on the industry's largest display screen in this class of instrument: a 9-in. (diagonal) capacitive touchscreen that, when teamed with a new user interface, helps speed and simplify the creation of the test signal waveforms needed to evaluate the latest electronic devices and systems.

The different members of the AFG31000 series of AFGs share the large display screen and intuitive user interfaces on their front panels *(Fig. 1)*. They leverage the handy capacitive touchscreens to ease instrument control and measurement programming as well as real-time waveform monitoring *(Fig. 2)*.

The test signal sources can operate in two operating modes: Basic and Advanced modes. The Basic mode can be thought of as a simple means of creating traditional waveforms, such as sinewaves or pulse trains, as well as defining arbitrary waveforms. The Advanced mode is for more elaborate sequences that may combine different waveforms and complex signals that could require some measure of programming. Still, the Basic mode does enable some useful degree of tuning that can aid certain measurements; for example, in Basic mode, it is possible to change frequency without changing waveform length or sample rate, which is useful when characterizing analog filter circuits.

1. The AFG31000 Series of arbitrary function generators (AFGs) combine precise signal-generation power with an intuitive user interface for ease of control.

2. A large capacitive touchscreen helps in creating and monitoring waveforms and sequences of waveforms.

ADVANCED MODE

To generate the complex waveform patterns typically associated with an arbitrary waveform generator (AWG), many users will explore the Advanced operating mode of these signal sources, exploiting its capabilities of orchestrating multiple waveforms with complex timing.

It will take quite an ambitious user to exceed the memory storage limits of the AFG31000 series, since these instruments incorporate enough waveform memory to store a list or sequence of waveforms from 1 to as many as 256 waveforms. Standard memory supports waveform length to 16 Mpoints/channel for those 256 waveforms, and as much as 128 Mpoints/channel memory is available as an option for one- or two-channel models.

Creating sophisticated sequences of waveforms takes time and will depend on the requirements of a particular DUT and its applications. However, the AFGs include functions such as repeat, wait, and jump to help speed and simplify the waveform/sequence creation process.

For establishing sequences of precisely controlled, individual waveforms, the Advanced mode incorporates variable-sample-rate technology. Every sample in a waveform is output once during each cycle of the waveform and synchronized to the sample rate for that waveform and/or test signal sequence. Since waveforms are not copied or duplicated, even the smallest differences between similar waveforms are preserved and all of the details of a complex sequence of waveforms are maintained. The Advanced mode is extremely useful for generating and saving unique waveforms, such as degenerative pulse trains or specialized versions of in-phase/quadrature (I/Q) signal modulation in high-data-rate communications links.

THE AFG31000 SERIES AT A GLANCE

Model	Bandwidth	Channels	Maximum sample rate
AFG31021	25 MHz	1	250 Msamples/s
AFG31022	25 MHz	2	250 Msamples/s
AFG31051	50 MHz	1	500 Msamples/s
AFG31052	50 MHz	2	500 Msamples/s
AFG31011	100 MHz	1	1 Gsample/s
AFG31102?	100 MHz	2	1 Gsample/s
AFG31151	150 MHz	1	2 Gsamples/s
AFG31152	150 MHz	2	2 Gsamples/s
AFG31251	250 MHz	1	2 Gsamples/s
AFG31252	250 MHz	2	2 Gsamples/s

PROVIDING PERFORMANCE

The AFG31000 series is designed to simplify the generation of complex waveforms, but they don't skimp on performance. Waveforms can be created with as much as 14-b vertical resolution and with sample rates of 250 Msamples/s, 500 Msamples/s, 1 Gsample/s, or 2 Gsamples/s to define the most imaginative wave shapes. Sampling clocks can be set across a wide range of rates, from 1 µsample/s to 2 Gsamples/s.

Output signal are delivered across an amplitude range of 1 to 10 V p-p into 50-Ω loads. For those who may just need a traditional test signal for the moment, the AFGs also provide a host of built-in waveforms available with the push of a button, including sinewaves, square waves, ramps, pulses, and noise outputs. Standard modulation formats are quickly available, too, including amplitude modulation (AM), frequency modulation (FM), phase modulation (PM), frequency shift keying (FSK), and pulse-width modulation (PWM).

Combined with their precise and accurate waveforms, the flexible control offered by the AFGs' capacitive touchscreens will provide a strong invitation for many engineers to try their hand (again, literally) at creating a required waveform or sequence of similar or different waveforms. For those comfortable with building a test waveform based on the measurement acquisitions of an oscilloscope, the AFG31000 series AFGs can also directly load .csv signal-acquisition files saved from an oscilloscope to replicate those waveforms on one of the AFG31000 AFGs.

