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PMI designs and manufactures a variety of coaxial monopulse compartors for beamforming antenna applications up to 26.5 GHz. Form, fit and functional designs can also be replicated to specific requirements. Standard models with various options are available at PMI's website (Link below)

http://pmi-rf.com/Products/monopulse_comparators/features.htm

Model: MPC-20R2G21R2G-CD-LNF
8 Input Monopulse Compartor with Gain

Frequency	20.2 - 21.2 GHz
Gain	0 dB, 5 dB Nom. (Selectable)
Noise Temperature /Figure	100 K / 1.3 dB Noise Figure
Phase Balance	±3° Maximum
DC Supply	+12 VDC @ 700 mA, -12 VDC @ 100 mA
Temperature	-55 °C to +85 °C

Package Size:
6.25" x Ø4.80" x 2.00"
Connectors: SMA (F)

Model: PMC-3G3D5G-6D8-SFF
4 Input Monopulse Comparator

Frequency	3.0 to 3.5 GHz
Insertion Loss	0.8 dB Max. - Measured 0.4 dB
VSWR	1.25:1 Max. - Measured 1.25:1
Isolation	23 dB Min. - Measured 25.052 dB
Amplitude Balance	±0.4 dB Max. - Measured ±0.2681 dB
Phase Balance	±5° Maximum - Measured ±3.2°
RF Input Power	Average: 11 Watt Max. Peak: 0.1 kW Max.
Temperature	-55 °C to +85 °C

Package Size:
3.23" x 3.23" x 0.43"
Connectors: SMA (F)

Model: PD-CD-001-1, 4 Way Phase Shift Power Divider with 0°, 90°, 180°, 270° Outputs

Frequency	9.3 - 9.9 GHz
Insertion Loss	8.0 dB Max. - Measured 6.97 dB Max
VSWR	2.0:1 Max. - Measured 1.60:1 Max.
Amplitude Balance	±0.5 dB Max. - Measured ±0.2 dB Max.
Phase Balance	±7.0° Max. - Measured ±4° Max.
RF Input Power	28 W CW, 750 W Peak
Temperature	-32 ºC to +77 ºC Operating

Package Size:
2.35" x 1.7" x 0.5"
Connectors: SMA (F)

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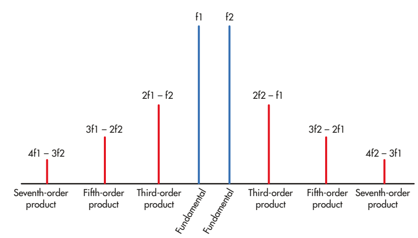

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defense electronics
Starts on p. **57**

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Featured MACOM MMIC Devices

Application	Function	Part Number
SATCOM	Ka-Band Power Amplifier	MAAP-011289, 28 - 30.5 GHz
	Doubler Power Amplifier	MAFC-011009, 28 - 30 GHz
	L-Band Power Amplifier Module	MAAP-011060, 1616 - 1627 MHz
Test & Measurement	Wideband Power Amplifier	MAAP-011247, DC - 22 GHz
	Wideband Low Noise Amplifier	MAAL-011141, DC - 26.5 GHz
	Wideband DBL BAL Mixer	MAMX-011036, 8 - 43 GHz
Aerospace & Defense	Octave Band VCO	MAOC-415000, 10 - 20 GHz
	Power Amplifier	MAAP-011232, 0.1 - 3 GHz
Industrial, Scientific & Medical	Low Noise Amplifier	MAAL-011129, 18 - 32 GHz
	Gain Block	MAAM-011206, DC - 15 GHz
Wired Broadband	Variable Gain Amplifier	MAAM-011194, 45 - 1218 MHz
	Gain Block	MAAM-011220, 45 - 1218 MHz
	Very Low Noise Amplifier	MAAL-011136, 45 - 1218 MHz

on microwaves&rf.com

THE POWER OF 5G ON TEST REQUIREMENTS

http://mwrf.com/blog/power-5g-test-requirements

With Fifth-Generation (5G) wireless communications systems imminent, test-equipment designers and suppliers are carrying a heavy load. In fact, it's no exaggeration to say that the expected needs of next-generation wireless networks are shaping the next generation of RF/microwave test equipment.

FROM ESOTERIC TECH TO MARKET MAINSTAY

http://mwrf.com/active-components/amplifiers-heighten-performance-satisfy-next-wave

The pressing needs of today's applications are prompting amplifier suppliers to deliver new products to meet current high-frequency demands. One specific area that is now driving a significant amount of product development is small-cell infrastructure, which is a growing market. As many are turning to small cells to drive wireless networks, amplifier suppliers are launching new products in support of this need.

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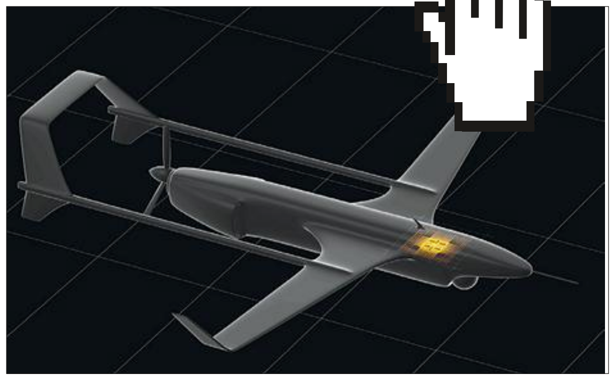


FLEXIBLE, COST-EFFECTIVE SOLUTIONS TRANSFORM THE MILITARY SECTOR

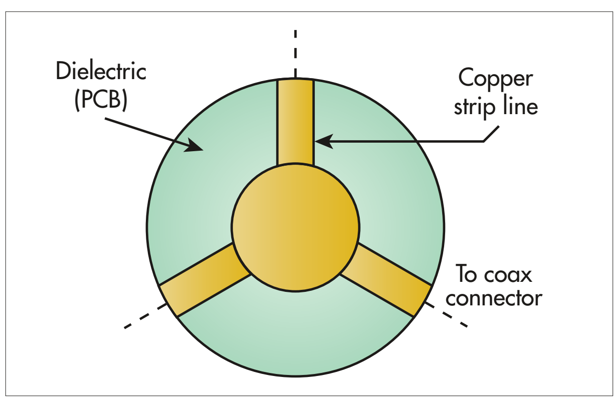
http://mwrf.com/defense/gan-open-systems-low-swap-platforms-transform-military-sector

To support current aerospace and defense systems, technology has moved beyond traditional constructs and iterations to completely new approaches and solutions. The RF/microwave industry faces the task of providing ever-advancing electronic-warfare (EW) solutions while meeting size, weight, and power (SWaP) constraints.

A PRIMER ON CIRCULATORS AND ISOLATORS

http://mwrf.com/components/primer-circulators-and-isolators

Circulators and isolators are three-port passive electronic devices that are and absolutely essential for directing the flow of microwave signals in RF equipment and systems. Here's everything you need to know about them.



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EDI CON Achieves First-Pass Success

EDI CON USA 2016 was held in Boston from Sept. 20 to 22, marking the first time the event took place here in the United States. The show had lots to offer in terms of both the exhibition as well as the wide variety of technical sessions. Many companies used this event as an opportunity to showcase their newest products, while the technical sessions covered a vast array of topics.

Among the technical sessions that I took in was one on 5G modulation-scheme candidates, presented by Kay-Uwe Sander from Rohde & Schwarz. The modulation-scheme candidates he mentioned were orthogonal frequency division multiplexing (OFDM), filter bank multi-carrier (FBMC) with offset-QAM, universal filtered multi-carrier (UFMC), generalized frequency division multiplexing (GFDM), and filtered-OFDM (F-OFDM). While I won't get into all the details here, this is definitely a topic under much investigation. With all of the talk surrounding 5G, we can surely expect to hear more about modulation schemes in the future.

Another technical session I decided to see was Dan Swanson's presentation, "Intuitive Microwave Filter Design with EM Simulation." In this session, Swanson described a design flow for both cavity and microstrip filters, demonstrating how to effectively use electromagnetic (EM) simulation. I thought this was a good presentation that could benefit anyone who is involved with microwave filter design.

Another point of interest was solid-state RF energy. Klaus Werner from the RF Energy Alliance spoke on this topic, discussing the future challenges and opportunities associated with solid-state RF energy. Magnetron-based microwave ovens have been in people's home for so long, which is why it is difficult to imagine anything different. However, people like Werner believe that solid-state RF energy will eventually overtake magnetrons. Werner has high expectations for solid-state RF energy, as he believes the technology will soon reach a number of markets.

The exhibition floor was an opportunity for many companies to showcase their latest and greatest. A number of new products were displayed, some of which have already been featured by Microwaves & RF. In addition, I was able to see a nice demo from Mitsubishi Electric. The company proved that its gallium-nitride (GaN) technology can deliver 70 W of output power at Ku-band (13.75 to 14.5 GHz).

Lastly, those who missed EDI CON this year will have another opportunity. The event will once again return to Boston in 2017. mw

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ZHL-4W-422+	500-4200	25	3	4	1160
ZHL-5W-422+	500-4200	25	3	5	1670
ZHL-5W-2G+	800-2000	45	5	5	995
ZHL-10W-2G+	800-2000	43	10	12	1295
• ZHL-16W-43+	1800-4000	45	12	16	1595
• ZHL-20W-13+	20-1000	50	13	20	1395
• ZHL-20W-13SW+	20-1000	50	13	20	1445
LZY-22+	0.1-200	43	16	30	1495
ZHL-30W-262+	2300-2550	50	20	32	1995
ZHL-30W-252+	700-2500	50	25	40	2995
LZY-2+	500-1000	47	32	38	2195
LZY-1+	20-512	42	50	50	1995
• ZHL-50W-52+	50-500	50	63	63	1395
• ZHL-100W-52+	50-500	50	63	79	1995
• ZHL-100W-GAN+	20-500	42	79	100	2395
ZHL-100W-13+	800-1000	50	79	100	2195
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Listed performance data typical, see minicircuits.com for more details.

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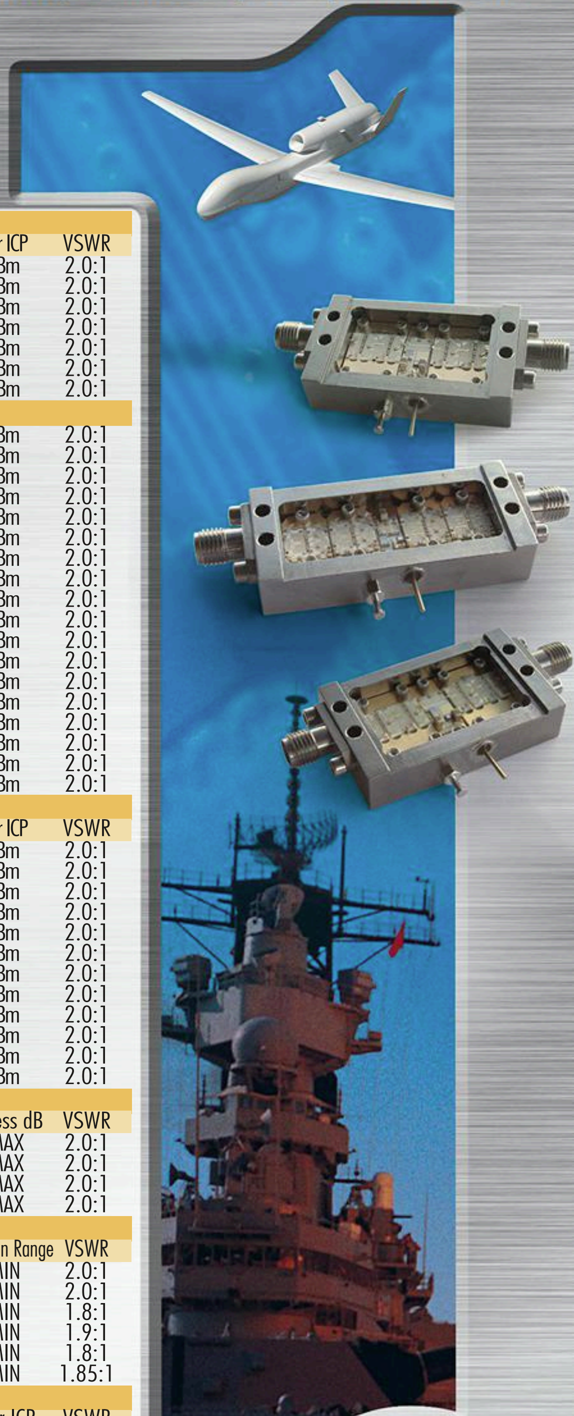

OCTAVE BAND LOW NOISE AMPLIFIERS

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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MICROSTRIP AND STRIPLINE: A DEEPER DIVE?

I thought your article *"What's the Difference Between Microstrip and Stripline?"* (September 2016) was a decent overview, but I would have expected a bit more on the practical application differences, especially regarding filters, amplifiers, and directional couplers.

Because of the radiation problems of microstrip, it is necessary to take special precautions in the design of filters and amplifiers. It is unfortunately easy for the input signal to jump right over the filter or amplifier layout through the air-space above the microstrip, thus leading to the complications of undesired feedback in amplifiers, leading to instability, and insufficient rejection in filter structures. This may be a job for stripline, even though active devices may present a mechanical problem.

Another special circumstance arises due to the non-uniform dielectric structure (substrate and air) in which microstrip propagation occurs, as you mentioned in the article. As a result of this non-uniform dielectric, coupled structures do not exhibit good directivity: the odd-mode and even-mode in coupled lines are of different electrical length. A typical directional coupler in microstrip may only provide directivity of 13 dB or so, whereas a number like 30 dB is reasonably achievable in stripline.

However, there is a major advantage to microstrip where it can be used: you can mount components--even large components like power devices, right on the surface. In addition, as the product is in development, it is possible to tweak the design a bit by adding bits of copper foil in judicious locations in order to improve matching of active devices, or frequency response of filters. The manufactured component then can incorporate these modifications by adding them to the artwork.

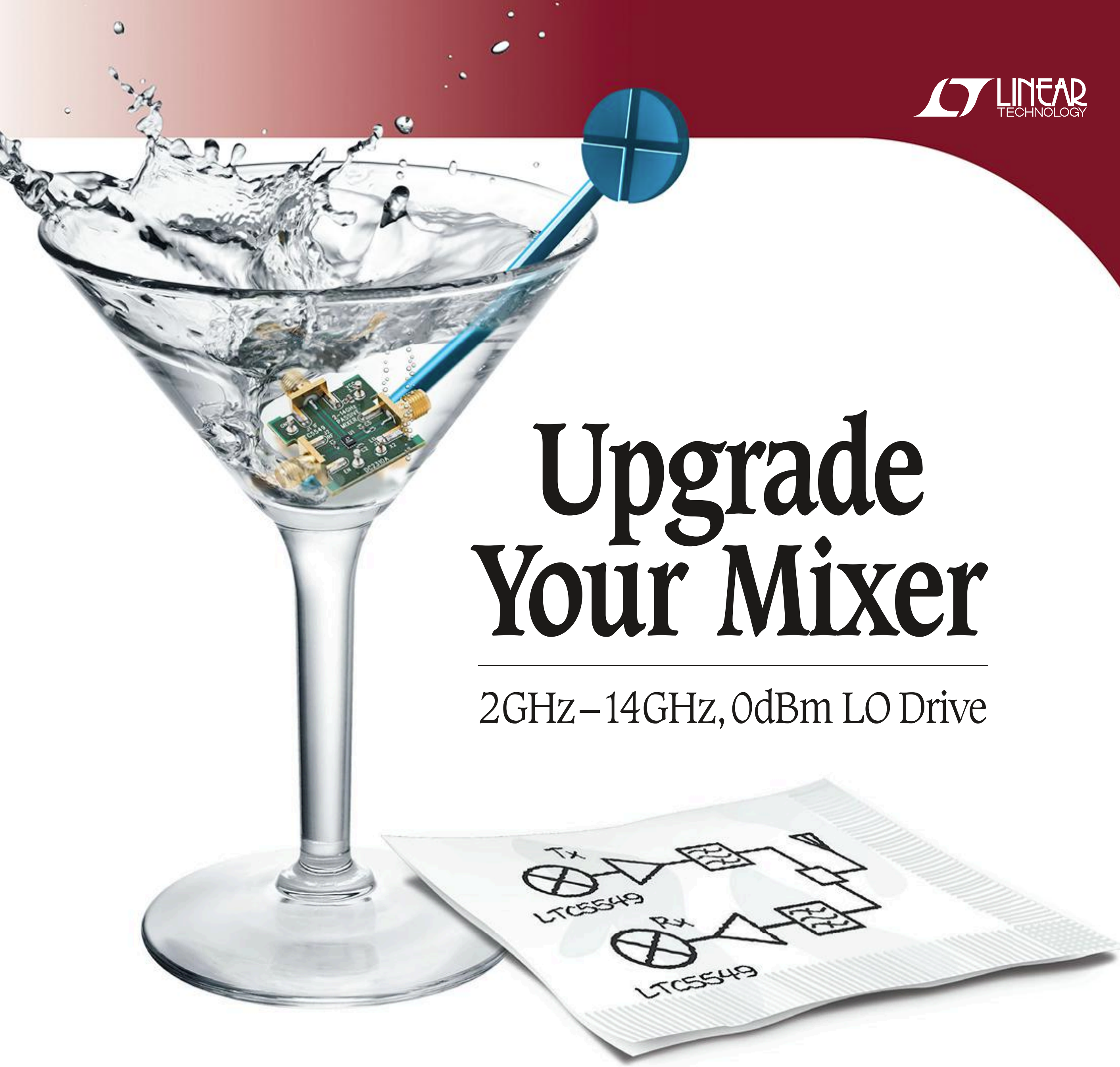
The engineer desiring to utilize the advantages of microstrip may find that a judicious application of microwave-absorbing material to the cover of the housing will provide considerable improvement to the output-to-input coupling problem.

Doug McGarrett

EDITOR'S NOTE

Thanks for taking the time to write, as well as for your thoughts. I think you are seeing what we editors face when trying to tackle a large topic like this in a short article. You definitely make me realize that there is a need for a follow-up story (or stories). Thanks again for reading and for your interest.

Jack Browne
Technical Contributor



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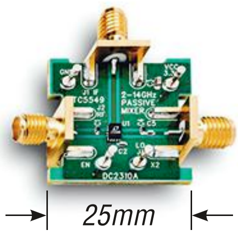

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News

MAKERS OF CHIPS, CARS, AND RADIO EQUIPMENT Join Forces to Connect Cars with 5G

(Image courtesy of BMW)

Germany's largest automakers are preparing to upgrade their cars with a new generation of wireless technology, and they have enlisted partners in radio infrastructure and semiconductors to help.

Audi, BMW, and Daimler said that they were partnering with two major chipmakers and telecommunications equipment makers Ericsson, Huawei, and Nokia to develop and test the fifth generation of wireless technology, or 5G. They will also aim to built consensus around issues like protecting cars from hackers and the privacy of drivers.

The organization, which also includes American chip giants Qualcomm and Intel, has been created at a time of significant upheaval in the automotive industry. Car manufacturers are working on vehicles that not only collect data from sensors and cameras but also using wireless technology to broadcast and receive location data from other cars—data that could help alert drivers about other vehicles on the road or even automatically avoid collisions.

The organization will focus on the tricky task of connecting cars to infrastructure, and other cars. Many wireless companies are experimenting with this technology—also known as Vehicle-to-X or V2X communications—and not without reason. In the United States, the Department of Transportation is considering rules that would require cars to broadcast their location to others on the road.

But enabling cars to share data with other vehicles requires cellular networks that are faster and more reliable than what smartphone users are familiar with. That is where 5G networks enter the picture. These networks, industry executives say, will connect to cars almost instantaneously and be reliable enough to meet the strict standards of highway regulators.

(continued on page 22)

SCIENTISTS STEER RADAR BEAMS with Slight Change of Perspective

THE IDEA OF METAMATERIALS brings to mind comic book elements like Captain America's vibranium shield or Wolverine's adamantium claws. But metamaterials are not fictional. They are synthetic materials that bend things like radio waves in ways that don't occur naturally.

One of the earliest applications for the technology is in radar systems. By applying voltages to an antenna built out of metamaterials, engineers can actively control the direction of the radar beam. That makes the radar system cheaper and smaller than ones steered by mechanical parts or other electronics.

But many engineers are not ready to stop using conventional materials to achieve similar results.

Last month, for example, scientists reported that they had built a new type of electronically-steered radar antenna. Writing in the Journal of Applied Physics, a team from the University of Wisconsin-Madison said that they had used a reflective antenna to bend radar beams in different directions.

The new technology brings together mechanical and electronic steering. A transmitter sends radio waves through an array of reflective antennas, which directs the radar beam depending on how the transmitter is tilted. The scientists are calling it a macro-electromechanical system (MÆMS)—a play on micro-electromechanical systems, or MEMS, which are widely used in sensors that react to tiny alterations in pressure or radio waves.

The team stressed that it will not use bulky mechanical rigs or specialized circuitry. "Our approach doesn't depend on exotic materials that bend the laws of physics," Nader Behdad, the electrical engineering professor who led the research, said in a news release.

"We've found a practical way to achieve beam steering that the antennas field has largely overlooked," he added.

Radar systems locate and track objects by emitting radio waves and measuring the reflected signals. Some of the most advanced systems use electronics to direct radio waves without having to mechanically point the antenna in different directions. But these antennas normally use expensive and bulky electronics, known as phase shifters, to steer the radar beams.