The AFGs come with one or two channels and many choices of performance levels *(see table)*. However, all share the usability of the capacitive touchscreen and powerful measurement software to make the task of waveform generation a bit easier.

For example, the patented, built-in InstaView technology allows operators to see what a test signal waveform looks like at a DUT. It even includes the amplitude and phase effects of interconnecting cables and connectors (which are added), without connecting an oscilloscope. The built-in multiple-unit sync, as a step-by-step wizard, also helps make a simple task of synchronizing multiple AFG31000 AFGs or other signal sources when extremely complex test signal waveforms are needed.

The PC that up to now has been required to configure waveforms on AFGs is not needed with the AFG31000 instruments, which include ArbBuilder software to create and edit arbitrary waveforms. For educational purposes, the AFGs are compatible with the company's TekBench software to allow students and engineers alike opportunities for studying created waveforms and sequences of waveforms. P&A: $2,210 and up. mw

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CHRIS DeMARTINO | Technical Engineering Editor

These Oscilloscopes Don't Leave Any Application Behind

With bandwidths that range from 13 to 110 GHz, this new series of oscilloscopes offers low-noise performance and multiple other features to appease all test situations.

While Keysight Technologies (*www.keysight.com*) is no stranger to oscilloscopes, the company reached a new milestone with the recent introduction of the Infiniium UXR-Series *(Fig. 1)*. Consisting of 21 models, this series of oscilloscopes covers bandwidths ranging from 13 to 110 GHz. Keysight boasts that the UXR-Series "provides the market's highest bandwidth along with industry-leading performance in terms of noise, jitter, and effective number of bits (ENOB)."

As stated, the UXR-Series consists of 21 models. Four channels are included with those models that have bandwidths ranging from 13 to 33 GHz. Customers looking for models with bandwidths anywhere between 40 and 110 GHz can choose either two- or four-channel versions.

Furthermore, 3.5-mm input connectors are built into UXR-Series models with bandwidths as high as 33 GHz; instruments with bandwidths between 40 and 70 GHz are built with 1.85-mm connectors. Also available for purchase is a 59-GHz model with 1.0-mm input connectors. Finally, 80-, 100-, and 110-GHz models all come with 1.0-mm connectors.

GETTING TO KNOW THE PERFORMANCE

One cannot help but notice the advanced technology built into the UXR-Series instruments. Specifically, a 110-GHz Infiniium UXR-Series oscilloscope with four channels contains over 80 custom application-specific integrated circuits (ASICs) and 13 field-programmable gate arrays (FPGAs). It also consists of nine monolithic microwave integrated circuits (MMICs) and 38 thin films.

A 10-bit analog-to-digital converter (ADC) architecture lies at the heart of the UXR-Series. It allows for a vertical resolution that's four times greater than what's attainable with an 8-bit ADC architecture. Employing a 10-bit ADC architecture also results in a better signal-to-noise ratio (SNR) in comparison to utilizing an 8-bit architecture. On top of that, the architecture enables hardware-supported vertical scaling as low as 4 mV/div. With software-assisted magnification, vertical scaling can be as low as 1 mV/div.

UXR-Series models with bandwidths as high as 33 GHz can achieve a maximum sampling rate of 128 Gsamples/s. All other higher-frequency versions reach a maximum sampling rate of 256 Gsamples/s. In addition, the ENOB is 6.8 bits at 13 GHz; 5.4 bits at 70 GHz; and 5.0 bits at 110 GHz.

Low-noise performance is a key aspect of the UXR-Series instruments. For example, a 13-GHz bandwidth model has a noise floor of 150 µVrms with a full scale of 32 mV. A 70-GHz version achieves a noise floor of 500 µVrms with a full scale of 60 mV. For a 110-GHz model, the noise floor is 860 µVrms with a full scale of 60 mV.

In terms of memory, the oscilloscopes offer a standard memory depth per channel of 200 Mpoints. Customers also have the option to upgrade to either 1 or 2 Gpoints.

OTHER SIGNIFICANT FEATURES

The UXR-Series is upgradable in more ways than one—Keysight offers the option to boost the bandwidth of these instruments. That means that the bandwidth of, say, a 13-GHz model can be upgraded to 110 GHz. In addition, any two-channel oscilloscope can be upgraded to a four-channel version.