The phase shifter's bulkiness and cost have largely kept electronically-steered antennas out of commercial applications, like drones or automated driving systems. They are mostly reserved for defense applications, like fighter jets. Raytheon, for example, has developed an active electronically scanning array (AESA) system, which can track multiple objects, like ballistic missiles, at the same time. Lockheed Martin and Boeing are two other companies that make AESA radars.

What sets the MÆMS technology apart is that it doesn't need solid-state devices or phase shifters integrated into the aperture of the antenna. The result, according to the scientists, is a radar system that can detect objects faster than mechanical radars used on airplanes and ships.

"In defense situations, you need to detect incoming objects where you are going very quickly," said John Booske, another electrical engineering professor that worked on the project, which received $1.1 million in funding from the United States Office of Naval Research.

"The ability of a mechanical rig to move a big, heavy parabolic dish back and forth limits how quickly you can respond to potential threats," Booske added.

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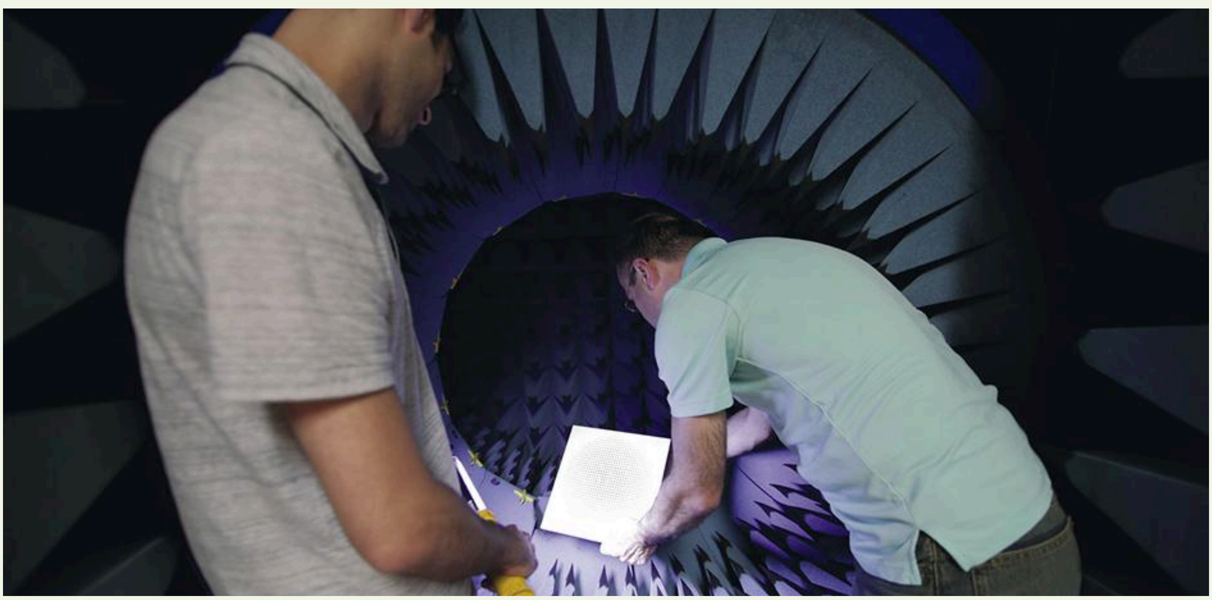


A team from the University of Wisconsin-Madison said that they had used a reflective antenna to bend radar beams in different directions.

(continued from page 20)

The 3G Partnership Project, an industry group that maintains cellular standards, has already completed a V2X standard, which will be released as part of a larger standard in 2017. 5G, industry analysts say, will likely appear in 2020.

But there are other technologies for connecting cars in the works. While 5G will have to share the airwaves with smartphones and other devices, a technology known as dedicated short range communications, or DSRC, has been developed specifically for cars. Several Silicon Valley startups like Autotalks and Savari specialize in making hardware and software based on the standard.

By sharing location data with other cars on the road, for instance, Savari's software can warn drivers of a possible collision or when other vehicles creep into blind spots. Paul Sakamoto, chief operating officer at Savari, said in an interview earlier this year that hardware in smartphones can be programmed to share the short-range data, so that drivers can avoid pedestrians with a phone in their pockets.

Rapidly and reliably sharing data is at the heart of automakers' big data projects. Last week, the three German automakers said that they would use a new service from digital mapmaker Here. It will warn drivers about accidents and locate parking spaces by pooling data from cameras and sensors inside hundreds of thousands of cars. That data will be sent wirelessly into the cloud and redistributed in real-time.

The new partnership will also examine privacy and security regulations, in response to rising concerns about how data from vehicles will be used. In August, U.S. lawmakers sent a letter urging the Federal Communications Commission to create privacy rules for connected cars. The letter expressed fears that data could be misused for targeted advertising – like what Google and Facebook are doing on the internet – which could appear on dashboard displays and billboards.

To help address these concerns, industry executive say that companies need input from multiple industries. It is necessary to "work closely together with the car industry to jointly develop solutions as well as provide input to regulation, certification, and standardization," said Ulf Ewaldsson, Ericsson's chief technology officer, in announcing the new organization.

Audi's Christoph Voigt will serve as the chairman of the 5GAA's board. The 3GPP's Dino Fiore will be the director general of the organization, according to a statement.

(continued from page 21)

The new antenna works by focusing microwave signals through an array of reflective patch antennas. To focus the signal into a beam, it alters the electronic properties of the individual elements in the array. In addition, the individual elements can be tuned to act like a phase shifter and direct the radar beam.

The approach is similar to phase-varied array antennas, the team said. These systems are made up of miniature transmitters that each emit a fraction of a signal, which adds up to a single beam. By altering the electronic properties of each individual part, the antenna can steer the radio beam.

The MÆMS array is also built out of many individual elements. The difference, according to the scientists, is that it uses a single transmitter instead of many partial ones. There is a drawback to this design: it is more difficult to tune the antenna and shape the radar beam.

The scientists found the solution in the mechanical motion that they had originally tried to eliminate. They discovered that tilting the ground plane underneath the antenna array would tune all the elements simultaneously, directing the radar beam.

Though the MAEMS device is mechanical, the small tilting movement requires less time and force than turning a large reflector dish.

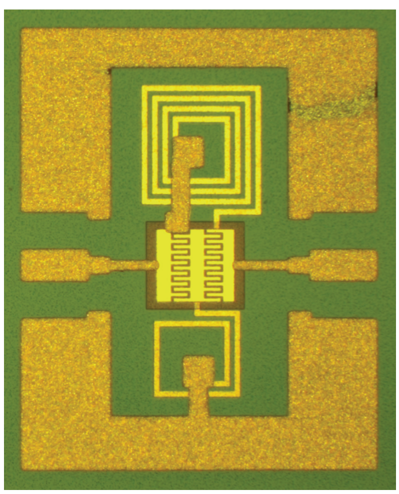
A prototype based on the research showed that slight tilts (around 0.05λ) in the ground plane could steer the beam +/- 10 degrees in two dimensions. Another prototype with the ground plane segmented into multiple parts was shown to steer beams +/- 30 degrees.

"Luckily for us, in order to do beam-steering, we really don't need to individually tune each element," said Behdad. "All we need to do is create a gradient and we can do that by simply tilting the ground plane."

TUNABLE ANTENNA CIRCUITS
May Adapt to Environment Prepare for Launch

IN 1944, THE United States Army Signal Corps started paying scientists to study materials that could be used in radio equipment. The first substance under investigation was known as barium strontium titanite (a powdered ceramic) which is capable of being altered when shocked with an electric current.

The researchers gave the material a lukewarm review. It could be made into delay lines and filters operating at microwave frequencies, they wrote in a report, but fabricating the material to jump between frequencies posed a significant challenge. Fast forward sixty years and engineers are still struggling with it.



(Image courtesy of University of California, Santa Barbara, and Applied Physics Letters)

Now, researchers from the University of California, Santa Barbara, recently announced a new method for shaping the barium compound into circuits – ones that can be reconfigured to access multiple frequencies. By reducing the amount of heat radiated from the material, the researchers were able to create smaller and more efficient circuits.

The work, which was based out of the UCSB Materials Research Lab, and which appeared in the journal *Applied Physics Letters*, breathes life into a material considered

(continued on page 26)

(continued on page 24)

defective by chip industry standards. The material is only used in a small number of wireless capacitors, which are paired with antennas to tune into different frequencies.

But the barium compound has potential. It could be used "to create tunable antennas for cellular communications, which allows a small antenna to be tuned over a wide frequency range or enables a phone to adapt to different surroundings for improved efficiency and battery life," said Robert York, an electrical engineering professor, in an article published with the research.

He also suggested the material could be used to create phase-shifters for phased-array antennas in satellite communications.

Materials like barium strontium titanate are known for having high dielectric constants, meaning that they can be adjusted with a pulse of high voltage electricity. The National Institute of Standards and Technology, which sponsored the research in 1944, is studying dielectrics to enable satellites and smartphones to tune into precise frequencies. Many chipmakers like Intel and Samsung are eyeing the materials to shrink computer circuits toward the atomic level.

These qualities have been both a blessing and a curse. The material's large dielectric constants "present fabrication challenges because the inherently high capacitance density of the films requires smaller electrode dimensions and finer lithography than many typical integrated capacitor structures," said York.

To manufacture the circuits, the researchers tweaked a widespread process for making compound semiconductors called molecular beam epitaxy (MBE). They were able to recalibrate the process to reduce current leakage, while keeping the circuits clean of contaminants.

The researchers also discovered that barium strontium titanite was weirdly susceptible to contamination, and that was probably a reason why engineers had struggled to increase quality over the years. Imperfections are also caused by high temperatures and oxygen involved in traditional manufacturing.

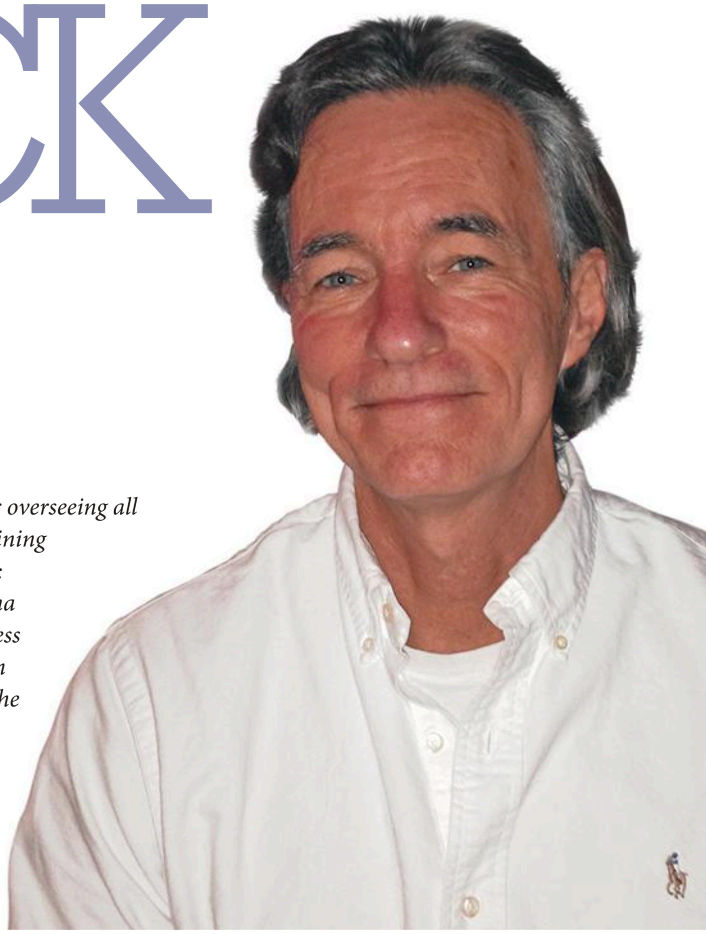
Once the researchers adjusted the fabrication process, the capacitors operated over a wide frequency range. When a prototype was embedded in a metal waveguide, the researchers found that it scattered radio signals from 100 MHz to 40 GHz.

If the material is to be used practically, the process and circuit design will need improvements, York said. But "the infrastructure for deposition and fabrication already exists within most semiconductor foundries," he said, "so the timeline for exploiting this advance could be relatively short compared to the typical timeline for a materials advance." ■

Inside TRACK with Jeff Shamblin,

Chief Scientist, Ethertronics

Interview by CHRIS DeMARTINO, Technology Editor



JEFF SHAMBLIN, Chief Scientist at Ethertronics, is responsible for overseeing all research and development projects for the corporation. Prior to joining Ethertronics, Shamblin worked for two RFID startup companies: SCS Corp. and Claridy Solutions. He has also served as an antenna consultant, providing design and analysis services to several wireless startups in the Southern California area. On top of that, Shamblin spent more than 20 years in antenna design and development in the aerospace industry at Lockheed Martin and Northrop Grumman. He holds seven patents related to antenna technology. Shamblin earned his bachelor's degree in physics from California State University, Northridge.

How has the approach to developing antenna solutions changed in the last five or 10 years?

Shamblin: Antenna design for consumer and commercial applications has undergone a few significant changes. One has been to put more emphasis on a system-level approach for the antenna system, where the antenna is designed for optimal RF system operation and for operation in conjunction with the many sensors that now populate a consumer mobile device, such as proximity sensors. A system-level approach is important to optimize the four to six antennas that now populate a smartphone, where isolation and correlation between the multiple antennas will, to a large extent, dictate the data rate that can be achieved, the quality of a voice call, or the accuracy of an embedded GPS receiver.

A second change involves designing the antenna system for the specific use cases that will likely be applied to the mobile device. For example, antenna performance can be optimized for a hand-loading condition for a smartphone, or a body-loading condition for a wearable fitness tracker.

"Interference mitigation will become more important as a larger number of RF-enabled devices are installed in homes and businesses."

What are some of the challenges in terms of developing antennas for cellular communications?

Shamblin: The increased number of cellular bands dedicated to LTE systems along with carrier aggregation, where two or more frequencies are aggregated to improve communication-system throughput, have added complexity to the multiple-input, multiple-output (MIMO) antenna system in a smartphone. Also, the trend to bring 2 × 2 MIMO at Wi-Fi frequencies to the smartphone requires the integration of additional antennas into a small, compact volume.

Wi-Fi has advanced significantly over the years, and it continues to transform. How will that affect antenna design—both now and in the future?

Shamblin: The main affect will be an added requirement to integrate a larger number of antennas into a device as higher orders of MIMO are brought to bear to increase data rates. Wi-Fi routers today will typically have three or four antennas installed to provide 3 × 3 or 4 × 4 MIMO capability—and 8 × 8 MIMO will soon be available for the Wi-Fi market.

Tell us a little bit about Active Steering technology.

Shamblin: Ethertronics has developed a technique to generate multiple radiation patterns from a single antenna structure. A small-form-factor antenna, along with a four-port switch and algorithm, comprise an Active Steering antenna system. The radiation pattern of the single antenna can be dynamically changed. The proprietary algorithm accesses a metric from the baseband processor—for example, SINR or RSSI. This metric is used to determine the radiation mode for optimal throughput. The end result is improved throughput and a more reliable communication link for cellular and Wi-Fi applications.

How have antenna testing requirements changed throughout the years?

Shamblin: In the cellular industry, handset antenna requirements have progressed from tracking radiation patterns and efficiency for 2G/3G systems to tracking total radiated power (TRP) and total isotropic sensitivity (TIS) performance for 3G systems. Requirements now include isolation and envelope correlation coefficient for 4G MIMO antenna systems. Another change has been to measure and use system-level performance metrics, such as throughput in Wi-Fi systems, to optimize the antennas during the antenna integration process.

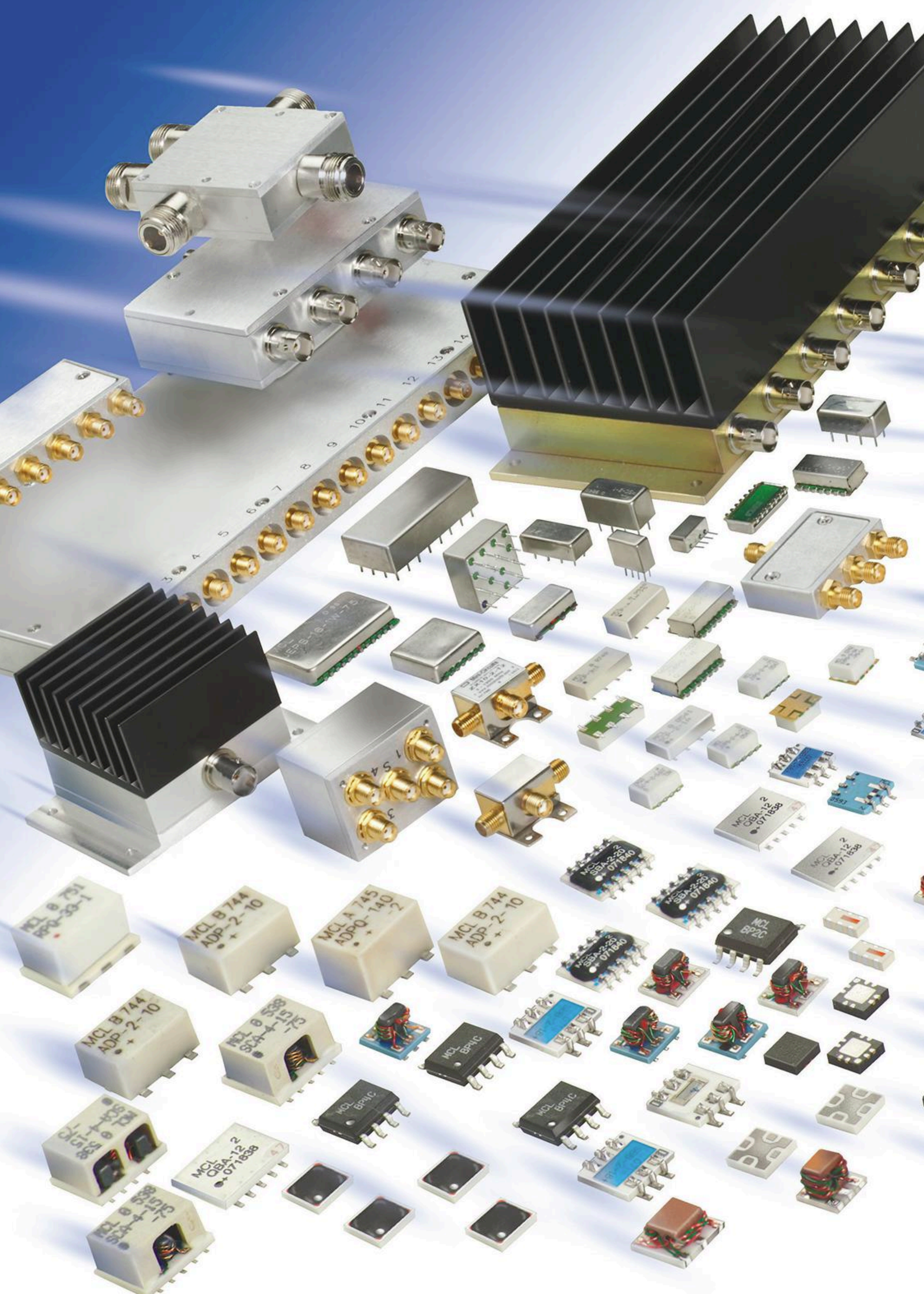
What challenges will the Internet of Things (IoT) bring to antennas?

Shamblin: Interference mitigation will become more important as a larger number of RF-enabled devices are installed in homes and businesses. Reliability of the communication link will also be important for this plurality of IoT devices to allow for continuous and seamless monitoring of a wide variety of devices. Ethertronics' Active Steering technology will be able to assist in decreasing interference, as well as making the RF communication links more reliable by bringing antenna diversity to each antenna port.

What impact do you think 5G will have on antenna development?

Shamblin: Some 5G implementations will require millimeter-wave antenna systems integrated into handheld and mobile devices, and these millimeter-wave antennas will require different manufacturing techniques to maintain tolerances and allow for better material selection. Millimeter-wave applications will require better control of the radiation pattern in comparison to 3G and 4G systems.

Another impact that will affect 5G systems at both sub-10-GHz and millimeter-wave frequencies will be the use of higher orders of MIMO to drive higher data rates. The need to integrate a larger number of antennas in a device where isolation and envelope correlation must be designed will create more difficulties in antenna-system design. Good antenna-system design practices will be required for optimized 5G communication systems. mw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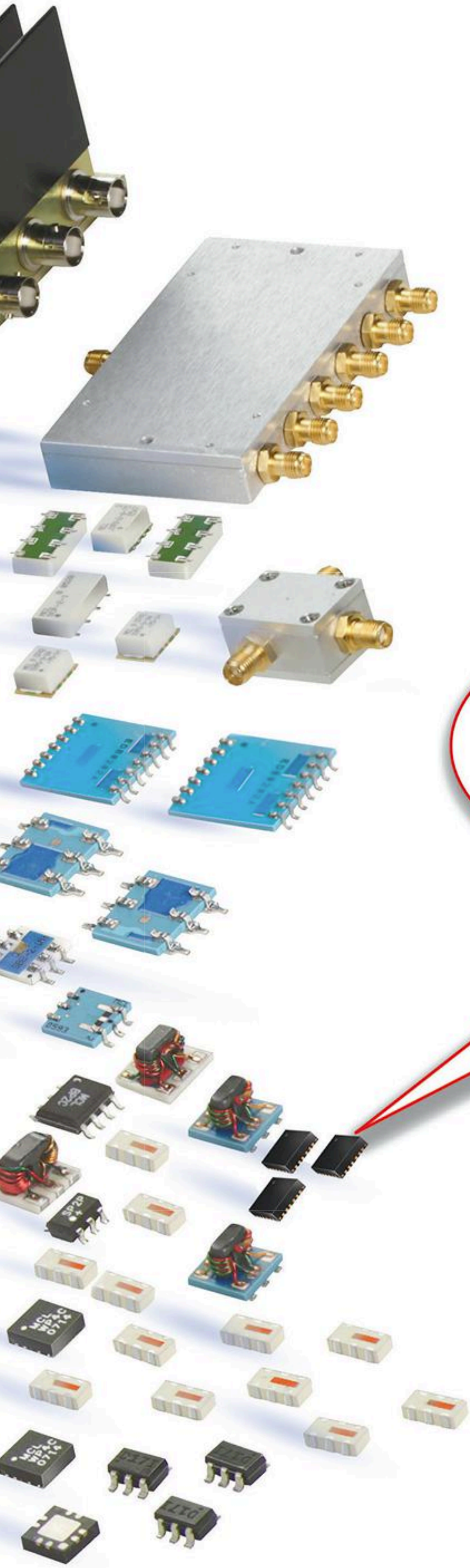


INNOVATIVE MODEL LEADS TO NOVEL BEAMFORMING TECHNIQUE

COMMUNICATIONS SYSTEMS AND other high-frequency electronic systems are now leveraging multiple-element antenna arrays rather than single antennas and advanced computer-modeling techniques to fine-tune physical designs. On that front, a group of researchers from China's Wuhan University applied mathematical modeling and modern sensing and sampling methods to optimize beamforming under various array element conditions. Beamforming is an important part of array signal processing in many applications, including radar, sonar, and satellite-communications (satcom) systems.

The researchers employed convex constrained optimization and compressed-sensing beamforming (CCOB-CS) models and an orthogonal matching pursuit (OMP) approach to achieve high mainlobe gain and low sidelobes with the aid of MATLAB mathematical-based computer modeling software from MathWorks *(www.mathworks.com)*.

Conventional beamforming (CBF) methods provide good directional resolution and rejection of interference under stationary conditions. When spatial signals are constantly changing, however, the steering vector of the desired signal will deviate, leading to signal error problems. Some of the limitations of CBF methods have been confronted by adaptive beamforming methods using neural networks to dynamically steer the main beam towards the desired signal. But the approach is relatively slow and requires a large amount of processing power, with compromises in beamforming gain.

The new beamforming optimization approach involves using an analog-to-digital converter (ADC) in the direction of moving signals to take a few samples for analysis. By using a small number of low-dimensional snapshots to accurately reconstruct the original signal, the approach can provide suitable gain without requiring a large amount of digital processing power.

In a scenario with little change, an ADC can capture a statistically valid number of samples to construct a good covariance matrix. But when changes become more frequent, the number of samples required to reconstruct the sampled signals increases dramatically, requiring gigasample-per-second sampling rates. For an array assumed to be a linear array, the direction of arrival (DOA) will change when the linear array is moving in a circular fashion as well as changing in angular velocity.

The research team focused their beamforming improvements on satellite signals, specifically on the Global Navigation Satellite System (GNSS), hoping to protect desired signals from loss and interference. To overcome estimated errors in the DOA of the satellite signals, the steering vector is estimated by the multiple-signal-classification (MUSIC) principle. Using an optimization equation, it is possible to obtain the best estimated value of the steering vector for the desired signal.

For further details, see "A Novel Beamforming Technique," *IEEE Antennas & Propagation Magazine*, Vol. 58, No. 4, August 2016, p. 48.

CIRCULARLY POLARIZED REFLECTARRAY SERVES KA-BAND SYSTEMS

A BROADBAND, CIRCULARLY polarized reflectarray (RA) has been developed for Ka-band radar and satellite-communications (satcom) applications. The printed-circuit reflectarray, which measures 25 × 25 RA with physical size of 90 × 90 mm2, consists of two dielectric substrate layers attached by adhesive. The lower substrate is Duroid 5880 circuit material with dielectric constant (Dk) of 2.2, and the upper is Duroid 6010 circuit with Dk of 10.2, both from Rogers Corp. *(www.rogerscorp.com)*. An international team of researchers from Egypt, France, China, and the University of Mississippi, Oxford, coordinated their efforts on the compact array's development by creating a unit cell and then optimizing it for best radiation pattern performance throughout the array.

The RA and its unit cell were simulated with the aid of the Microwave Studio wcomputer-aided-engineering (CAE) software from Computer Simulation Technology (CST). It predicted the effects of signal-incidence angle on the RA's performance as well as the effects of air holes and metallic plated viaholes on the multiple-circuit-board RA structure.

The software was also used to design a dual-mode, circularly polarized feed horn for the RA. The dual-mode feed horn uses separate coaxial connectors for left-handed circular polarization (LHCP) and right-handed circular polarization (RHCP). The RA was designed as a broadside radiator with a design frequency of 30 GHz. Simulations of radiation patterns agreed closely with measurements at microwave and millimeter-wave frequencies (from 27 to 35 GHz) made on commercial test equipment.

See "Ka-Band Circularly Polarized Reflectarray," *IEEE Antennas & Propagation Magazine,* Vol. 58, No. 4, August 2016, p. 60.

All Quiet on the Compensation Front

Although concerns and challenges exist, the RF/microwave industry is continuing to provide stable salaries along with high job satisfaction.

What's the good news in this year's *Microwaves & RF* Annual Salary & Career Report? For one thing, 90% of those who responded report being satisfied in their current position. This high number seems to indicate that the RF/microwave industry is a good one to be a part of. The same number (90%) also said they would recommend engineering as a career path to a young person. As one respondent explained, "The field is wide open. The possibilities are only limited by a person's interest in advancing." Another noted, "You can work on new technology and influence the future in a positive way. You can continue to learn and grow—and often achieve fulfillment doing worthwhile things.

ON THE OTHER HAND....

Not all the respondents were so optimistic. Despite the high level of job satisfaction, work environment concerns were voiced. One respondent said, "There is constant pressure from management to force cookie-cutter solutions where they clearly don't fit." And another bemoaned "the lack of good design discipline and commitment to good products."

This year's survey—the third for *Microwaves & RF*—consisted of a total of 1,393 respondents. Job titles varied among those surveyed, allowing insight to be provided from a range of perspectives.

In terms of compensation, the average base salary was reported to be $110,844, and 68.2% of respondents said they felt adequately compensated for what they do. Furthermore, the average bonus came out to $4,182.

The survey responses also demonstrated the need to bring young engineers into the industry. Just over 40% of respondents are age 60 or older, with an average age of about 53. With many engineers approaching retirement, the industry clearly needs a next generation of engineers who will continue to drive RF/microwave technology in the future.

INFORMATION EVERYWHERE

Keeping up with the latest technology is another common theme, proving that an engineering career involves lifelong learning. Many of those surveyed continue to educate themselves in various ways. White papers, publications, webcasts, and seminars were the most commonly used forms of education. Other methods include engineering videos, textbooks, and more.

One prevalent challenge among respondents is finding the time to stay current with engineering information. Moreover, some expressed dissatisfaction regarding the quality of published information.

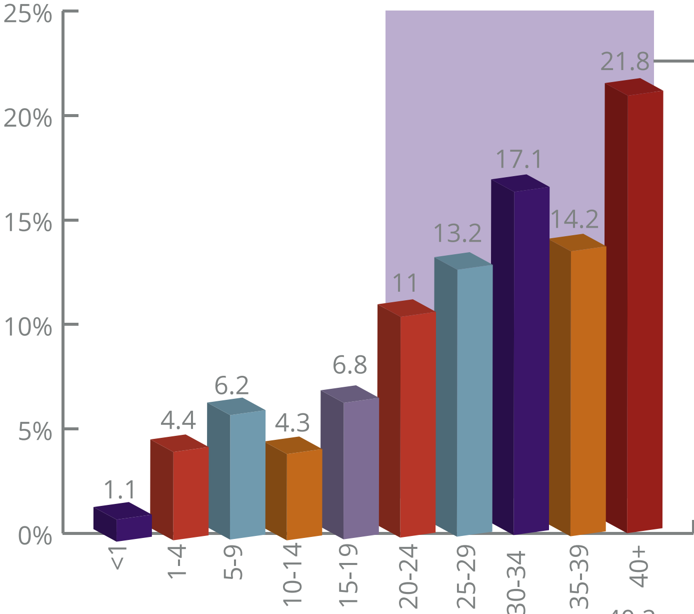
One respondent stated, "There is too much information on the web. Often times, this information is vague, not detailed, or is inaccurate. The challenge is to verify and validate the information." Another noted, "Much of the information is veiled advertising. Products are often made to seem better—or easier to use—than they turn out to be." Yet another respondent offered, "It takes work to recognize value when there are also many 'fluff' articles and emails."

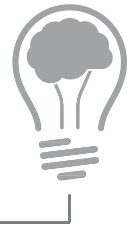
Overall, the *Microwaves & RF* Annual Salary & Career Report results present the RF/microwave industry in a positive light. While not everything is perfect, engineers seem to be both well compensated and satisfied at the same time. With that being said, the industry appears to be in good shape. mw

—Chris DeMartino, Technical Editor

THE TYPICAL ENGINEER

YoY - Years in the Profession

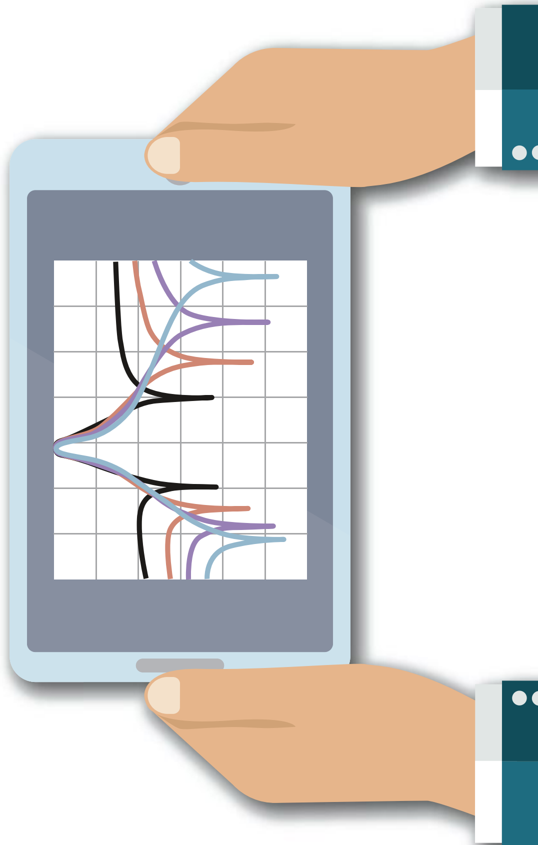


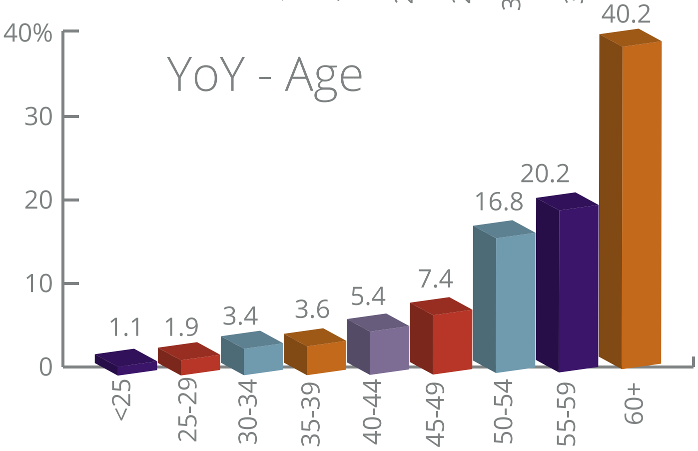


In 2016

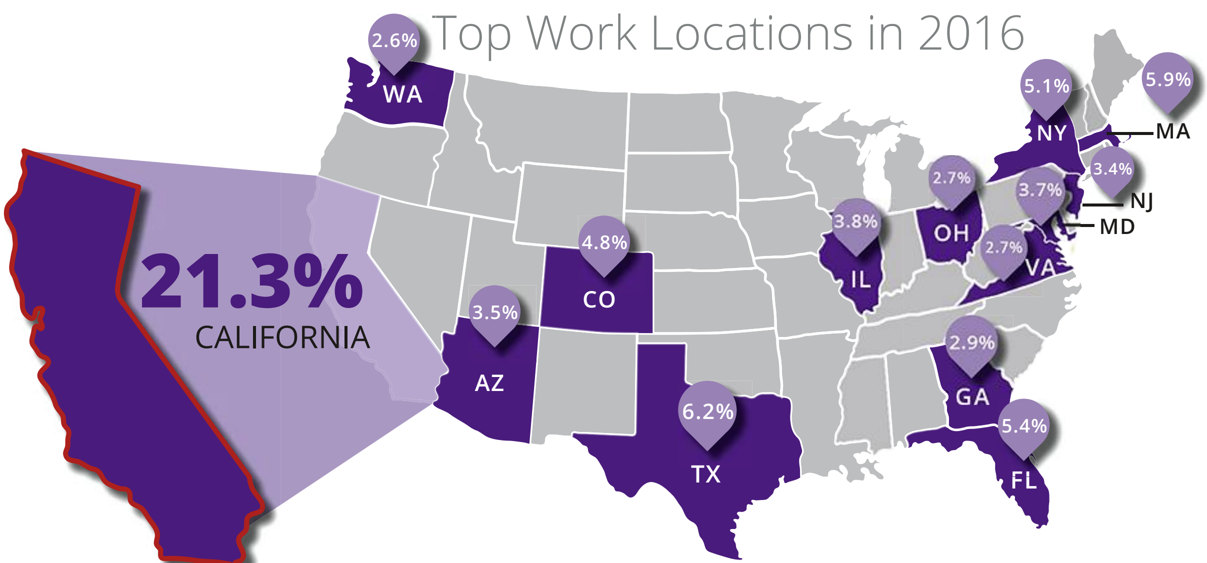
77%

of engineers have
20+ years of experience





Top Work Locations in 2016



COMPENSATION

Average Salary in 2016

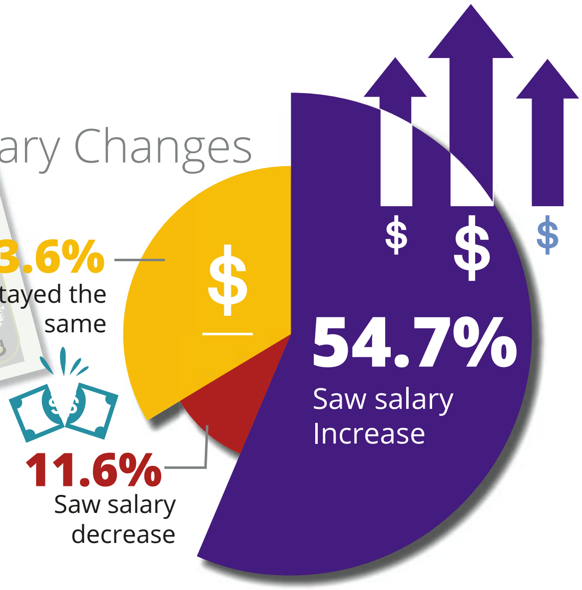
$110,844

$4,182
Average Bonus

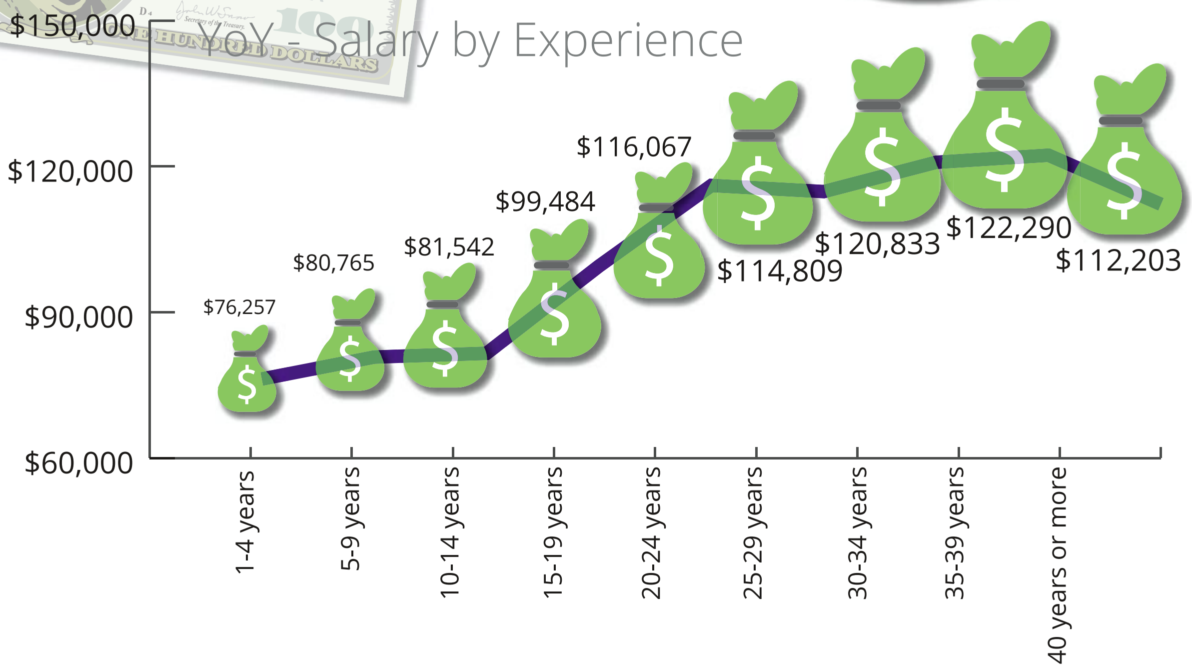
$2705
Average Stock Options

$2,458
Average Other Options

Salary Changes

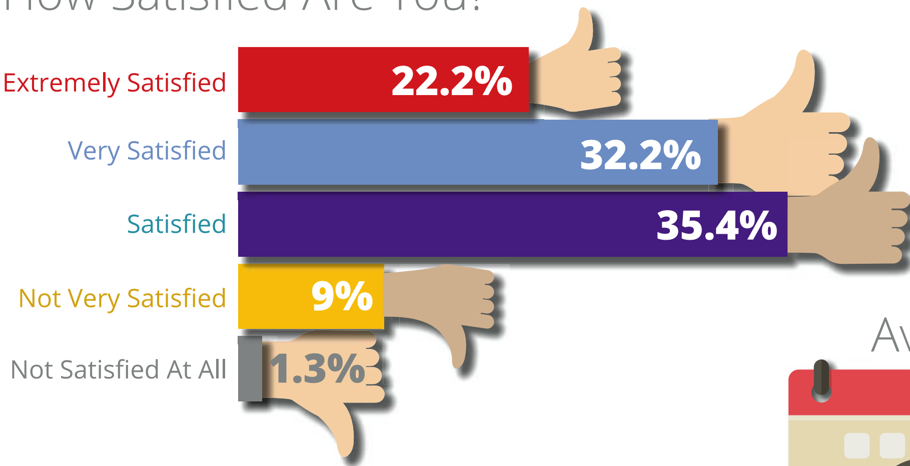


YOY - Salary by Experience

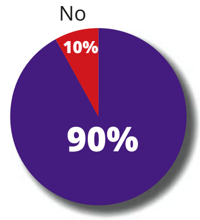


JOB SATISFACTION

How Satisfied Are You?