Backwards compatibility is another notable feature of the UXR-Series. The instruments run the same software used with older Infiniium S-, V-, and Z-Series oscilloscopes; they support existing Infiniium applications; and they will run with remote command programs that have already been written.

In addition, models with bandwidths ranging from 13 to 33 GHz have the same AutoProbe II interface as Infiniium V- and Z-Series oscilloscopes. That means the same probes used with those older oscilloscopes can still be used with the UXR-Series instruments. For higher-frequency models, the same probes can be employed by applying a simple adapter.

A Keysight proprietary indium-phosphide (InP) integrated-circuit (IC) process is leveraged in the UXR-Series. This process is used in the preamplifier, trigger, sampling, and probe amplifier IC designs. The custom InP ICs designed for the UXR-Series enable the instruments to achieve bandwidths as high as 110 GHz without frequency interleaving. This is significant because frequency interleaving is a process that introduces noise and distortions to the measured signal.

1. Shown is the UXR0704A Infiniium UXR-Series oscilloscope, a four-channel model with a bandwidth of 70 GHz.

2. The N2126A self-calibration module is intended for UXR-Series oscilloscopes that have bandwidths ranging from 40 to 70 GHz.

Customers who purchase an Infiniium UXR-Series oscilloscope can also take advantage of an optional self-calibration module. With these modules, factory-quality frame calibrations can be performed on-site and under customer-specific environmental conditions. Three calibration modules are offered: the N2125A, N2126A, and N2127A *(Fig. 2)*.

In addition to high-speed digital applications, the UXR-Series can be used for a wide range of applications like optical research, aerospace and defense, 5G, and a host of others. mw

PCB Antenna

(Continued from page 52)

3. This low-profile PCB antenna assembly can support a wide range of frequencies covering a total range of 824 through 2170 MHz. *(Courtesy of Taoglas Antenna Solutions)*

4. This miniature flexible PCB antenna assembly is designed to cover the WLAN frequency bands of both 2.4 to 2.5 GHz and 4.90 to 5.85 GHz. *(Courtesy of Pulse Electronics)*

A growing trend in the design of PCB antennas is multiple-frequency-band coverage to accommodate systems with wideband frequency ranges and/or multiple applications. For instance, the CW3315B0100 line of flexible PCB antennas from Pulse Electronics (*www.pulseengineering.com)* features dual-band Wi-Fi antennas designed to cover the WLAN frequency bands of both 2.4 to 2.5 GHz and 4.90 to 5.85 GHz *(Fig. 4)*.

These are also PCB antenna assemblies, with 100-mm cables and standard IPEX connector for ease of connection to an application. The miniature antenna assemblies, which offer high efficiency of better than 50%, are designed for internal mounting in Wi-Fi products. The CW3315B0100's dual-band/wideband coverage represents a practical antenna solution for industrial applications and IoT devices as well as applications in Public Safety devices.

The ease of mounting such miniature PCB antennas using adhesives may at times result in the absence of a ground plane of any kind, which reduces efficiency. While the underside of a PCB antenna laminate is typically a ground plane, the larger ground planes required for higher efficiency can add to the physical size of a PCB antenna and must be considered when mounting the antenna in an application. mw

CHRIS DeMARTINO | Technical Engineering Editor

Average Power Sensors

Don't Settle for Average Performance

We got our hands on a new series of average power sensors from a company that's been in the business for a long time. Do they measure up?

In any RF test lab, power sensors are counted on to accurately measure RF power. Determining what power sensor to buy depends on the types of signals that need to be measured, such as continuous-wave (CW) or pulsed signals, along with other factors. This article presents a hands-on look at one of the newest power sensors on the market today from one of the long-standing firms in the industry.

Boonton Electronics *(www.boonton.com)*, located in Parsippany, N.J., has been at the forefront of RF power-measurement technology for many years. The company, a subsidiary of Wireless Telecom Group *(www.wirelesstelecomgroup.com)*, offers a range of power meters and power sensors. One of its latest to hit the market is the CPS2000 Series of true average connected power sensors *(Fig. 1)*.

1. The CPS2000 Series power sensor covers a frequency range of 50 MHz to 8 GHz.

AN OVERVIEW OF THE CPS2000 FAMILY

Boonton speaks very highly of the CPS2000 Series—the company boasts that it's "the most cost-effective average RF power sensor in its class." But how does it really stack up? Let's take a look.