Recommend Engineering



Average Hours per Week

55

Reasons Engineers Would Leave the Profession

33.5% Try something different

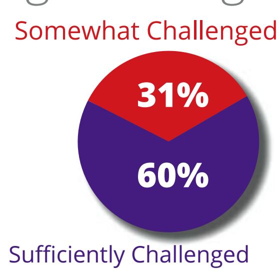
27.1% Pursue other opportunities

19.1% Do something more fulfilling

26.4% To make more money

23.7% To do something less stressful

Feeling Challenged



Most Important Factors in Job Satisfaction

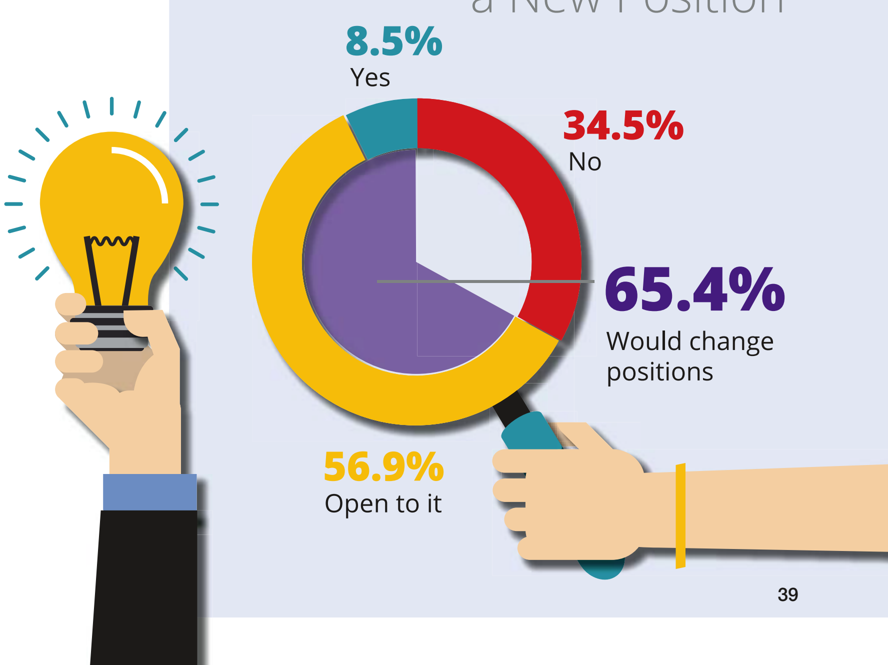
Research
Researching potential design solutions

Challenges
The challenges that accompany the design of new products

Benefits Society
Opportunity to design products that can benefit society

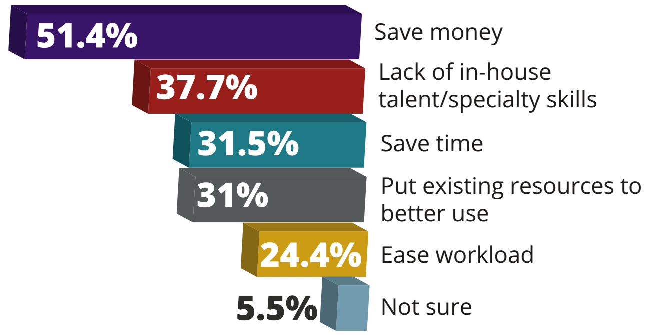
EMPLOYMENT OUTLOOK

Actively Seeking a New Position

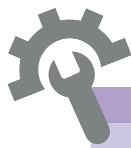


OUTSOURCING

Reasons for Outsourcing



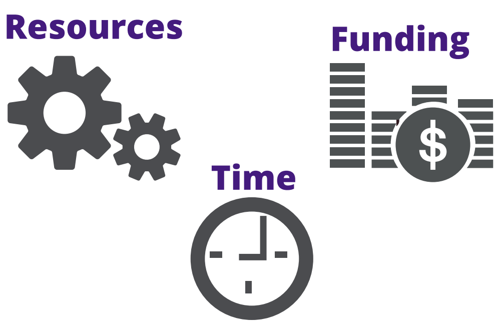
Work Being Outsourced



Manufacturing/assembly	46.6%
Software engineering/development	42.6%
Design	36%
PCB layout	32.7%
R&D	22.7%
CAD/CAE	22.3%
Software verification/test	21.4%
Design verification	15.5%
Final test	14.7%
Drafting	11%
Incoming inspection	3.4%

CONCERNS

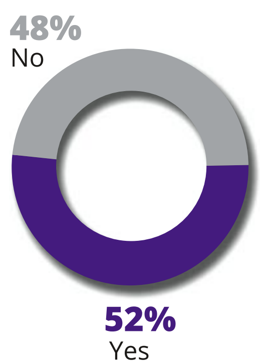
Top Concerns at Work



On a scale of 1-10, with 10 being most pressing, how pressing are each of the following problems in your work?

Insufficient human resources to get job done	6.9
Finding the optimal components for my designs	6.83
Insufficient funding for my design projects	6.71
Having to compromise my design approaches	6.54
Time-to-market pressures	6.4
Inability to adequately test product designs	6.14
Competitive market pressures	5.87
Shrinking product life cycles	5.87
Lack of design management direction	5.66
Politics at work	5.33
Second sourcing for the components specified	5.31
Management taking company in wrong direction	4.93
Seniority issues	4.3

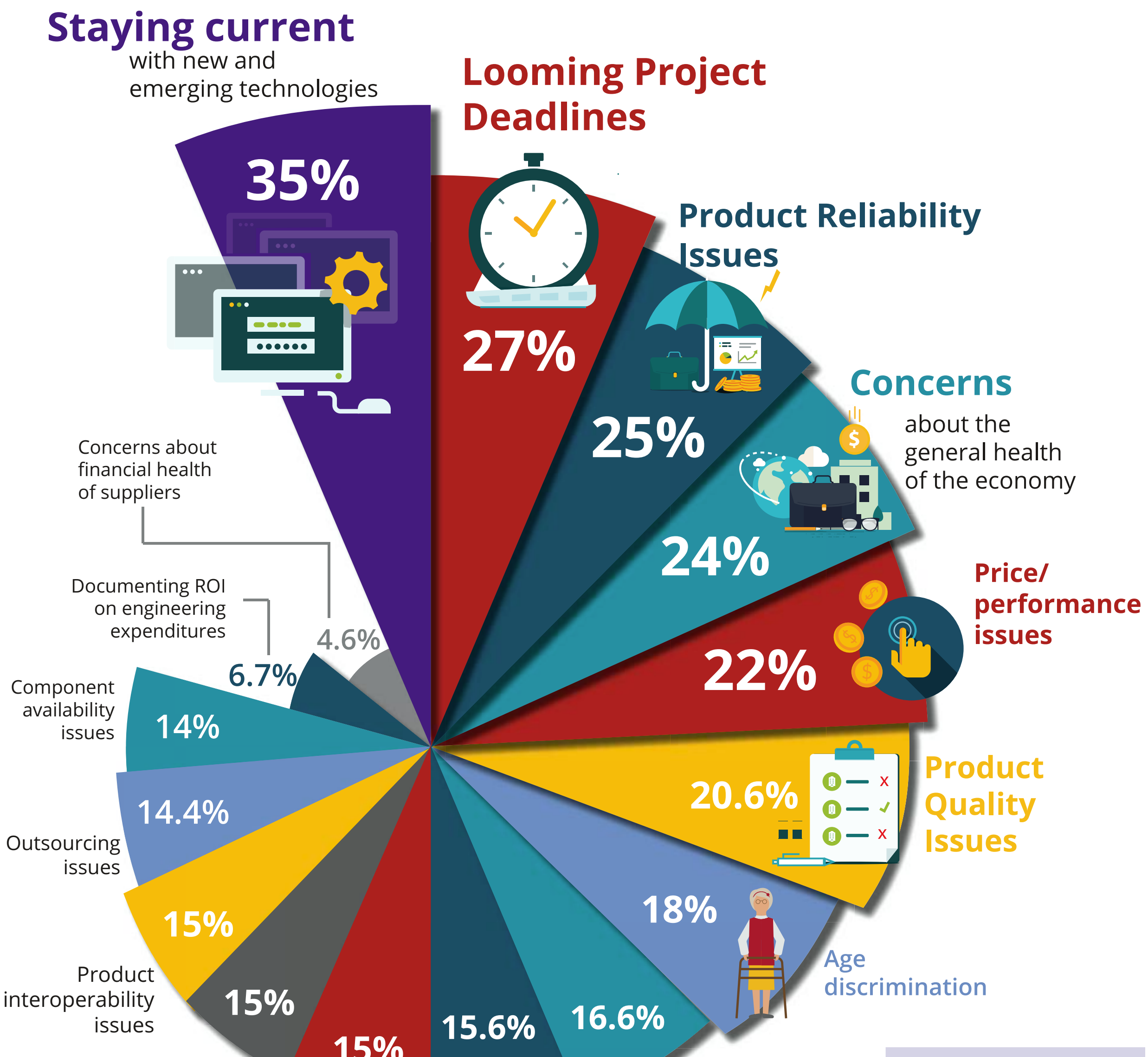
Currently Outsourcing?

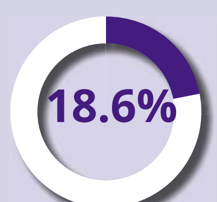


ANNUAL Salary & Career REPORT

2016

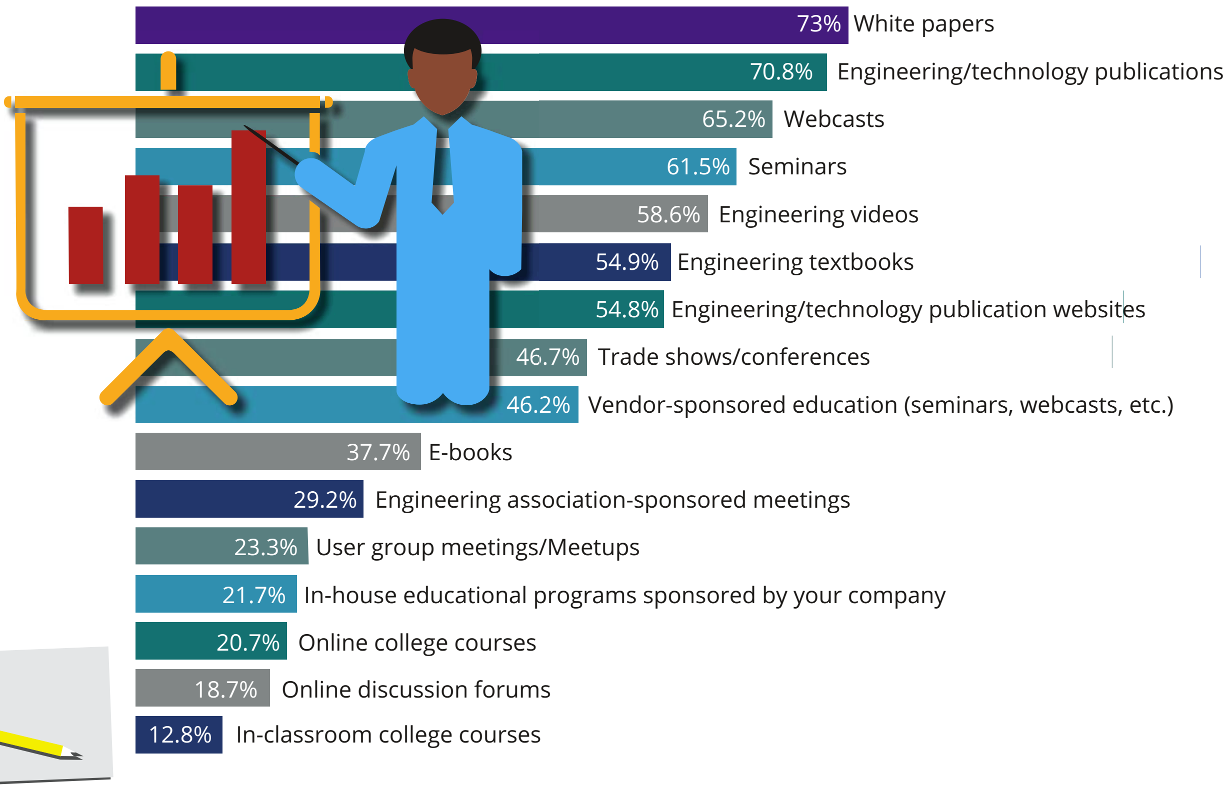
WHAT'S KEEPING ENGINEERS UP AT NIGHT?



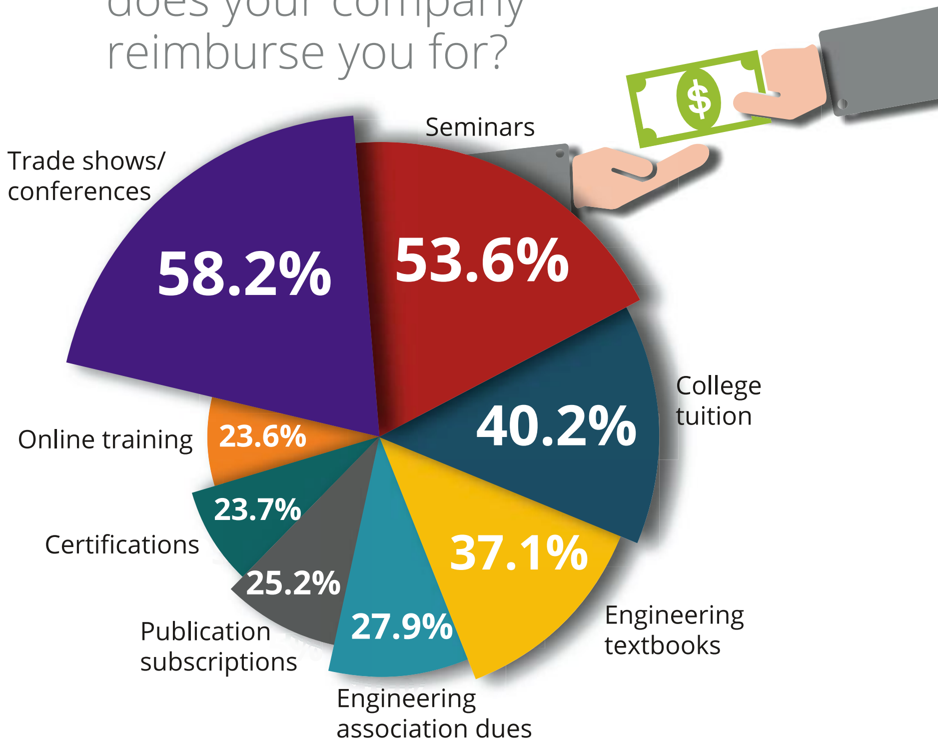


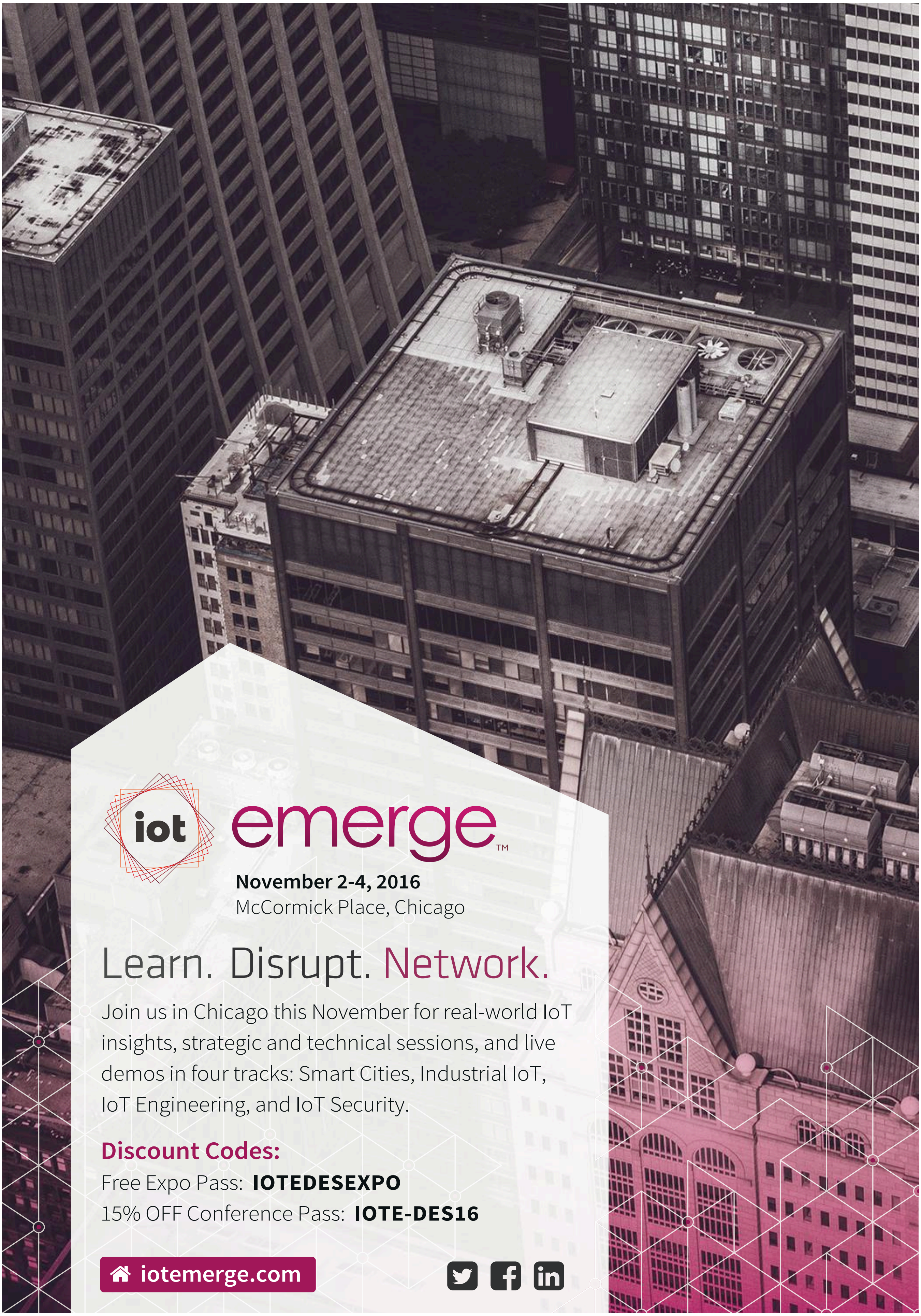
Nothing keeps me up at night

How engineers are keeping up



Which forms of education does your company reimburse you for?

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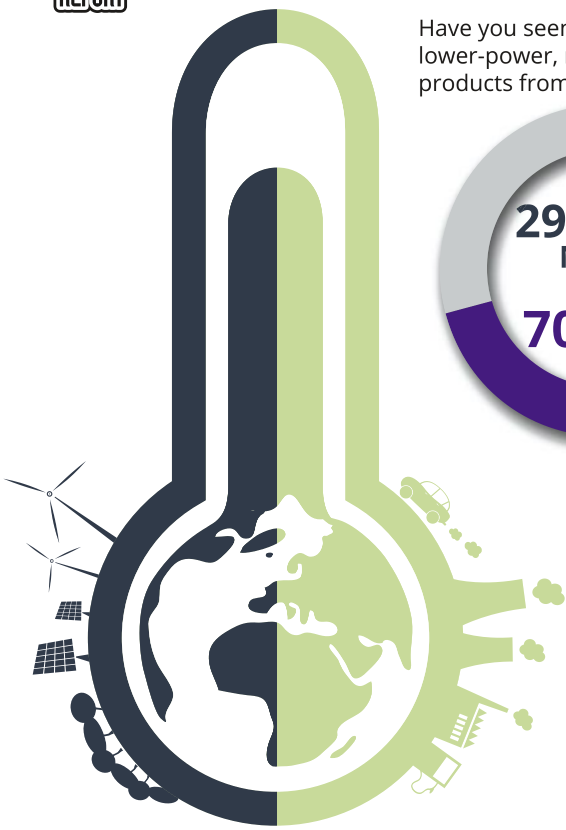
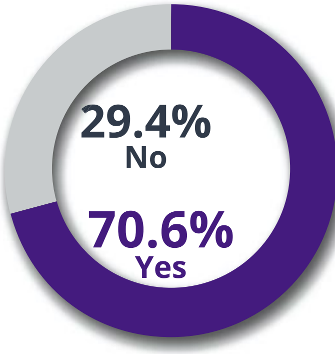
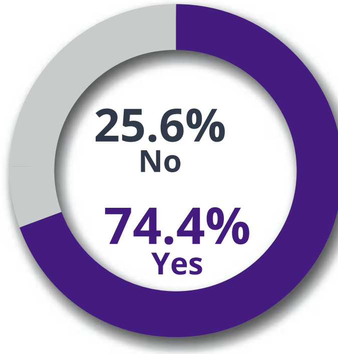
EFFICIENT ENGINEERING



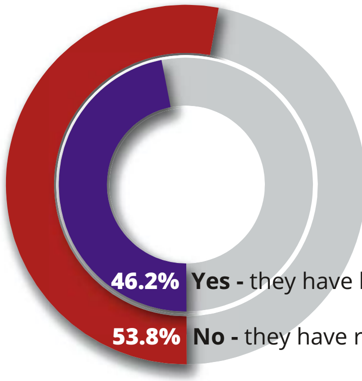
Have you seen growing demand for lower-power, more energy-efficient products from your customers?



Have you seen growing demand for miniaturization in your product designs?



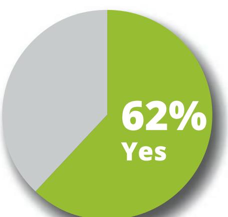
Have these low-power requirements become stricter over the last year?



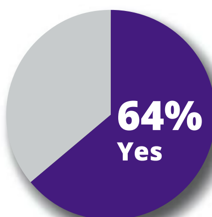
46.2% **Yes -** they have become stricter

53.8% **No -** they have remained as strict as always

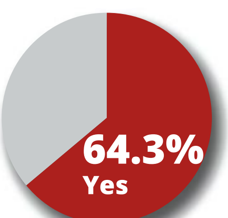
TEST & MEASUREMENT



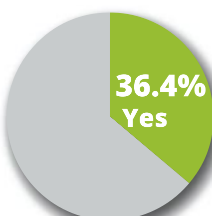
Do you feel that your company invests sufficiently in test and measurement equipment to support your design needs?



Do you think testing is still a challenge for the design process in terms of time consumption?

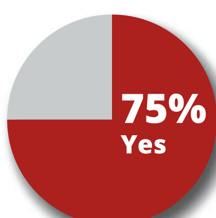


Is there sufficient training and documentation for your test requirements?



Do you expect the Internet of Things to affect test methodologies at your company?

Say their company has replaced box test instruments with modular solutions like PXI.



Do you use design simulation software in your product design process?