Covering a frequency range of 50 MHz to 8 GHz, the CPS2000 sensors can perform true average RF power measurements of CW and modulated signals. The sensors measure signals from 50 MHz to 6 GHz at power levels ranging from −40 to +20 dBm. For signals from 6 to 8 GHz, the measurement range spans −35 to +20 dBm.

One significant aspect of the CPS2000 sensors is measurement speed—they can make over 100 measurements per second. Boonton states that is 3 to 10 times faster than other sensors in the

The latest product information presented by

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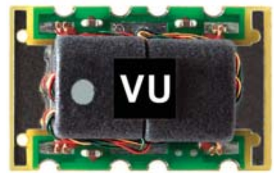
Product SPOTLIGHT

Two-Way Splitter/Combiner Covers 0.5 to 26.5 GHz

Mini-Circuits' model ZC2PD-5R263+ is a high-power, DC-pass power splitter/combiner with wideband frequency coverage of 0.5 to 26.5 GHz. It handles as much as 14 W power as a splitter with insertion loss of typically 1.8 dB or less (above the 3-dB power split). The full-band isolation between ports is typically 35 dB while VSWR is typically 1.19:1 or better at all ports. The RoHS-compliant power splitter/combiner maintains amplitude unbalance of typically 0.10 dB or better and phase unbalance of typically 1.16 deg. or better. The rugged power splitter/combiner measures 5.88 × 1.04 × 0.5 in. (149.35 × 26.42 × 12.70 mm) with super SMA connectors and has an operating temperature range of -55 to +100°C.

Miniature Surface-Mount RF Transformer Handles 15 W



Mini-Circuits' model SYTX1-53HP-15W+ is a high-power, surface-mount RF transformer for use from 20 to 520 MHz. The transformer has a secondary/primary impedance ratio of 1:1 and is capable of handling RF power levels as high as 15 W and DC current to 30 mA with proper heat sinking. Typical insertion loss is only 0.4 dB across the full frequency range, with typical amplitude unbalance of 0.15 dB and typical phase unbalance of 2 deg. The RF transformer features core-and-wire construction on a printed laminate base and is supplied in a miniature shielded packaging measuring just 0.43 × 0.69 × 0.28 in. (11.00 × 17.53 × 6.99 mm) and designed for operating temperatures from -40 to +85°C.

Ceramic Balun RF Transformer Spans 4900 to 5875 MHz

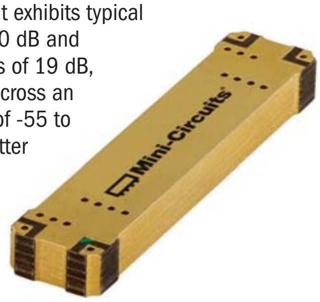
Mini-Circuits' model TCW2-63+ is a ceramic balun RF transformer with wide frequency range of 4900 to 5875 MHz well suited for radar, Wi-Fi, and WLAN wireless transmitters and receivers. The wideband 50-Ω transformer has a typical impedance ratio of 2:1 and typical low insertion loss of 1.1 dB across its full frequency range. The typical amplitude unbalance is 0.3 dB while typical phase unbalance is 4 deg. The aqueous-washable, RoHS-compliant RF transformer features low-temperature-cofired-ceramic (LTCC) construction. It measures just 0.063 × 0.031 × 0.024 in. (1.60 × 0.79 × 0.61 mm) and has an operating temperature range of -55 to +100°C.

Low-Noise Amplifier Has High IP3 from 0.5 to 8.0 GHz

Mini-Circuits' model CMA-83LN+ is a monolithic pHEMT amplifier with low noise figure and high output third-order intercept point (IP3) from 0.5 to 8.0 GHz. It has a noise figure of typically 1.6 to 1.8 dB from 0.5 to 8.0 GHz with typical gain of 19.2 dB at 8.0 GHz and 21.2 dB at 0.5 GHz. It achieves typical output IP3 of +29.4 dBm at 0.5 GHz and +26.7 dBm at 8.0 GHz, with typical output power at 1-dB compression of +17.6 dBm at 0.5 GHz, +18.0 dBm at 4 GHz, and +16.9 dBm at 8.0 GHz. The 50-Ω, RoHS-compliant amplifier operates on a single 5- or 6-V DC supply, with typical current consumption of 62 mA at 6 V DC. It is supplied in a low-profile, hermetically sealed and nitrogen-filled ceramic package measuring 0.12 × 0.12 × 0.045 in., with operating temperature range of -40 to +125°C.