DUAL or SINGLE LOOP

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Up to 30 GHz*

Features:

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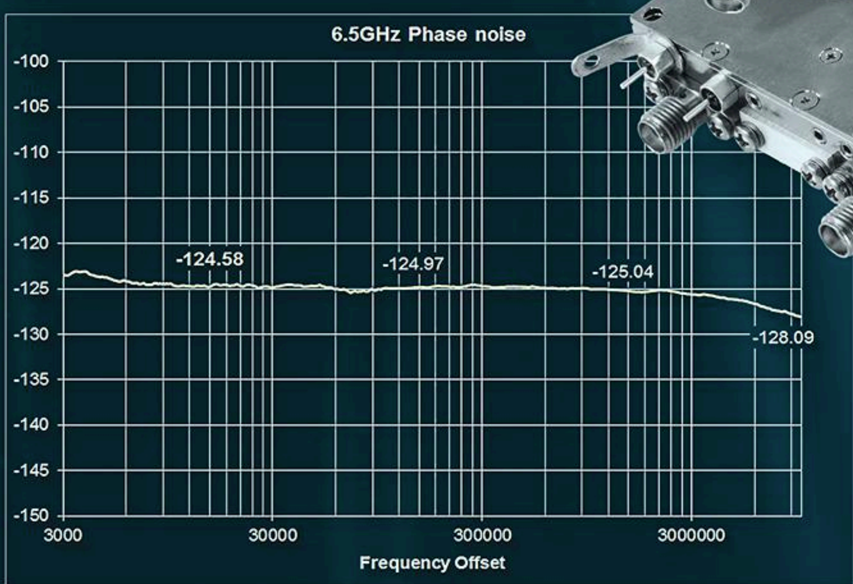
- Output frequencies from 100 MHz locked crystal to 30 GHz
- Available with reference clean up dual loop, or single loop for very low noise reference
- Parallel fixed band stepping or SPI interface synthesized up to octave bandwidths
- Reference input range 1 MHz to 1.5 GHz
- Dual RF output or reference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

Applications:

- SATCOM, RADAR, MICROWAVE RADIO

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



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JACK BROWNE | Technical Contributor

Differentiating BAW and SAW Technologies

BAW and SAW technologies both make use of acoustic waves—albeit in different ways and at different frequencies—as part of high-frequency filters, resonators, and delay lines.

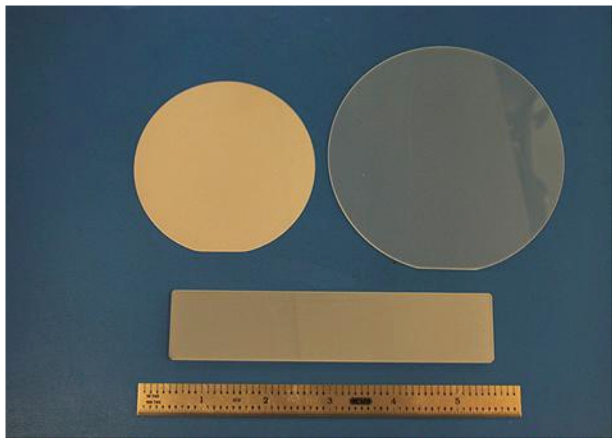
ACOUSTIC WAVES ARE PART of the operating mechanisms of both surface-acoustic-wave (SAW) and bulk-acoustic-wave (BAW) components, although the two acoustic component types and technologies have essential differences. Both technologies can support a number of resonant-type components, including oscillators, filters, and delay lines. SAW components are limited in frequency compared to their BAW counterparts. However, both technologies provide effective circuits within their frequency ranges, and in small sizes that make them attractive for a wide number of applications in commercial, industrial, and military systems.

Both SAW and BAW components leverage the electromechanical properties of certain materials, notably anisotropic piezoelectric materials. Piezoelectric materials transform applied mechanical stress into electrical energy and can also convert electrical energy into mechanical stress.

SAW components make use of the electromechanical properties of these materials through the propagation of acoustic waves along the surface of the piezoelectric material. The acoustic waves travel through the interleaved metal "fingers" of interdigital transducers (IDTs) fabricated on the appropriate piezoelectric substrate.

Piezoelectric materials can produce electricity from applied mechanical stress, in addition to transforming applied electrical energy into mechanical energy, such as acoustic waves. This is accomplished by fabricating interdigital transducers (IDTs) on the surface of a piezoelectric substrate, such as lithium tantalite ($LiTaO_3$, lithium niobate ($LiNbO_3$), or quartz crystal.

Electrical RF/microwave energy at one end of the transducer is transformed into mechanical energy in the form of acoustic waves that travel along the interleaved metal fingers, and are transformed back to electrical RF/microwave energy at the other end of the transducer. With the slower velocity of these acoustic waves compared to the input RF/microwave waveforms, signal processing such as filtering and time delays can be performed in the acoustic frequency range, and then realized in the RF/microwave frequency range at the output of the SAW transducer.



1. Large circular and rectangular piezoelectric substrate wafers enable large volume manufacturing of SAW components. In this case, these wafers are used strictly for custom SAW components and modules for military applications. *(Courtesy of Phonon Corp.)*

Commercial SAW components can be fabricated on relatively large piezoelectric wafers (*Fig. 1*) compared to the smaller wafers used for fabricating semiconductor devices. Using larger wafers enables the production of relatively large volumes of SAW components for relatively low cost, with the opportunity to fabricate RF/microwave bandpass and other filters in much smaller sizes than ceramic filters for the same center frequency.

SAW components are typically manufactured at frequencies to about 2 GHz. Since the dimensions of the IDT structure shrink with increasing frequency, the challenges of producing SAW components with sufficiently small IDT dimensions to support those higher frequencies make it impractical at higher frequencies.

BAW components typically operate at higher frequencies that SAW components, almost starting where SAW components leave off—at about 1.5 GHz and higher. BAW components are also fabricated on piezoelectric materials, although typically using different substrate materials than their SAW counterparts.

> **"At frequencies of about 2 GHz or below, SAW filters are capable of excellent rejection of unwanted, out-of-band signals while maintaining flat amplitude response across the passband frequency range."**

In fact, one of the more popular piezoelectric substrate materials for BAW components is aluminum-nitride (AlN). BAW components also function differently than SAW components. In a BAW component, the acoustic waves travel and are stored in the piezoelectric material rather than across the top surface of the substrate.

Metallization for a BAW component is deposited on the top and bottom of the piezoelectric material, creating a form of acoustic channel for the waves. The acoustic waves essentially bounce between the metal layers and through the piezoelectric material, forming a standing acoustic wave. The resonant frequency of the standing wave is a function of the substrate thickness and the mass and type of metallization, with thinner substrates yielding higher operating frequencies.

Different types of metal films are used in BAW components than in SAW components—typically aluminum metallization for lower-power components and tungsten (W) for higher-power components. Although BAW components such as filters can be fabricated for use at frequencies below 1.5 GHz, and well into the frequency range of SAW components, the larger sizes of BAW components at those lower frequencies results in lower yields of components per piezoelectric wafer, making it difficult to be cost-competitive with SAW filters or even ceramic filters at those lower frequencies.

BAW components operate to higher frequencies than SAW components—about 15 GHz and higher compared to SAW components, which are available to about 2 GHz. The nature of BAW components, with high-density acoustic energy stored within the metal plates of a piezoelectric substrate, results in lower-loss components at higher frequencies than SAW components.

They are also capable of high-quality-factor (high-Q) resonators in relatively small sizes for microwave filters with high rejection and sharp band edges. In general, BAW components (such as filters) can typically achieve lower passband insertion loss than SAW filters, although usually at higher frequencies.

2. Manufacturing of high-performance SAW components requires computer-controlled automated measurements of SAW component performance. *(Courtesy of Phonon Corp.)*

At frequencies of about 2 GHz or below, SAW filters are capable of excellent rejection of unwanted, out-of-band signals while maintaining flat amplitude response across the passband frequency range. In general, SAW components exhibit greater variations in performance with temperature than BAW components at their higher frequencies, although careful selection of SAW substrate materials can help limit these performance variations. In addition, some manufacturers offer temperature-compensated SAW (TC-SAW) components to minimize temperature variations without sacrificing the excellent electrical performance of SAW technology.

Similarly, some suppliers offer BAW components, mainly filters, based on "low-drift" piezoelectric materials that minimize variations in frequency with temperature, usually characterized in parts per million per degrees Centigrade (ppm/°C). The temperature shifts for these components can be in terms of negative or positive values (changes in frequency with temperature), with an ideal component characterized by 0 ppm/°C. At least one manufacturer offers these low-drift BAW components at frequencies to 9 GHz and higher.

By applying consistent manufacturing practices, quality control, and computer-controlled test methods (*Fig. 2*), some manufacturers of SAW components—such as Phonon Corp. (www.phonon.com)—have succeeded in achieving some of the highest quality levels in SAW components like filters, delay lines, oscillators, and modules. These quality levels are sufficient for an exclusively military customer base. mw

JOHN COONROD | Technical Marketing Manager
Rogers Corp., Advanced Connectivity Solutions,100 South Roosevelt Ave., Chandler, AZ 85226-3416;
(480) 961-1382, www.rogerscorp.com

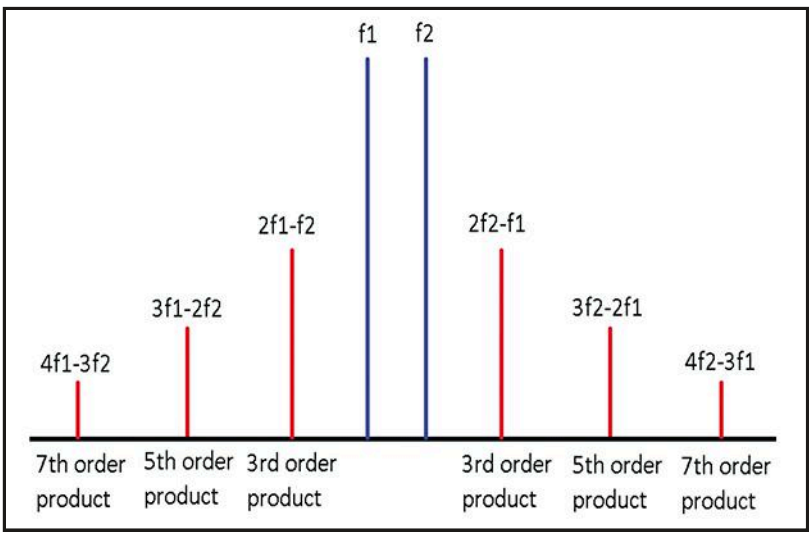
Materials Make the Difference in Low-PIM PCB Antennas

Certain characteristics of circuit materials can indicate whether a material will contribute to higher or lower levels of PIM for a printed-circuit RF/microwave antenna.

Antennas are the beginning and end components of many communications systems, and the performance of modern wireless communications networks depends on these antennas achieving low passive-intermodulation (PIM) levels. PIM is a complex phenomenon that results in the generation of spurious energy. It is not caused by circuit materials, but results from the design and mechanical structure of high-frequency circuits, from circuit-assembly practices, and/or from system-level effects.

Still, circuit materials can play a part in achieving low PIM in PIM-sensitive applications. For low-PIM printed-circuit-board (PCB) antennas, some of the PIM performance depends on the design, and some on the choice of PCB materials. Understanding how PCB characteristics influence PIM performance can ease the task of choosing circuit materials for low-PIM PCB antennas.

Maintaining low PIM in a communications system is a complex problem due to the large number of variables that contribute to PIM. A quick list of PIM-causing variables includes cables, connectors, passive components, solder joints, and even placement of hardware. It gets even more complex with interactions among variables. The proper choice of circuit materials for a PCB antenna can at least shrink one list of variables.



1. This plot shows how intermodulation products result from the mixing of two fundamental-frequency signals and their harmonics.

RISE OF PIM

PIM has become more of a design issue in recent years with the growing number of wireless applications and their associated signals occupying a limited amount of available bandwidth. Two or more closely spaced signals within the same operating band can produce intermodulation distortion due to the mixing of their lower-order harmonics and the mixing of those harmonics with the two fundamental signals (*Fig. 1*). The signals may come from the same wireless base station, or they could be signals reaching the antenna from additional, outside sources.

Such intermodulation was once only associated with active devices, such as semiconductor mixers and amplifiers, but in recent years it has become evident that intermodulation can be caused by passive components, too, including antennas. It can affect applications with single antennas used for transmit and receive functions and multiple carrier frequencies, especially when those antennas exhibit the nonlinear behavior that could create PIM. When the amount of spurious energy produced as PIM falls within the operating frequency range of a receiver, it can qualify as interference.

At the system level, anything in the RF signal path between the transmitter and receiver can cause PIM, especially ferromagnetic materials or metals and any materials with ferromagnetic properties. Materials such as rust and metals like nickel and iron can be sources of PIM. Anything that interrupts the signal path of a transmission line, e.g., poorly fitted interconnections or debris in the mating area of connectors, can cause PIM. Even a rusty fence in the vicinity of a wireless transmitter could trigger PIM, with sufficiently high transmit power.

In a PCB-based antenna, such as a microstrip patch antenna, circuit cleanness (or lack thereof) may also cause problems. For example, residue remaining on a PCB following fabrication and left behind by inadequate PCB cleaning procedures can be sufficient to induce nonlinear effects that result in PIM. A number of different kinds of plated finishes on PCBs can contribute to higher levels of PIM—electroless nickel, immersion gold (ENIG), and electroless nickel, immersion palladium, immersion gold (ENIPIG) are two such types.

MATERIAL CONSISTENCY

The choice of PCB material itself may also play a part in the PIM performance of a PCB antenna. Several circuit material parameters can be used to project how well a PCB antenna is expected to perform, including consistency of dielectric constant (Dk), stability of Dk with temperature, and mechanical stability with temperature. Ideally, the Dk of a circuit substrate material should be uniform throughout each board and consistent from board to board for good circuit-to-circuit repeatability.

Because Dk determines the circuit dimensions required for optimum antenna performance at a desired wavelength/frequency, any circuit material intended for PCB antenna design should feature dielectric constant within a tight tolerance. Although predicting PIM performance for any antenna design is difficult, using the optimum circuit material to achieve the best performance for a printed antenna will also generally deliver the best PIM performance.

The Dk determines the impedance of the patch pattern and the microstrip transmission lines feeding the patch. Consequently, excessive variations in a circuit material's Dk will result in changes in impedance and frequency throughout the printed antenna circuit and unwanted variations in antenna radiation pattern. A Dk tolerance of ±0.05 is considered quite good for printed antennas, as well as for most other high-frequency circuit applications.

Consistent circuit material Dk is also desirable across a wide operating-temperature range. That's because printed antennas and their transceivers may be asked to perform flawlessly over a wide range of operating conditions, from day to day or from season to season in outdoor base stations and cell sites.

The parameter that provides insight into the stability of a circuit material's Dk with temperature is the thermal coefficient of Dk (TCDk). For a given material, this parameter notes by how many parts per million (ppm) the Dk will change per change in temperature in degrees centigrade (°C). If the TCDk value of a material is high, the Dk will change by a relatively large amount with temperature, and will change the antenna's resonant frequency as well as alter the radiation pattern for the desired frequency range.

A TCDk value can be positive or negative, depending upon the formulation of the circuit material. Considering the absolute value of a material's TCDk, a value of 50 ppm/°C or less is quite good, or within the range of ±50 ppm/°C.

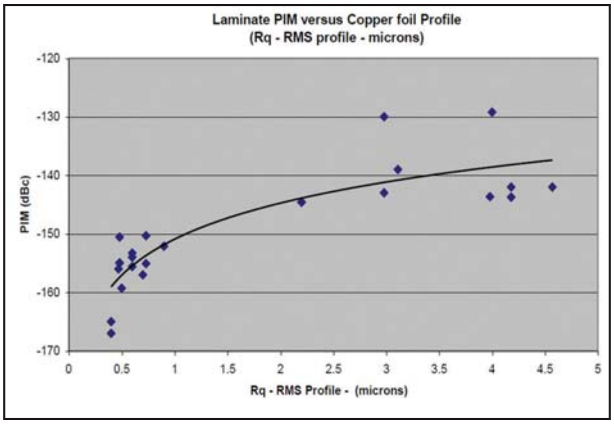
In terms of real-world circuit materials used for PCB antennas, FR-4 typically represents a low-cost circuit-material solution. However, the tradeoff for low cost is a Dk that varies widely with temperature, characterized by a high value of TCDk. When room temperature (or +25°C) is used as the starting point for normalized Dk, a circuit material's Dk may increase or decrease at other temperatures. When compared to other circuit materials, the changes for FR-4 can be dramatic, with significant decreases in Dk at temperatures below +25°C and large increases in Dk for temperatures above +25°C.

Ideally, materials for PCB antennas should provide stable Dk with temperature, denoted by lower values of TCDk. Depending on formulation, commercial materials, such as RO3003 and RO4003 laminates from Rogers Corp. (www.rogerscorp.com) can have negative or positive TCDk values, describing how the material Dk changes with temperature.

For RO3003 laminates, which are polyetrafluoroethylene (PTFE) circuit materials reinforced with ceramic fillers, the TCDk is extremely low and negative, at only –3 ppm/°C, for very little change in Dk with temperature. This material has a Dk of 3.00 with tolerance of ±0.04. For RO4003 laminates, which also have quite low TCDk, the value is positive at 40 ppm/°C. This hydrocarbon circuit material, reinforced with ceramic filler, has a Dk value of 3.38 and tolerance of ±0.05.

Another circuit-material parameter for antennas related to temperature is coefficient of thermal expansion (CTE). Though also given in units of ppm/°C, it is a measure of the mechanical changes in a circuit material due to changes in temperature. Because a material will expand and contract according to changes in temperature in its x, y, and z axes, the CTE of candidate materials for an antenna design must be compared in all three axes.

In particular, these CTE values should be compared to the CTE values for other materials used on a PCB. This includes the copper used to form a patch antenna pattern and its microstrip



2. A PCB laminate's copper conductor roughness can impact the amount of PIM produced by circuits fabricated on that circuit material.

feed lines, in addition to copper plating used on plated through-holes (PTHs) that might connect an antenna to the different layers of a multilayer circuit. In the x and y dimensions, the circuit patterns and the dielectric material will expand and contract; in the z dimension, the metal of the PTHs and the thickness of the dielectric material will change with temperature.

Ideally, the CTE values for all materials of interest should be fairly closely matched. This will prevent stresses at the interfaces of different materials caused by mechanical changes with temperature. Since the CTE of copper is about 17 ppm/°C, a CTE value for a PCB material that is within range of copper is considered good, such as 60 ppm/°C or less. The CTE is not just a factor to consider for printed-antenna performance and reliability. It is also an indicator of a circuit material's capability to withstand the high temperatures used when manufacturing a printed antenna, such as for lead-free solder-reflow processes.

PATROLLING ANTENNA PIM

When considering high-frequency circuit materials for printed antennas, metallic rather than dielectric materials are the main concern. Rough copper-laminated surfaces of PCB materials are a leading source of PIM in such antennas. Ideally, the surface of a PCB's copper laminate should be as smooth as possible to promote linear behavior. Specifically, the surface of concern is the copper-substrate interface of the laminate. As the roughness of the copper surface increases, the EM behavior of the copper as a conductor becomes increasingly nonlinear and more subject to generating higher levels of PIM as an antenna circuit (*Fig. 2*).

As noted earlier, treatments applied on the copper foil can raise a PCB antenna's level of PIM. Treatments are often performed to improve the adhesion of the copper layer to the

> "Although PIM is a type of distortion that affects system-level communications performance, it starts at the component level (i.e., connectors, antennas, etc.)"

dielectric layer. However, a copper treatment with ferromagnetic properties such as nickel-based treatments can be a source of higher PIM levels; therefore, it's a good idea to minimize use of such PIM-causing treatments.

In terms of a PCB's dielectric material, for low PIM levels, the guidelines provided earlier should be followed for consistent Dk held within a tight tolerance window. In addition, the dielectric material should exhibit low loss as evidenced by a low value of dissipation factor (Df).

Furthermore, as a simple rule of thumb, a thinner circuit laminate will yield worse PIM performance than a thicker circuit laminate, although this is not due to the dielectric properties. The amount of PIM is very much subject to the design of the printed circuit. In a thinner antenna circuit, greater power density is concentrated in a smaller area than a thicker antenna circuit with wider conductors. If any conditions for PIM are present, such as rough copper foil or residue from PCB fabrication, the higher power density will add to conditions favorable for generating higher levels of PIM.

Although PIM is a type of distortion that affects system-level communications performance, it starts at the component level (i.e., connectors, antennas, etc.). As wireless communications services extend throughout the world, with strong competition for available frequency bands, PIM becomes more critical than ever. As a result, lower levels of PIM are required to maintain system-level performance and avoid symptoms such as dropped calls and diminished coverage areas.

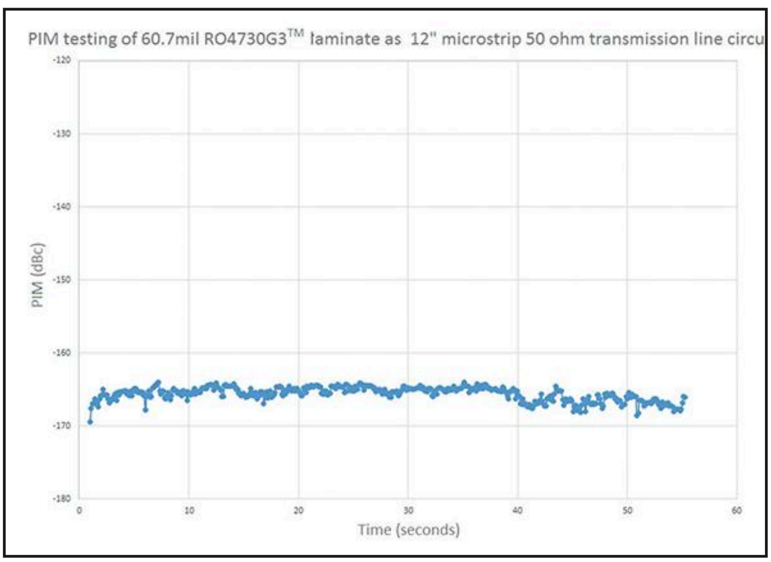
PIM performance can be compared in terms of dBm (power relative to 1 W) or dBc (power relative to the carrier). A PIM level of –145 dBc was once considered satisfactory. But as the number of subscribers increased along with the number of cell sites to serve them, required PIM levels continued to drop. They initially fell to –150 dBc, and now –153 dBc is considered adequate.

To achieve printed antennas with the performance required for low PIM, the circuit materials must play their parts to help minimize intermodulation distortion. Although no industry-standard test methods exist for characterizing circuit materials for PIM, a technique was developed to characterize the latest generation of low-PIM circuit laminates, such as RO4730G3 circuit material from Rogers Corp. (see "*Laminates Lay Foundation for 5G Antenna Circuits*" *on mwrf.com*).

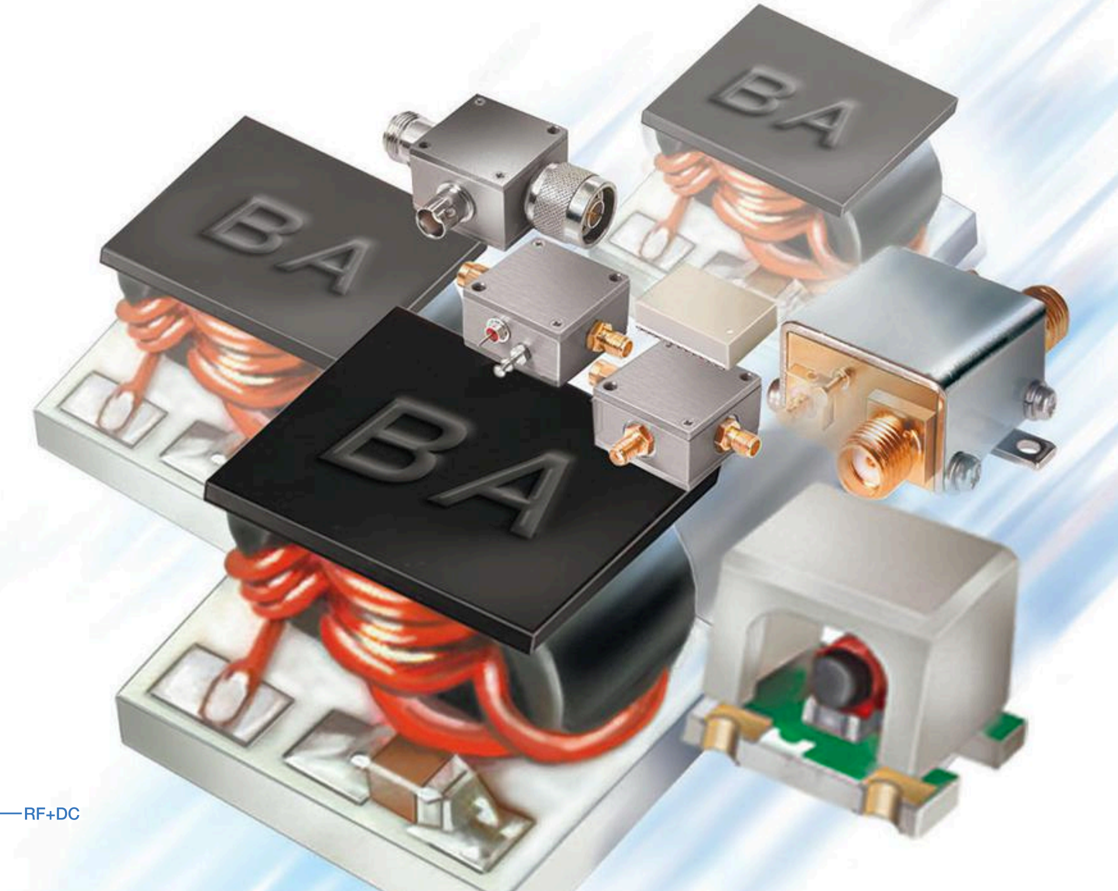
Evaluation involved the fabrication of a 12-in.-long microstrip transmission-line circuit on 60.7-mil-thick RO4730G3 laminate. Since so many variables can impact PIM and its testing, a circuit's PIM performance may change dramatically over even the short period of time required for testing (i.e., a few seconds). To reveal consistency in PIM performance, measurements should be performed for a time period much longer than just those few seconds. Thus, the microstrip circuit's PIM performance was measured for a total of 55 s, with 10 data points collected every second to produce a total of 550 plots of PIM versus time (*Fig. 3*).

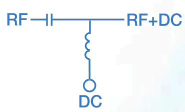
The RO4730G3 material, which was engineered for printed antennas, is capable of PIM levels of –163 dBc or better. It is an example of a material with the characteristics—tight Dk tolerance, smooth copper foil, excellent CTE—that support low PIM levels for printed-circuit antennas. mw

Editor's Note: To learn more about the test methods used to characterize circuit laminates for PIM, copies of "PIM and PCB Antennas: Your Guide to Circuit Materials for Low Passive Intermodulation (PIM) Antennas" are available for free download at www.rogerscorp.com.



3. PIM testing as a function of time was performed on RO4730G3 circuit laminates using a 12-in.-long microstrip transmission-line circuit on 60.7-mil-thick circuit material.





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TCBT-6G+**	50-6000	0.7	28	200	7.95*
TCBT-14+***	10-10000	0.35	33	200	8.45
TCBT-14R+***	10-10000	0.6	33	200	8.45

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*U.S. Patent 7,012,486** U.S. Patent 8,644,029****

Model	Freq (MHz)	Insertion Loss (dB)	Isolation (dB)	Max Current mA	Qty.1-9
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JEBT-4R2GW+	0.1-4200	0.6	40	500	59.95
PBTC-1G+	10-1000	0.3	33	500	28.20
PBTC-3G+	10-3000	0.3	30	500	38.20
PBTC-1GW+	0.1-1000	0.3	33	500	38.20
PBTC-3GW+	0.1-3000	0.3	30	500	49.20
ZFBT-4R2G+	10-4200	0.6	40	500	59.95
ZFBT-6G+	10-6000	0.6	40	500	79.95
ZFBT-4R2GW+	0.1-4200	0.6	40	500	79.95
ZFBT-6GW+	0.1-6000	0.6	40	500	89.95
ZFBT-4R2G-FT+	10-4200	0.6	N/A	500	79.95
ZFBT-6G-FT+	10-6000	0.6	N/A	500	79.95
ZFBT-4R2GW-FT+	0.1-4200	0.6	N/A	500	79.95
ZFBT-6GW-FT+	0.1-6000	0.6	N/A	500	89.95
ZFBT-282-1.5A+	10-2800	0.6	45	1500	59.95
ZFBT-352-FT+	30-3500	0.4	23	4000	49.95
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RADAR TECHNOLOGY CONTINUES TO ADVANCE

Military radar systems are moving away from vacuum tubes, embracing GaN semiconductors and solid-state amplification for improved power efficiency and long-term reliability.

RADAR TECHNOLOGY has been the backbone of the electronic military for many decades. Even as the technology continues to extend as the basis for numerous collision-avoidance systems in commercial automobile markets, it also expands into a growing number of military applications—specifically, as part of surveillance and tracking systems on the ground, at sea, in the air, and in outer space.

In the case of some airborne systems, such as in unmanned aerial vehicles (UAVs), an operator may be quite a distance from the radar system. In all cases, the feedback that these radar systems provide is invaluable.

(continued on p. 64)

1. The long evolution of synthetic-aperture-radar (SAR) technology has enabled the development of dependable, solid-state ground-based surveillance and early-warning systems. *(Photo courtesy of Lockheed Martin)*

NAVY PICKS Lockheed Martin for Frigate Combat Management

THE U.S. Navy selected Lockheed Martin (www.lockheedmartin.com) and its COMBATSS-21 as the combat-management system for Navy frigates, awarding a contract worth as much as $79.5 million for fiscal years 2016 through 2021. COMBATSS-21—the open-architecture combat-management system deployed on cruisers, destroyers, and littoral combat ships—will now also be deployed on Navy frigates.

COMBATSS-21, an abbreviation for COMponent-BAsed Total-Ship System-21(st century), is built from Aegis Common Source Library (CSL) code. It has a framework similar to Aegis Baseline 9 software developed for the Aegis cruiser and destroyer ships, Littoral Combat Ships (LCS), and U.S. Coast Guard national security cutters.

Rich Calabrese, director of mission systems at Lockheed Martin, says that using the CSL code is both efficient and cost-effective: "Using the CSL enhances life-cycle affordability by reducing costs for integration, test, and certification—and delivers an open combat system architecture in line with the Navy's objective architecture, driving affordability and increasing interoperability across the entire fleet." This shared use of the CSL code makes it possible for combat ships to quickly integrate new capabilities, incorporating new sensors and weapons in response to new threats. ■

(continued on p. 60)

Radar Embraces Remote Control

RADAR HAS long been the "backbone" technology of military electronics. It is the means by which an adversary's troops and their movements can be detected from a distance, and has served as a reliable early-warning system for decades.

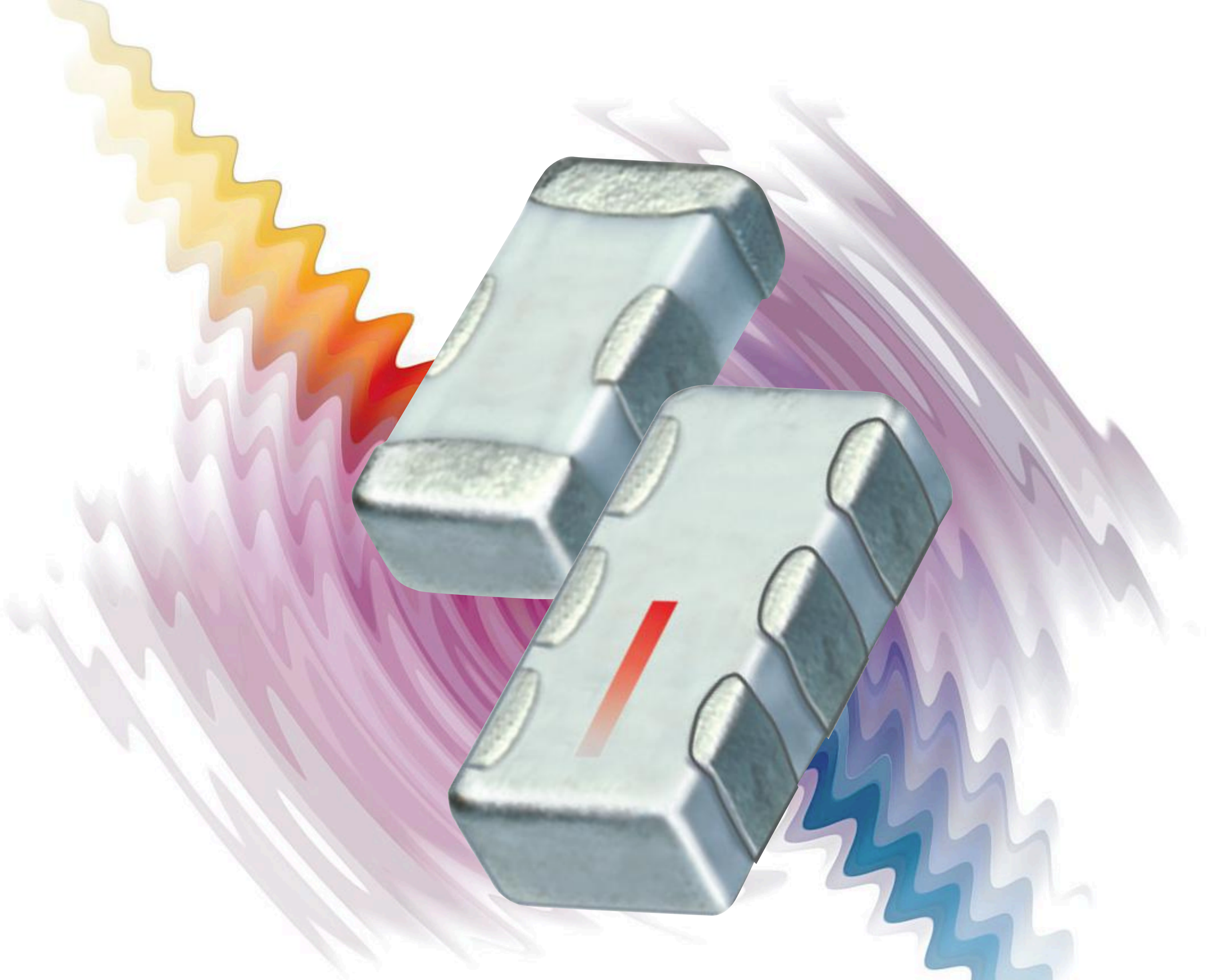
Radar technology is ever-evolving and improving along with enhancements to RF/microwave components and developments in signal-processing components, such as digital signal processors (DSPs) and field-programmable gate arrays (FPGAs). It is also teaming with another technology, unmanned aerial vehicles (UAVs), to provide remote vision for military surveillance.

Of course, creating a remote-controlled UAV with a radar system, or even an onboard camera system, is no trivial task. Radar systems have traditionally relied on high-power pulsed signals to illuminate targets, which makes generating signals of sufficient amplitude with batteries on a UAV a challenge. The weight of the radar system is also a concern, since it must juggle the tradeoff between weight and transmit power to make it a viable subsystem onboard a UAV, or even an unmanned ground vehicle (UGV).

Then there is the matter of transferring intelligence on the radar returns from the drone to a remote operator. Wireless radio links must be secure, and they must also contain sufficient bandwidth for communications and control signals—as well as video signals, if the UAV is equipped with a monitoring camera.

Military interest in radar-equipped UAVs is so strong that research efforts analyzing the design challenges of creating UAVs with remote-controlled radar systems are spreading. For example, work at the University of Denver's Unmanned Systems Research Institute has included the development of a fully working prototype, with antenna, amplifier, processor, transmitter/receiver, and wireless data link. The prototype weighs 230 g and consumes only 4.5 W power.

This prototype system was initially developed to serve the Federal Aviation Administration (FAA) and air-traffic-control applications. Consumer and commercial interest in UAVs is so great that there is concern among FAA officials about excessive airborne congestion and in-flight accidents. Adding radar technology to commercial UAVs can prevent them from crashing into each other or, more importantly, into manned aircraft. de



German Security Relies on R&S Scanner

SECURITY SCANNERS from Rohde & Schwarz (www.rohde-schwarz.com) will soon be essential tools for the German Federal Police Force, thanks to a major contract awarded to the firm by the German Federal Ministry of the Interior. The primary application for the 300 new R&S QPS200 security scanners will be for security at German airports. Terms of the contract will be fulfilled over a three-year period.

The scanners use millimeter-wave technology to automatically detect potentially dangerous objects hidden on a body or under clothing, whether they are rigid, flexible, fluid, metallic, or non-metallic. They operate at frequencies between 70 and 80 GHz and at extremely low, safe radiated power levels. The scan of a passenger or person is comfortable, requiring only milliseconds to complete. Privacy is maintained by means of a neutral graphical display. The scanners have been certified by the European Civil Aviation Conference (ECAC) and thoroughly tested for suitability by the German Federal Police. ■

Scanners operating between 70 and 80 GHz will be used for security purposes at German airports.

Sidewinder Missle Tests Hit the Mark

RAYTHEON CO. (www.raytheon.com) recently teamed with the U.S. Air Force and Navy on test firing three AIM-9X Block I ("Sidewinder") missiles from an F-35A aircraft, the first short-range, air-to-air missile to be used on the F-35 Joint Strike Fighter. These tests demonstrated the effectiveness of numerous functions required for successful missile deployment, including loading, target acquisition by the aircraft, missile target acquisition and tracking, launch initiation, in-flight guidance, and impact/proximity fusing at the interception of the target.

"These tests validated the on-board communications and handoffs between the aircraft and the missile required to prosecute an aerial target," says Mark Justus, AIM-9X program director for Raytheon Missile Systems. "AIM-9X will help ensure our pilots and allies have the most reliable and effective weapons on the F-35." A fourth guided missile test of the AIM-9X Block I missiles is expected later this year.

An F-35 can carry two AIM-9X missiles on its wings, and four AIM-120 missiles internally, when properly configured. These test firings were intended to ensure integration of the advanced missile systems with their introduction across the F-35 fleet expected in 2017. ■

This file photo shows U.S. Navy aviation crewmen handling a Sidewinder missile, recently exercised through a series of tests. *(Photo courtesy of the U.S. Navy)*

NEWS SHORTS

Strong Growth Expected for Military Aerostat Markets

MILITARY AEROSTAT systems, including unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs), will be heavily enlisted both on the battlefield and as a means of preventing conflicts during the next decade. According to the 165-page study "Military Aerostats Market Report: 2016-2026," compiled by market researcher Visiongain (www.visiongainglobal.com), the continued growth of national threats worldwide will fuel the need for military aerostat systems. These include different types of radar, surveillance, and imaging systems for homeland security, law enforcement, border patrols, and tactical applications.

The report notes an anticipated compound annual growth rate (CAGR) of 4.8% for the five-year period from 2016 through 2021. In addition, the market size of $4.17 billion in 2016 is expected to grow to almost $5.3 billion by the end of 2021. The detailed report, which references such companies as BAE Systems, the Boeing Co., Elbit Systems, Lockheed Martin Corp., Northrop Grumman Corp., and Raytheon Co., offers insights on how to compete in this lucrative and dynamic market. ■

ROCKWELL COLLINS Demonstrates Wideband HF from Airborne C-17

FOR THE first time, Rockwell Collins (www.rockwellcollins.com) completed a complex data transfer from an airborne C-17 aircraft to a ground station using a wideband high-frequency (WBHF) communications channel. The air-to-ground data link was accomplished in collaboration with the U.S. Air Force. It took place over the duration of a two-day flight, between Dover Air Force Base (AFB) Delaware and Joint Base Lewis-McChord, Washington, using a WBHF receiver-exciter configured for airborne operation.

The demonstration included transfers of streaming video, real-time chat, file transfers, and digital voice audio over distances of 1,500 miles and more. Compared to traditional HF communications, WBHF provides much higher data throughput. It is an effective complement to satellite-communications (satcom) links where satellite signals are limited or unavailable. WBHF systems can perform transfers of large data files at speeds comparable to narrowband satcom systems. ■

An airborne C-17 aircraft was part of a test of examining the capabilities of performing air-to-ground communications using wideband high-frequency (WBHF) communications equipment. *(Photo courtesy of the Boeing Co.)*

Over the course of six decades, radar supplier Lockheed Martin (www.lockheedmartin.com) has evolved its use of synthetic-aperture-radar (SAR) technology at lower frequencies, most recently expanding into highly efficient solid-state SAR systems. The firm's solid-state ground-based surveillance and early-warning systems *(Fig. 1)* are capable of providing intelligence at any time.

These systems are neither limited by weather nor the atmospheric attenuation of conventional radars and electro-optical imaging systems. In addition to being used for moving target indication (MTI), the VHF/UHF SAR sensors have been used for ocean spill monitoring, polar ice assessment, intelligence acquisition, and battlefield reconnaissance.

Military radar systems have traditionally been large electronic systems using vacuum-tube amplification to achieve megawatts of transmitted pulse-modulated output power at RF and microwave frequencies. The radar signal frequencies have always been dictated by the performance goals of a particular radar system. Lower frequencies and their longer wavelengths provide better surveillance of targets of interest at longer distances than higher-frequency signals and their shorter wavelengths, which offer more precise tracking at shorter distances.

A number of different signal-generation and -amplification electron-tube devices have been used in military radar systems, with magnetrons capable of producing output signals at megawatts of power and klystrons serving as effective amplifiers through kilowatts of output power. Traveling-wave tubes (TWTs) and TWT amplifiers (TWTAs) have also been utilized to amplify radar signals, as have crossed-field amplifiers (CFAs).

However, as has been true for frequencies from the audio range through microwave bands, designers have sought solid-state replacements for vacuum tubes. The basic tradeoff between the two technologies is that vacuum tubes provide

2. The Patriot radar system was recently upgraded to GaN-based T/R modules and AESA technology for full 360-deg. scanning capability. *(Photo courtesy of Raytheon Co.)*

3. The AN/TPS-80 Ground/Air Task-Oriented Radar (GATOR) is now being assembled with solid-state GaN modules. *(Photo courtesy of Northrop Grumman)*

enormous output-power levels compared to solid-state devices, but with much higher bias requirements and much shorter operating lifetimes. Thus, the key to using solid-state devices in applications such as radar systems that require high output signal levels is to combine the individual outputs of multiple transistors in parallel to achieve higher output-power levels.

Gallium nitride (GaN) is a high-power semiconductor technology that has proven its worth in lower-microwave-frequency commercial applications such as Fourth-Generation (4G) wireless communications systems, and is gaining ground as an amplification solution for military radar systems. Earlier this year, one of the leaders in military radar technology, Raytheon Co. (www.raytheon.com), upgraded the main array of the Patriot Air and Missile Defense System with 360 deg. of coverage, along with GaN-based active electronically scanned array (AESA) technology.