Two-Way 90-deg. Splitter Commands 1.0 to 6.5 GHz

Mini-Circuits' model QCH-652+ is a two-way, 90-deg. power splitter capable of handling as much as 60 W power from 1.0 to 6.5 GHz. With excellent typical peak-to-peak amplitude unbalance of 0.80 dB and typical phase unbalance of ±5 deg., the broadband power splitter is a good fit for a wide range of commercial and military systems and applications, including for amplifier and antenna feeds. It exhibits typical full-band insertion loss of 0.60 dB and typical isolation between ports of 19 dB, with typical VSWR of 1.20:1 across an operating temperature range of -55 to +105°C. The 50-Ω power splitter is supplied in a low-profile, RoHS-compliant housing measuring 1.600 × 0.400 × 0.190 in. (46.72 × 10.16 × 4.83 mm).



Lowpass Filter Passes Signals Below 11 GHz

Mini-Circuits' model ZLSS-11G-5+ is a suspended-substrate-stripline lowpass filter that passes signals from DC to 11 GHz with low loss and can be used for signal rejection at stopbands to 33 GHz. The 50-Ω lowpass filter features sharp roll-off characteristics between passband and stopband, with low typical passband insertion loss of 2.0 dB and typical passband VSWR of 2.0:1. The stopband rejection is typically 30 dB from 12.5 to 14.5 GHz, 90 dB from 14.5 to 26.5 GHz, and 20 dB from 26.5 to 33.0 GHz, with typical VSWR of 20.0:1 from 12.5 to 33.0 GHz. Fabricated with reliable suspended-substrate-stripline circuit technology, the RoHS-compliant lowpass filter is supplied in a compact housing measuring 0.90 × 0.70 × 0.60 in. (22.86 × 17.78 × 15.24 mm) with SMA female connectors. It has an operating temperature range of -40 to +85°C.

same class, making the CPS2000 Series well-suited for manufacturing test applications.

The CPS2000 sensors are intended to be used in conjunction with a PC. They can connect to a PC via a USB cable and be powered by that same connection. An alternative approach is to connect via Ethernet while powering the sensor using Power-over-Ethernet (PoE). The third option is to connect a sensor to a PC via Ethernet while powering it with a USB power adapter.

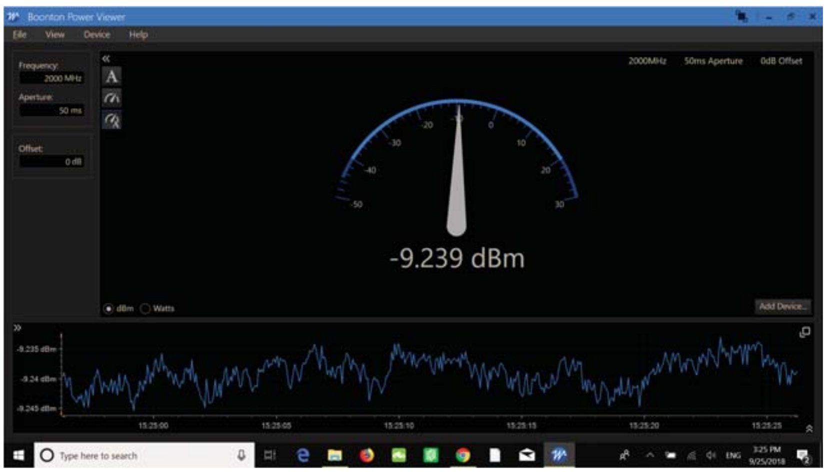
To operate the CPS2000 power sensors, one must download the Boonton Power Viewer software from the company's website (the software is discussed in more detail later on). Furthermore, the sensors are compatible with Windows and Linux systems, and include the necessary drivers for programming.

As mentioned, the CPS2000 sensors are a good fit for manufacturing test applications. Walt Strickler, VP/general manager at Wireless Telecom Group, explains, "The main application for the CPS2000 Series is in manufacturing test. In that application, RF power measurement is typically a coarse measurement. With the addition of wireless technologies to so many products (e.g., the Internet of Things, machine-to-machine, vehicle-to-vehicle, and vehicle-to-infrastructure), more products than ever have wireless connectivity. In most cases, companies buy pretested wireless modules and simply need to do a quick verification when included with their products. A cost-effective average sensor is ideal for that application."