"A GaN-based AESA radar benefits netted sensors, and gives Patriot greater capability and reliability while significantly reducing operations and sustainment cost," explains Ralph Acaba, vice president of Integrated Air and Missile Defense at Raytheon's Integrated Defense Systems business. "Raytheon recognizes how important this capability is for the warfighter, and is investing in its own resources to bring Patriot's GaN-based AESA radar to the point where it can enter engineering and manufacturing development with low risk."

The main AESA array measures about 13 × 9 ft. and is a bolt-on forward-facing replacement antenna. Earlier in the year, Raytheon built a GaN-based rear-panel array for the Patriot system *(Fig. 2)* as part of the efforts to enable a full 360-deg. view for the system. Raytheon also uses solid-state GaN technology for a U.S. Navy radar and jammer, and is exploring the use of the technology for the compact version of the Pentagon's pain ray. Known as the Active Denial System, the pain ray uses a beam of RF/microwave energy to repel a living target by heating the skin.

Recently, Northrop Grumman Corp. (www.northropgrumman.com) received an award from the U.S. Marine Corps for nine AN/TPS-80 Ground/Air Task-Oriented Radar (GATOR)

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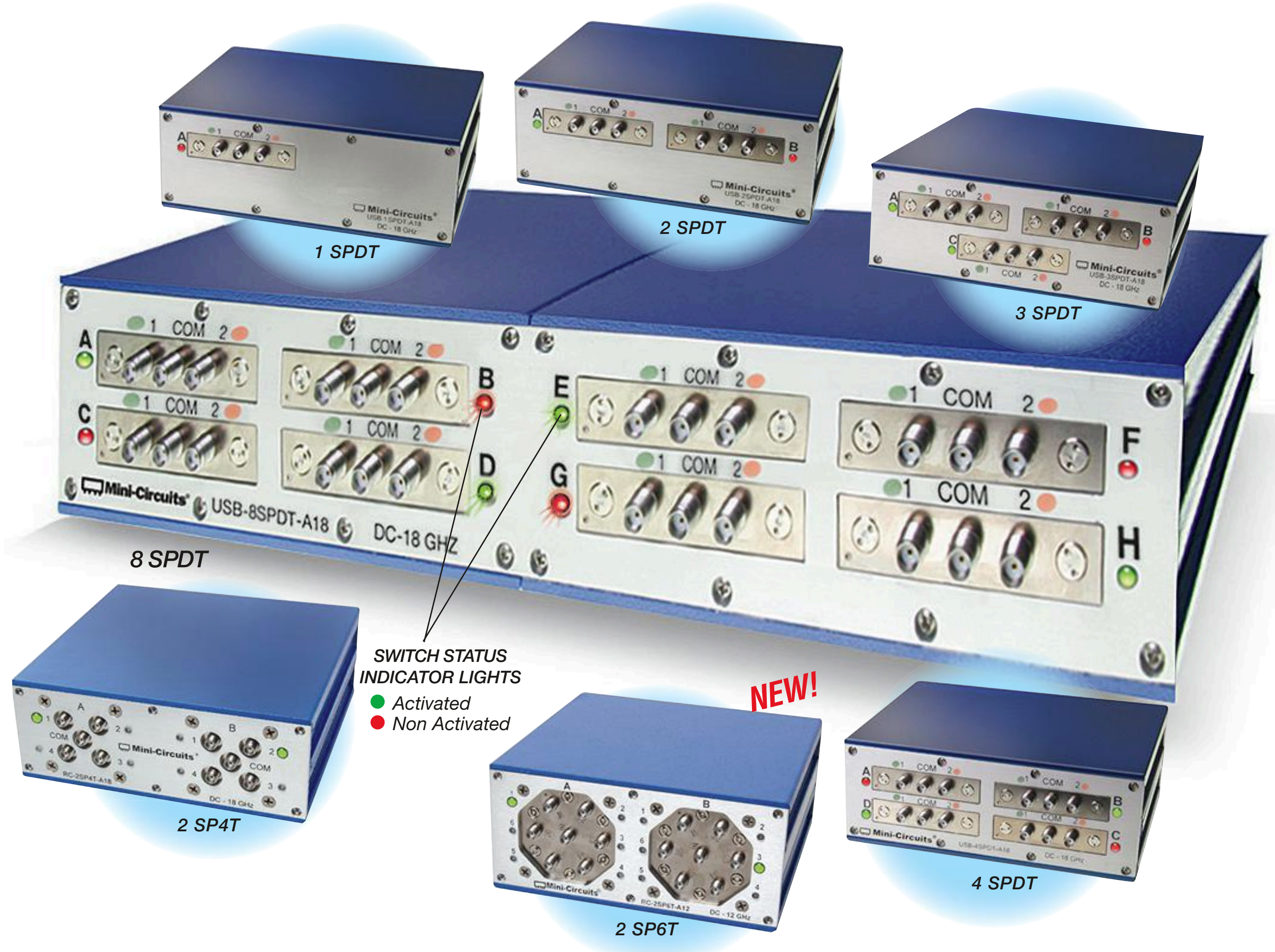

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low-rate initial production (LRIP) systems *(Fig. 3)*. The systems support air surveillance, weapon cueing, counter-fire target acquisition, and air-traffic control.

Northrop Grumman was previously contracted to supply six of the G/ATOR LRIP systems to the Marines, the first of which is scheduled for delivery by February 2017. By designing these latest nine systems around solid-state GaN technology for microwave amplification, the defense contractor has provided the Marine Corps with nearly $2 million in lifecycle cost savings per system.

"There are no other GaN ground-based AESA radars in production today," says Roshan Roeder, director of mission solutions for Northrop Grumman. "G/ATOR is the first DoD ground-based AESA system to incorporate GaN in a production program. We proposed this technology as a cost-savings measure for the government and funded risk reduction internally to ensure a seamless insertion into the G/ATOR system. We are continuing to look at future technology insertions to continue providing the best capability out there to our warfighters at an affordable cost."

GaN is a wide-bandgap semiconductor technology, with low parasitic capacitance and high breakdown voltage. It has wider bandgap than silicon-bipolar, silicon-carbide (SiC), and gallium-arsenide (GaAs) transistor technologies, and amplifier designers have succeeded in using GaN devices in high-efficiency Class E and Class F amplifier designs, with efficiency levels theoretically approaching 100%.

GaN material has excellent thermal-conductivity properties for low self-heating effects at high power levels. It also exhibits higher breakdown voltage, but lower carrier mobility, than GaAs, which will limit the upper frequency limits of GaN devices compared to GaAs transistors.

GaN-based power amplifiers for radar and other applications are available from a growing number of suppliers, including GaN-on-silicon-carbide (GaN-on-SiC) substrates for high-power amplifiers. For example, component supplier Aethercomm (www.aethercomm.com) recently delivered an L-band amplifier with Class-F efficiency to a major defense contractor. The amplifier was based on off-the-shelf, packaged, GaN high-electron-mobility-transistor (HEMT) devices. The amplifier was capable of more than 50 W output power with efficiency of 60% or more.

The same company's model SSPA 0.1-1.0-300 is a wideband amplifier that offers evidence of the capabilities of

GaN technology. Designed for military and commercial applications, the GaN amplifier measures 5.25 × 10.15 × 1.97 in., weighs 8.5 lb., and is capable of 250 to 300 W average power from 10 to 1,000 MHz. It provides high efficiency and operates from a MIL-STD-461 aircraft power supply or an input voltage from +18 to +36 V dc.

In terms of radar market size, a number of market research forecasts agree that steady growth is expected for military radar markets around the world. British researcher Business Reports Updates (www.vgdefence.com) offers "Military Radar Systems Market Outlook 2016-2026," a 329-page report that looks at 211 specific contracts by countries and breaks down markets into land-based, airborne, and maritime radar systems. It also provides profiles of the leading 13 military radar companies based on 2016 sales. The company also compiled the "Military Simulation, Modeling, and Virtual Training Market Report: 2016-2026," a report on markets for military simulation.

According to a report from Market Research Media (www.marketresearchmedia.com), "U.S. Military Unmanned Aerial Vehicles (UAV) Market Forecast 2013-2018," the use of radar technology is expected to increase dramatically in UAVs for the next several years. UAVs equipped with low-power radar systems are viewed as attractive tools for performing remote surveillance.

The report projects the market for UAV radar systems to grow to $86.5 billion by 2018, rising at a compound annual growth rate (CAGR) of 12%. The use of solid-state GaN-based amplification can form the basis for lower-voltage radar systems that are practical, portable, and light in weight for realistic use in military and even government-sponsored UAVs, such as for weather radar UAVs.

In commercial markets, radar technology is being adopted widely in automotive safety systems for forward- and rear-looking, radar-based collision-avoidance systems. These are much higher-frequency radar emitters than in most military radar systems, operating at millimeter-wave frequencies up to 77 GHz and at frequencies well beyond the limits of GaN semiconductor technology—they typically use lower-power GaAs and silicon-germanium (SiGe) devices.

Whether for military, industrial, or commercial automotive applications, the spread of radar technology is almost relentless. Device technologies will continue to be developed or adapted to meet the different requirements.

JACK BROWNE | Technical Contributor

Deciding on DSPs and FPGAs for EW

Digital components like DSPs and FPGAs can provide the signal processing needed in modern radar and electronic- warfare systems, all the while helping to save size, weight, and power.

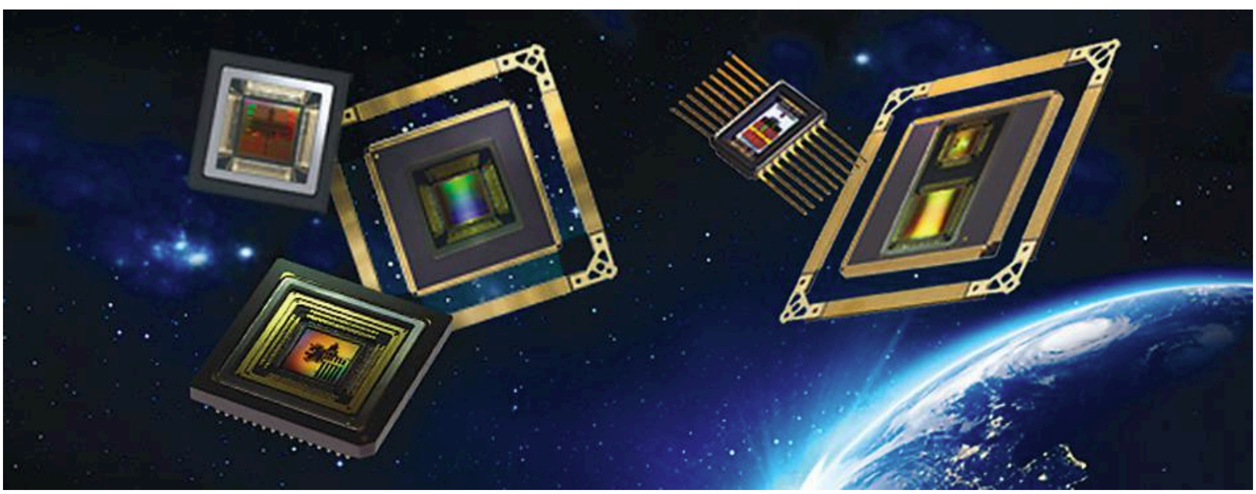
SIGNAL PROCESSING is often the difference between missing and identifying a radar target, delivering an effective electronic-warfare (EW) response, or maintaining secure communications. A number of digital components perform signal processing in military electronic systems, with digital signal processors (DSPs) and field-programmable gate arrays (FPGAs) often used separately or together. Finding the right component match for an application can be a challenge, although understanding key performance parameters and how they relate to different military electronic applications can help ease the process.

DSPs are essentially types of microprocessors aimed at performing math-intensive operations. The processing power of a DSP can be determined by its clock rate and the number of operations it can perform per clock cycle, such as how many additions or multiplications per second. Its processing capabilities are typically characterized in terms of millions of instructions per second (MIPS).

A DSP must be preconditioned or programmed to perform a particular function, usually by "C" programming code or some other assembly language. DSPs are designed to work with external memory on a printed -circuit board (PCB) or within a system, and can work with large amounts of available data for handling large processing operations. As a tradeoff, accounting is necessary for transferring data between a DSP and the memory locations, plus any required transfer times.

An FPGA, on the other hand, is a collection of transistor gates that are able to change functions in the field. The array of gates can be connected together to achieve different functions, such as addition or multiplication, without the prior programming required for a DSP. In some ways, an FPGA can be thought of as multiple DSPs or processors, each with its own dedicated memory, so that multiple functions can be performed.

In addition to performing very-high-level operations—like finite-impulse-response (FIR) filters, infinite-impulse-response filters (IIR), or fast-Fourier-transform (FFT) functions—FPGAs can perform DSP functions (e.g., the aforementioned addition and multiplication) at very high clock rates. Again, with an FPGA, comparing performance is a



1. A line of FPGAs includes different radiation-hardened models that offer long, reliable operating lifetimes in outer space. *(Photo courtesy of Atmel)*

2. Stratix 10 FPGAs can operate at clock rates to 1 GHz, and with power efficiency to 80 GFLOPS/W.
(Photo courtesy of Altera)

matter of determining how many useful functions can be performed per clock cycle, or how many total operations can be performed per second.

In contrast to DSPs, FPGAs are designed and fabricated with internal memory. This enables functioning without any memory-transfer delays, with fast data input/output (I/O) rates. As a tradeoff, the amount of memory and the size of the data sets processed are limited compared to a DSP. Of course, when an FPGA must handle large, complex data sets, it can be designed into a PCB or module with dedicated external memory to increase its processing capabilities with minimum data I/O delays.

One way to think of the difference between an FPGA and DSP for a military system is to imagine how a block diagram of part of the system (a receiver, for instance) might be handled by each component. In an FPGA, equivalent receiver components (e.g., frequency mixers, filters, and amplifiers) are defined as specific functions within the FPGA. Once those functions are defined, the FPGA provides fairly efficient operation. However, the functions cannot be easily changed, since the gates within the device have been set for the desired signal processing.

In a DSP, though, the block diagram is defined by programming code in terms of its functionality. If necessary, a DSP programmed as a receiver could be reprogrammed as a transmitter, with the signal branching and complex decision making determined as responses to the programming code.

In many military electronic systems (portable systems, in particular), power efficiency is important in maintaining military design goals for size, weight, and power (SWaP). The power efficiency of signal processing as performed by multicore processors, DSPs, or FPGAs is usually compared in terms of millions of floating-point operations per watt (MFLOPS/W) and billions of floating-point operations per watt (GFLOPS/W). FPGAs typically excel in this area compared to DSPs. de

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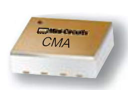

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REAL-WORLD SOLUTIONS

AS EXAMPLES OF the processing capabilities available from high-speed DSPs, models C6654 and CC6652 are (respectively) fixed- and floating-point DSPs recently introduced by Texas Instruments (www.ti.com). Based on the firm's KeyStone multi-processor core architecture, and incorporating the new C66x DSP core, these DSP devices run at clock speeds to 850 MHz (C6654) and 600 MHz (C6652). With an extended operating temperature range of –40 to +100°C, the devices are suitable for avionics and other defense applications as well as for ruggedized commercial applications.

Each DSP features two on-chip phase-locked loops (PLLs), two channels of 8- or 16-b processing, 8 GB of addressable memory space, and I2C and SPI interfaces. The model TMS320C6652 DSP provides a cycle time of 1.167 ns at 600 MHz, delivering 19.2 GMACS and 9.6 GFLOPS at 600 MHz. The model TMS320C6654 has a cycle time of 1.175 ns at 850 MHz, providing 27.2 GMACS and 13.6 GFLOPS at 800 MHz.

Additional suppliers of DSPs include Analog Devices (www.analog.com), Infineon Technologies (www.infineon.com), Intersil (www.intersil.com), Microchip Technology (www.microchip.com), NXP Semiconductors (www.nxp.com), ON Semiconductor (www.onsemi.com), STMicroelectronics (www.st.com), and Zilog (www.zilog.com).

As an example of a military-grade FPGA, the Virtex-7 X980T FPGA from Xilinx (www.xilinx.com), has been used in a 24-channel portable radar beamformer and demonstrated as much as 987 GFLOPS capability with lower power consumption. Fabricated on a 28-nm silicon semiconductor process, the FPGA achieves as much as 2.8- Tb/s total serial bandwidth with as many as two million logic cells.

Atmel (www.atmel.com) has been a longtime supplier of both radiation-tolerant and radiation-hardened (rad-hard) FPGAs for space-based applications *(Fig. 1)*. As an example, model AT40KEL040 is a rad-hard FPGA dedicated for space use. It is based on a static-random-access-memory (SRAM) architecture with 46,000 application-specific-integrated-circuit

(ASIC) gates and fabricated in a 0.35-µm silicon CMOS semiconductor process. The FPGA, which operates at internal clock rate of 60 MHz, provides 18-ns memory access speed over an operating temperature range of –55 to +125°C.

Altera (www.altera.com), now part of Intel Co. (www.intel.com), offers high-performance Stratix 10 FPGAs that support advanced beam-forming functions in many stationary and portable military radar systems *(Fig. 2).* Capable of operating at clock rates to 1 GHz, these FPGAs can perform at rates to 10 TFLOPS with power efficiency to 80 GFLOPS/W.

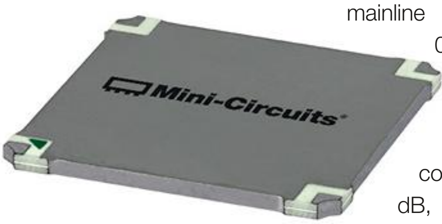
In addition, Microsemi Corp. (www.microsemi.com) supplies high-performance, low-power and radiation-tolerance FPGAs and systems-on-a-chips (SoCs) for commercial, industrial, and military applications. Earlier this year, the company acknowledged its support of defense contractor Lockheed Martin during the U.S. Navy's successful 158th, 159th, and 160th test launches of the Trident II D5 Fleet Ballistic Missile (FBM). Lockheed Martin has been the U.S. Navy's strategic missile prime contractor, and Microsemi has played a strong part in achieving the signal-processing goals of these missile guidance systems with its FPGAs and SoCs.

In many defense systems, signal processing is not accomplished solely by DSPs or FPGAs, but through a combination of the two, along with multiple-core microprocessors and various other digital components. Suppliers of DSPs and FPGAs typically offer sample boards for different applications, such as secure communications systems and portable radar systems, to help users through their own system-design process. System designs employing both DSPs and FPGAs offer a great deal of flexibility, since different types of functions, such as fixed-point and floating-point operations, can be directed to the different types of processors.

In addition to sample boards, many component suppliers also support their devices with model libraries that can speed the design process, such as models for FIR filters, FFTs, and IIR filters. Design support should be a consideration in addition to component performance when selecting and specifying a DSP or FPGA. ■

Coupler Passes DC, Power Levels to 200W

CAPABLE OF PASSING dc and handling high-frequency power levels to 200 W for signals from 225 to 450 MHz, the model MBDA-30-451HP 50-Ω bidirectional coupler offers low loss and high directivity. This compact 30-dB coupler features mainline insertion loss of only 0.15 dB and directivity of 28 dB. Typical input and output return loss is 30 dB. Typical coupling flatness is ±0.85 dB, with worst-case coupling flatness of ±1 dB. Well-suited for use in VHF and UHF radios for antenna feeds and with high-power amplifiers, the miniature coupler operates over a temperature range of –55 to +105°C. It measures just 1.0 × 1.0 × 0.051 in.



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HIGH-RELIABILITY (HI-REL) frequency dividers have been developed in bands from 0.5 to 18.0 GHz. Available in divide-by-two, four, five, eight, and 10 configurations, the frequency-divider modules are well-suited for use with phase-locked loops (PLLs) in frequency synthesizers. Based on GaAs heterojunction-bipolar-transistor (HBT) monolithic-microwave-integrated-circuit (MMIC) technology, the frequency dividers operate on a single +5-V dc supply and can achieve typical additive phase noise of –155 dBc/Hz offset 100 kHz from the carrier. They provide output-power levels from –1 to –4 dBm and are qualified to EAR99 requirements. All models come with field-replaceable SMA connectors in Kovar packages and meet MIL-STD-883 requirements. They have an operating temperature range of –55 to +85°C.

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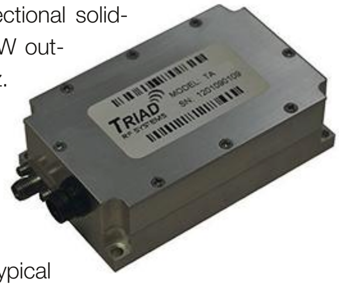

MODEL TTRM1010 is a bidirectional solid-state amplifier capable of 3 W output power from 30 to 3,000 MHz. Well-suited for small- to medium-sized unmanned-aerial-system (UAS) applications, the amplifier incorporates power-supply circuitry for operating from power sources from +9 to +36 V dc. Typical gain is 23 dB, while typical noise figure is 3 dB. The amplifier measures 3.25 × 2.00 × 0.993 in.