THE CPS2000 IN ACTION

So, how well does the CPS2000 Series perform? We put the sensor to work. *Figure 2* shows a CPS2000 sensor connected to a Boonton demo aid that's capable of generating various signals. The sensor is connected to a laptop with a USB cable.

2. In this setup, a CPS2000 Series power sensor is measuring a signal from a Boonton demo aid.



3. Here, the Boonton Power Viewer software displays a power measurement reading of –9.239 dBm.

As mentioned previously, the CPS2000 sensors are used with the Boonton Power Viewer software. *Figure 3* shows the software's graphical interface when making a power measurement. In this case, a 2-GHz CW signal from the demo aid is being measured.

Users have three options for displaying power measurements when applying this software. One option is to display measurements with just text. Alternatively, users can choose to have power measurements displayed with a gauge. The third option is to view measurements with both text and a gauge, as is the case for the measurement shown in *Fig. 3*. Furthermore, users can display measurements in either dBm or watts.

In addition, users can specify *Aperture,* which is defined as the total time that the sensor observes the input signal to make one power measurement. *Aperture* can range from 1 ms to 2 s. For

Covering a frequency range of 50 MHz to 8 GHz, the CPS2000 sensors can perform true average RF power measurements of CW and modulated signals. The sensors measure signals from 50 MHz to 6 GHz at power levels ranging from –40 to +20 dBm. For signals from 6 to 8 GHz, the measurement range spans –35 to +20 dBm.

the measurement in *Fig. 3*, *Aperture* was set to 50 ms. *Fig. 3* also reveals the *Offset* text box, which allows users to apply corrections to measurements.

Another key feature is the *Live Power vs. Time* graph, shown at the bottom of *Fig. 3.* This aspect allows power to be monitored over a specified time interval. In this example, the time interval was set to 30 s. Checking *Auto-scroll* enables power measurements to be continuously monitored over time.

Lastly, the software supports connections to as many as eight different sensors. To connect to additional sensors, users must click *Add Device*. When multiple sensors are connected, the software also allows for ratio measurements.

CLOSING THOUGHTS

From my perspective, I think the CPS2000 Series is a worthy addition to Boonton's product line. It offers proven performance for those in need of average-power measurements. I also found the Boonton Power Viewer software to be very easy to operate. It features a simple interface that should have a familiar feel to those with experience using power meters/sensors. And while the gauge-display feature may not seem necessary for people like myself, others are likely to appreciate it.

Furthermore, the *Live Power vs. Time* graph is a nice feature that's easy to use. One should be aware that Boonton only lets users select from six different time-duration options: 10 seconds, 30 seconds, one minute, five minutes, 30 minutes, and one hour. One suggestion of mine would be to provide more options and/or allow users to enter their own time duration.

If you're in need of a power sensor, you may want to consider the CPS2000 Series. The sensors have a price tag of $1,395. mw

Circuit Materials

(Continued from page 39)

IMPACT OF SUBSTRATE DISSIPATION FACTOR AND COPPER-FOIL SURFACE ROUGHNESS ON INSERTION LOSS

Product at 5-mil dielectric thickness	Substrate dissipation factor at 10 GHz	½ oz. copper foil type	R_q copper-roughness (µm)	Insertion loss at 77 GHz from Fig. 1 (dB/in.)
RO3003 laminate	0.0010	Rolled copper	0.4	0.9
		VLP ED	0.7	1.3
		Standard ED	2.0	2.0
RO4830 laminate	0.0033 (SPDR)	LoPro reverse-treated ED	0.9	2.2

(V2V) and vehicle-to-infrastructure (V2I) systems, as well as vehicle-to-networks (V2N). V2V systems enable a vehicle to know that a vehicle two or three car lengths ahead and out of sight has just stopped, allowing the current vehicle to slow down and avoid a collision. V2I could enable the vehicle to communicate with infrastructure equipment at an intersection to let the vehicle know that a light will turn red or another vehicle is approaching from a blind alley. Downloads of high-resolution maps, software updates, and even downloads of entertainment content may be enabled by V2N wireless connections.

V2V communications will occur at 5.9 GHz. Significant investments have been made in the U.S. in recent years to develop dedicated short-range communication (DSRC) safety applications based on IEEE 802.11p standards. In Europe, the European Telecommunications Standards Institute (ETSI) has also supported ITS-G5, which uses the same protocol. In recent years, with the anticipation of 5G wireless cellular communications networks, a competing cellular V2X, or C-V2X protocol, has been developed to also support V2V communications.

Since the governmental organizations in the U.S. and Europe are not expected to mandate a specific technology protocol for V2V applications, it may be up to individual automotive original equipment manufacturers (OEMs) or OEM consortiums to choose a V2V technology. Likely, the communications protocol will not significantly affect the antenna hardware design.

Antenna performance requirements will drive circuit-material performance requirements, which may also be affected by available locations within each vehicle for antenna placement and by coverage requirements. If FR-4 circuit materials cannot provide the performance levels needed for V2V PCB antennas, a variety of high-frequency commercial circuit materials may be candidates, such as RO4000 Series or AD Series laminates from Rogers Corp., available with different Dk values. mw

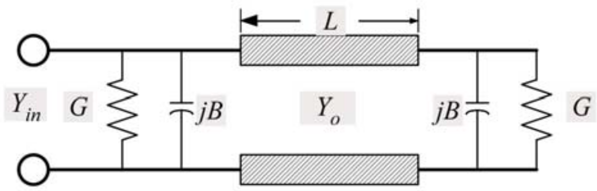
(Continued from page 42)

$$G = \frac{1}{120\pi^2} \cdot \left[1 - \frac{(k_o h)^2}{24}\right]$$

$$B = \frac{2\pi \Delta L \sqrt{\varepsilon_{eff}}}{\lambda_o Z_o}$$

$$Y_{in} = G + jB + Y_o \frac{G + j\left(B + Y_o \tan\left(k_o \sqrt{\varepsilon_{eff}} L\right)\right)}{Y_o + j(G + jB)\tan\left(k_o \sqrt{\varepsilon_{eff}} L\right)}$$

While the equations for the slot admittance are convenient, improved accuracy is achieved by using the equivalent admittance of the radiating slots available from the cavity model.



6. Microstrip antenna equivalent circuit.

CAVITY MODEL

Meticulous examination of the microstrip antenna construction discloses that the air dielectric at the sides and conductors at the top and bottom boundaries may define a resonant structure, also referred to as a resonant cavity. Cavity resonators are typically low-loss structures. Therefore, a mechanism must be defined to simulate the radiation loss at each edge of the microstrip conductor.

Once again, the radiating slot finds application. However, in the case of the cavity model, the radiation admittance is evaluated from an EM field perspective of significant mathematical rigor that's not appropriate for this tutorial venue. Notwithstanding, the results of the cavity model are applicable and provide improved accuracy for the calculation of driving point impedance and resonant frequency. Utilizing the cavity model yields the following equations for the calculation of the resonant input resistance of the rectangular microstrip resonator. Note that the ± sign refers to the specific mode field configuration of the cavity resonance beneath the conductor. mw

$$R_{in} = \frac{1}{2(G_1 \pm G_{12})}$$

$$G_1 = \frac{I_1}{120\pi^2} \quad \text{where} \quad I_1 = \int_0^{\pi} \left[\frac{\sin\left(\frac{k_o W}{2}\cos\theta\right)}{\cos\theta}\right]^2 \cdot \sin^3(\theta) d\theta$$

$$G_{12} = \frac{1}{120\pi^2} \cdot \int_0^{\pi} \left[\frac{\sin\left(\frac{k_o W}{2}\cos\theta\right)}{\cos\theta}\right]^2 \cdot J_0(k_o L \sin\theta) \sin^3\theta \cdot d\theta$$

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Directional Coupler Spans 0.5 to 40.0 GHz

MODEL ZCDC10-K5R44W+ is a wideband, dc-pass directional coupler with outstanding performance from 0.5 to 40.0 GHz. The 50-Ω coupler maintains 10-dB coupling within typically ±2.2 dB across the frequency range, with typical coupling flatness of ±0.9 dB. Mainline loss is typically 0.9 dB from 0.5 to 8.0 GHz, 1.3 dB from 8.0 to 18.0 GHz, 1.6 dB from 18.0 to 26.5 GHz, and 2.1 dB from 26.5 to 40.0 GHz. Input and output return loss is typically 35 dB from 0.5 to 8.0 GHz, 29 dB from 8.0 to 18.0 GHz, 25 dB from 18.0 to 26.5 GHz, and 25 dB from 26.5 to 40.0 GHz. Directivity is typically 30 dB from 0.5 to 8.0 GHz, 23 dB from 8.0 to 18.0 GHz, 21 dB from 18.0 to 26.5 GHz, and 16 dB from 26.5 to 40.0 GHz. Well-suited for wideband communications applications and laboratory use, the RoHS-compliant directional coupler offers typical power-handling capability of 15 W. It measures 4.40 × 0.7 × 0.3 in. (111.76 × 17.78 × 7.62 mm) with female 2.92-mm connectors. It's designed for operating temperatures from –55 to +100°C.

MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500, www.mini-circuits.com

Miniature Oscillators Aid Medical Applications

A LINE OF miniature hermetic crystal oscillators from Statek provide the high-reliability and low-current operation that makes them strong candidates for implanted medical applications. The CXOU line of oscillators, which is available with operating frequencies from 32.768 to 100.000 kHz, are supplied in highly reliable ceramic housings. The oscillators run on startup voltages from 0.9 to 5.0 V with current consumption from 1.75 to 3.9 µA, depending on frequency. Typical startup time is 200 ms with rise/fall time of 30 ns and aging rate of ±2 ppm for the first year of operation. The standard CMOS output load is 100 pF with other loads available upon special order. The crystal oscillators are capable of withstanding peak shock to 5,000 g's. The oscillators, which measure 1.2 × 2.0 × 0.76 mm, are tested to MIL-PRF-55310 for military use and suit many medical implantable applications, including in pacemakers and defibrillators.

EUROQUARTZ LTD., Blacknell Lane, Crewkerne, Somerset, UK TA18 7HE; +44 (0) 1460 230000, FAX: +44 (0) 1460 230001; e-mail: info@euroquartz.co.uk, www.euroquartz.co.uk

Flexible Waveguide Span 5.85 to 50.0 GHz

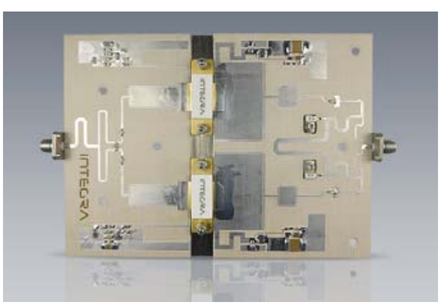
A LINE OF twistable and seamless flexible waveguide covers 10 frequency bands from WR-137 to WR-22 and a total frequency range of 5.85 to 50.0 GHz. Well-suited for communications and test applications, the waveguide are available in lengths of 6 to 36 inches and with UG-style square/round cover and CPR-style flanges. They achieve VSWR as low as 1.05:1 with insertion loss as low as 0.15 dB and power-handling capability to 1.5 kW. P&A: stock.

PASTERNACK ENTERPRISES, 17802 Fitch, Irvine, CA 92614; (866) 727-8376, (949) 261-1920, www.pasternack.com

WR-28 Feed Horn Antenna Covers 24 to 42 GHz

MODEL SAH-2434231060-358-S1-280-DP is a dual-polarized, WR-28 choke flange feed horn antenna assembly with broad frequency coverage from 24 to 42 GHz. The antenna assembly combines an integrated orthomode transducer (OMT) with high isolation and good cross-polarization cancellation and a broadband scalar horn with low sidelobe levels. It provides 10-dBi typical gain at 33 GHz with 35-dB typical isolation and has a typical half-power beamwidth of 60 deg. with −25-dBc E-plane sidelobes and −35-dBc H-plane sidelobes. The OMT enables the antenna to separate a circular or elliptical polarized waveform into two linear, orthogonal waveforms or vice versa. The dual polarized horn also supports either vertical or horizontal polarized waveguide forms with more than 30-dB cross polarization rejection. Horizonal and vertical ports are equipped with WR-28 waveguide with UG-599/U flanges and 4-40 threaded holes.

SAGE MILLIMETER INC., 3043 Kashiwa St., Torrance, CA 90505; (424) 757-0168, FAX: (424) 757-0188, www.sagemillimeter.com



Power Module Drives L-Band Avionics Systems

SUITABLE FOR L-BAND uplink and downlink avionics applications, model IGNP1011L2400 is a high-power, 50-Ω-matched, GaN-on-SiC RF power module designed for Identify Friend or Foe (IFF) and Secondary Surveillance Radar (SSR). It can operate under Mode S ELM (32 µs on and 18 µs off) or standard Mode S (128 µs long pulse at 2% duty cycle) conditions. Under mode S ELM conditions, the module delivers 2200 W output power with 16-dB gain and 55% drain efficiency over the instantaneous L-band frequency range from 1.03 to 1.09 GHz. The module operates from a 50-V dc supply.

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