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Frequency Synthesizer Tunes 3 to 6 GHz

LOW NOISE frequency synthesizer model KMTS2500-300600-10 combines the best in direct-digital-synthesis (DDS) and voltage-controlled-oscillator (VCO) technologies for excellent spectral purity from 3 to 6 GHz. The synthesizer achieves 1-Hz tuning resolution with less than 2-W power consumption and is ideal for use in radar systems, unmanned aerial vehicles (UAVs), communications systems, and test equipment. It provides at least +4 dBm output power across the tuning range. Typical phase noise is –87 dBc/Hz offset 1 kHz from the carrier and –93 dBc/Hz offset 100 kHz from the carrier. Typical harmonic level is –18 dBc, with typical spurious of –50 dBc. The synthesizer operates on +12-V dc supplies and has an operating temperature range of –20 to +70°C.

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Bandpass Filter Screens 0.7 to 6.0 GHz

MODEL DTRA-00014 is a digitally tunable filter with continuously adjustable bandwidth from 700 MHz to 6 GHz. Since different passbands of bandpass filters are often required to suppress signals in commercial, industrial, and military electronic applications, this single bandpass filter can be set for typical passbands of 5, 10, 15, 20, and 40 MHz to eliminate unwanted interference within a particular passband and center frequency. The rack-mount filter, which includes Ethernet and General Purpose Interface Bus (GPIB) interfaces, is also well-suited for use in automatic-test-equipment (ATE) systems.

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Design Feature

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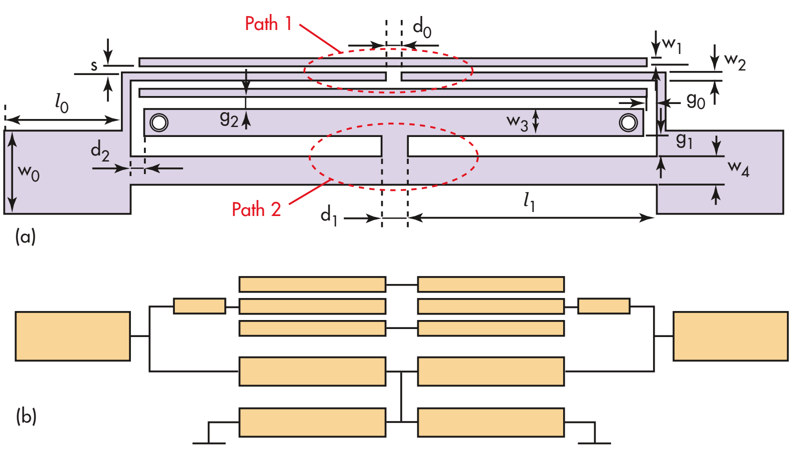
UWB Bandpass Filter Includes Notched Band

Leveraging two interdigital coupled three-line structures with bandpass characteristics, this compact ultrawideband filter incorporates a notched band with 25-dB rejection.

Development of ultrawideband (UWB) communications systems requires the design of many different component functions, including bandpass filters (BPFs) with acceptable selectivity. To serve UWB communications applications, a compact UWB BPF with reasonable selectivity and an integral notched band was fabricated with two interdigital, coupled, three-line structures. Selectivity was improved by adding another signal path loaded by two short-circuit stubs. The filter exhibits sharp rolloff to its rejection bands with a wide fractional bandwidth of 116%, with 25-dB rejection in the notched band.

The UWB spectrum from 3.1 to 10.6 GHz has attracted lots of attention in recent years due to its excellent energy efficiency—it supports short-range transmission of very high data rates while only requiring very low power levels. This spectrum was authorized for commercial radio use at low transmit levels in 2002.[1]



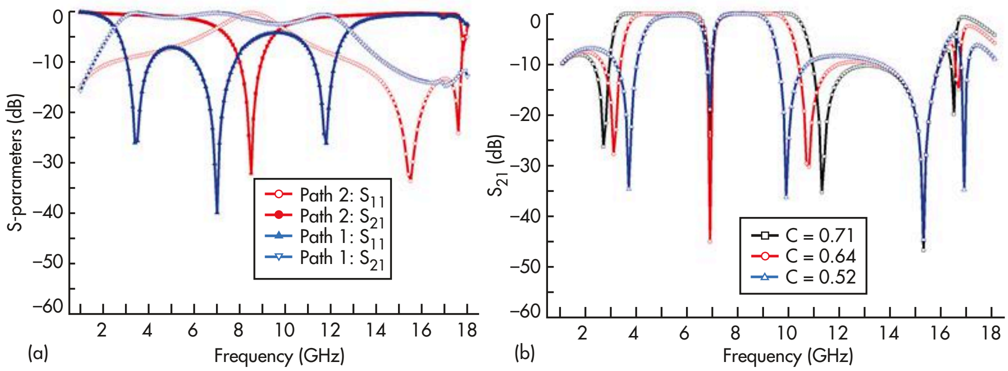
1. These diagrams show the basic BPF configuration with (a) Path 1 and Path 2 and (b) an equivalent transmission-line model of the filter.

A great deal of research has been reported on efforts to develop BPFs with high selectivity for UWB use while achieving wide stopband, low insertion loss, and compact size.[2-12] One approach, with three coupled interdigital transmission lines, has proven popular in recent UWB BPF designs.[2,3]

Other UWB BPF design approaches involve the use of transitions between different microwave transmission lines, such as microstrip and coplanar waveguide (CPW). These UWB BPFs have incorporated both CPW-to-microstrip transitions[4] and microstrip-to-CPW transitions.[5] In ref. 6, a new approach involving a bandpass defected microstrip resonator was used to implement an UWB BPF.

Because UWB signals are used at such low levels over such wide bandwidths, interfering signals are inevitable, leading to the development of various methods to create a notched band within the passband of an UWB BPF.[7-12] For example, an L-shaped open-end slot was inserted in a trisection-stepped-impedance-resonator (TSSIR) to generate a notched band at 5.5 GHz.[7] In ref. 8, a parasitic coupled line was added to achieve an UWB BPF with a notched band. In ref. 9, a microstrip-to-stripline transition was used in the UWB BPF, and a microstrip stub located at the feedlines helped to reject wireless-local-area-network (WLAN) signals within the UWB frequency range.

In ref. 10, a slow-wave, half-mode, substrate-integrated-waveguide (SW-HMSIW) UWB BPF design achieved a notched band through the use of an L-type resonator. More recently, several novel structures were reported to implement a notch band, such as the via-loaded ring resonators[11] and a spiral defected ground structure.[12]



2. These plots show simulations of (a) the filter's Path 1 and Path 2 transmission paths and (b) the equipment circuit representation of the filter of Fig. 3.

DESIGN DETAILS

To achieve good selectivity over the wide UWB frequency range, a BPF with a novel structure based on three interdigital coupled lines was developed *(Fig. 1)*. To facilitate the design process, an equivalent-circuit transmission-line model was constructed using the Advanced Design System 2009 (ADS 2009) computer-aided-engineering (CAE) simulation software from Agilent Technologies (now Keysight Technologies).

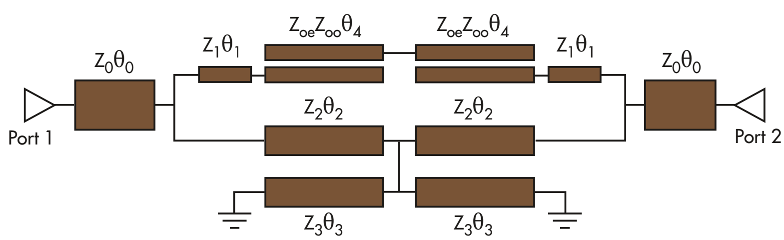
Compared with traditional UWB BPFs based on the interdigital coupled three-line structures, the proposed filter offers improvements in terms of selectivity, small size, and low insertion loss. The filter also achieves a notched band at 7.3 GHz with a maximum rejection loss of 25 dB. A prototype was fabricated and measured using commercial test equipment, with test results matching closely with the computer simulations.

Figure 1 shows the basic structure of the UWB BPF and its equivalent-circuit transmission-line model. Input signals travel through two different signal paths. The filter's main transmission path consists of two interdigital coupled three-line structures. The other signal path is a transmission line loaded with two short-circuited stubs.

As the simulations of paths 1 and 2 show in *Fig. 2a*, the interdigital coupled three-line structures of path 1 exhibit bandpass characteristics. These characteristics are not directly usable for UWB filtering because of unsatisfactory out-of-band characteristics like poor selectivity and narrow upper stopband. Additional filtering is provided by the transmission line loaded by the two short-circuited stubs (*path 2*), which functions as a narrow bandpass filter.

To simplify analysis, as detailed in ref. 13, the three interdigital coupled lines can be converted to an asymmetric parallel coupled-line structure. For convenience's sake with respect to the filter design, its equivalent circuits (*Fig. 3*) are analyzed by ADS 2009. The simulated results of the equivalent circuits with different coupling coefficients are shown in *Fig. 2b*. In this work, its coupling coefficient of coupled lines is 0.64 due to limitations of manufacturing technology and the requirement of UWB. The optimized parameters for the proposed filter using ADS software were as follows:

Z1 = 143 Ω;
Z2 = 93 Ω;
Z3 = 93 Ω;
θ1 = 26 deg.;
θ2 = 90 deg.;
θ3 = 90 deg.;
Zoo = 62 Ω;
Zoe = 278 Ω; and
θ4 = 90 deg.



3. This simplified equivalent circuit represents the UWB BPF.

4. The UWB BPF was fabricated on 0.787-mm-thick RT/duroid 5880 circuit-board material (from Rogers Corp.) with relative permittivity of 2.2.

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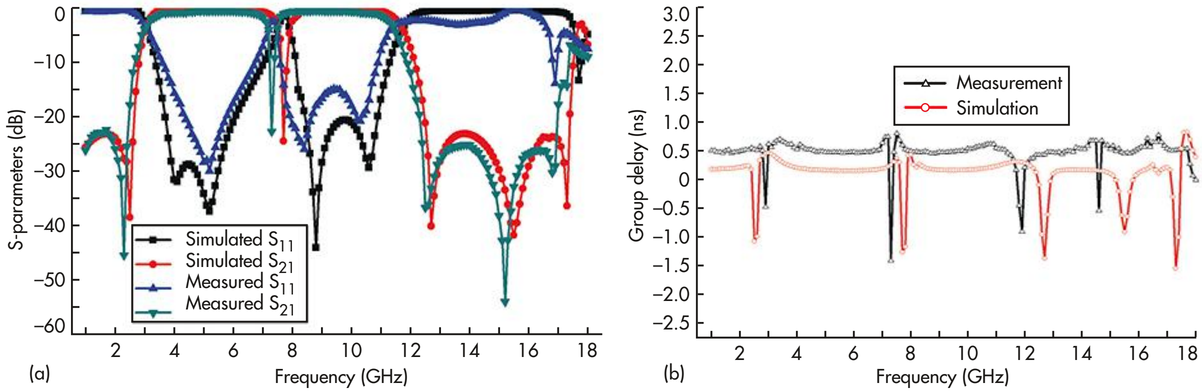

5. These plots show simulated and measured results for (a) transmission loss and (b) group delay behavior.

Introducing the transmission line with two stubs generates two transmission zeros around the passband edges, significantly improving the UWB BPF selectivity. Moreover, a notched band at the passband center frequency is obtained.

Finally, according to parameters provided by ADS 2009, an UWB BPF was fabricated on RT/duroid 5880 from Rogers Corp. *(www.rogerscorp.com)* for experimental analysis. The circuit material has a dielectric constant (relative permittivity) of 2.2 measured at 10 GHz in the z-axis (thickness); circuit materials with 0.787-mm thickness were used for the filter.

Figure 4 presents a photograph of the fabricated UWB BPF. The filter was assembled according to the following parameters, developed with the aid of the ANSYS High Frequency Structure Simulator (HFSS) electromagnetic (EM) simulation software (V 13) from ANSYS *(www.ansys.com)*:

w0 = 2.4 mm;
l0 = 4 mm;
s = 0.1 mm;
d2 = 0.425 mm;
g2 = 0.35 mm;
d0 = 0.45 mm;
w1 = 0.1 mm;
w2 = 0.25 mm;
g0 = 0.15 mm;
g1 = 0.35 mm;
w3 = 0.8 mm;
d1 = 0.7 mm;
l1 = 7.03 mm;
w4 = 0.8 mm;

COMPARING THE PROPOSED FILTER DESIGN WITH OTHER FILTERS

Reference	SF	3-dB FBW	$\|S_{11}\|$ (dB)	$\|S_{21}\|$ (dB)	F_c (GHz)	Size ($\lambda_g \times \lambda_g$)
2	0.88	108%	>10	NG	12.6	1.12 ×0.84
3	0.82	103%	>15.1	<0.6	15.1	0.94×0.63
4	0.50	95%	>11	<1.83	16	1.07×0.35
5	0.80	116%	>14	<0.68	12.4	1.10×0.55
6	0.65	110%	>10	<1	13.5	1.67×0.08
7	0.80	118%	>11.5	<1	13.6	0.98×0.35
8	0.54	103%	>12.5	<0.45	NG	0.75×0.40
9	0.8	114%	>10	<0.83	14.5	1.14×0.90
10	NG	113%	>14.9	<1.77	NG	0.87×0.66
11	0.74	109%	>10	<1.5	27.6	0.82×0.50
12	0.72	110%	>11	<0.6	15.6	0.68×0.50
Current work	0.91	116%	>15	<0.6	17.5	0.51×0.11

Notes: The selectivity factor (SF) = Δf(3 dB)/Δf(20 dB); F_c = the upper stopband frequency for 20-dB insertion loss; NG means not given; λ_g = the guided wavelength at 6.85 GHz.

TEST RESULTS

The S-parameters of the fabricated filter were obtained through measurements with a model E8383B vector network analyzer (VNA) from Agilent Technologies (again, now Keysight Technologies). As shown in *Fig. 5*, good consistency between the simulation and experiment results is observed except for the tiny frequency shift mainly caused by the machining and assemblage errors.

The measured results reveal that this filter achieves a very wide fractional bandwidth of 116% (3.05 to 11.4 GHz) with good return loss. Besides, this filter has a low insertion loss (>0.6 dB) within the passband. Obviously, it achieved sharp selectivity due to the transmission zeros at the lower and upper passband edges, respectively. Moreover, a notched band with a maximum rejection loss of 25 dB at 7.3 GHz was obtained. The group delay is relatively flat across the full UWB passband, with 0.25 ns or less variation (not including the notched band).

The *table* compares the performance of this UWB BPF with notched band to other UWB filters reported in the technical literature. Looking at the table, this novel UWB BPF has lower insertion loss, more compact size, wider passband bandwidth, and somewhat sharper selectivity.

The compact UWB filter shows measured performance that compares favorably with the best published results for UWB BPFs, including good selectivity, low insertion loss (>0.6 dB), compact size ($0.51\lambda g \times 0.11\ \lambda g$), good return loss (<15 dB), and wide bandwidth (3.05 to 11.4 GHz). Such performance levels make it a likely candidate for UWB communications systems, especially when the notched band can be applied to diminish the effects of troublesome interference within the UWB frequency range. mw

ACKNOWLEDGMENTS

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Design Feature

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Split-Ring Resonators Add to SIW Bandpass Filter

Complementary split-ring resonators etched into substrate-integrated-waveguide circuits can form the basis of broadband PCB bandpass filters at microwave frequencies.

Waveguide has long been a reliable, low-loss transmission line technology capable of handling high power levels and forming high-quality-factor (high-Q) resonators. But it is large and heavy compared to transmission-line technologies constructed on printed-circuit-board (PCB) materials. Substrate-integrated-waveguide (SIW) transmission-line technology brings some of the features of rectangular waveguide to the miniature size of PCB circuits.

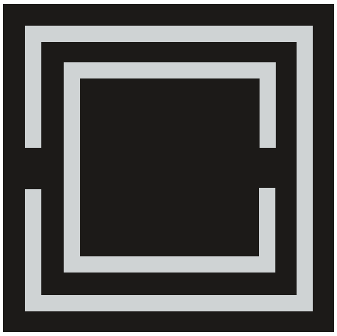
In addition, SIW transmission lines are easy to fabricate. By using SIW transmission lines to fabricate complementary split-ring resonator (CSRR) structures, it is possible to achieve waveguide-like filter performance from a planar PCB.

As with metallic waveguides, SIW circuits with CSRR elements are capable of achieving high-quality-factor (high-Q) performance. By combining SIW technology with CSRR circuit elements, it is possible to build a low-profile planar bandpass filter on a single substrate with high-Q performance for radio front ends in broadband communication systems *(Fig. 1)*.

CSRRs etched in the ground plane or conductor strip of a planar transmission media, such as microstrip or coplanar waveguide (CPW), provide a negative effective permittivity to the structure. In doing so, they preclude signal propagation and provide stopband behavior at the resonant frequency of the CSRR structure.[1]

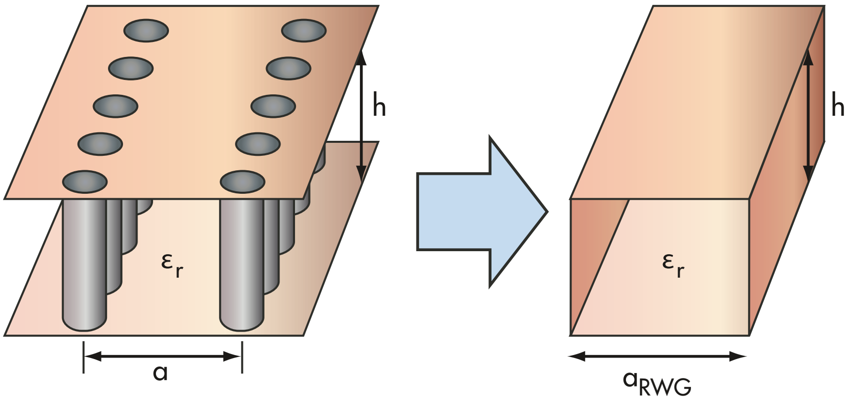
CSRRs have been proposed for the synthesis of negative permittivity and left-handed (LH) metamaterials in planar configurations.[1-3] CSRRs are the dual counterparts[2] of the split-ring resonators (SRRs) proposed by Pendry.[4] CSSRs have been applied to the design of compact bandpass filters with high performance and controllable characteristics.[5,6]

By forming them with SIW technology, it is possible to achieve excellent filter performance from small planar circuits. SIW transmission lines are created by forming two rows of metallized viaholes in a PCB substrate. The field distribution in a SIW transmission line is similar to that in a conventional rectangular waveguide.

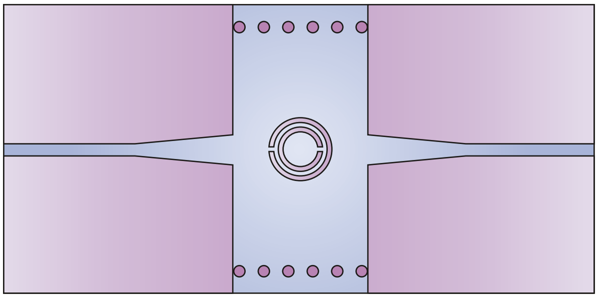


1. This is the basic structure of a CSRR, with inner and outer rings and the dark areas representing metallization of the rings.

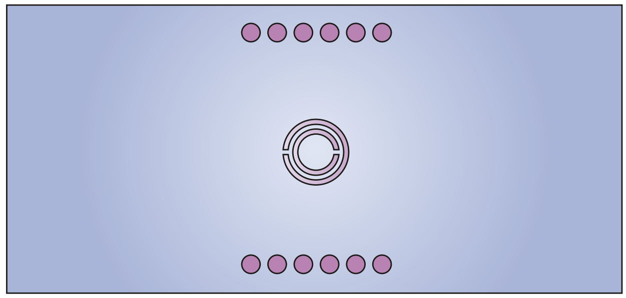
Figure 2 shows the basic structure of an SIW transmission line. It has two rows of metallized viaholes on both sides of the substrate. The key design parameters for achieving a desired level of performance include the diameter of the viaholes, the separation between two successive viaholes, and the separation between the rows of viaholes. Such parameters are



2. A simplified view of a SIW transmission line (left) is shown next to a cross-sectional view of a dielectric-loaded rectangular waveguide (right).



3. The top view of a PCB substrate shows an SIW circuit with etched CSRR.



4. The bottom view of a PCB substrate shows the bottom of the CSRR etched in the substrate.

essential for designing low-loss SIW circuitry. To design an SIW circuit with low radiation loss, several conditions should also be met:

$D < \lambda_g/5$

and

$b = 2D$

where

a = the center-to-center distance between two parallel metallized viaholes;
b = the height of the substrate;
c = the speed of light in a vacuum;
d = the diameter of the metallized viaholes;
D = the periodic distance between two viaholes;
λ_g = the wavelength of the waveguide;
a_{RWG} = the width of a dielectric filled metallic waveguide equivalent to the SIW

Parameter b should be as small as possible to minimize radiation losses. Parameter D, which also impacts the loss performance of an SIW circuit, will change according to b. The ratio of b to D is more critical in maintaining low radiation loss than the individual values of b and D.

When designing SIW transmission lines for a particular frequency range, the cutoff frequency, f_c, is determined as a function of the width and length of the SIW structure. An SIW structure has highpass characteristics. It exhibits a transverse electromagnetic (TE) TE10 mode with dispersion characteristics—characteristics that are almost identical with the same mode of a dielectric filled rectangular waveguide with an equivalent width.

The effective width of an SIW structure is given by:

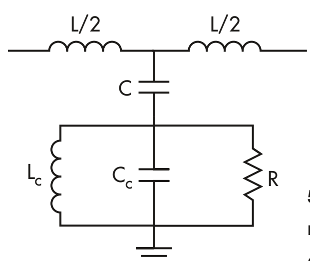
$a_{RWG} = a - (D^2/0.95b)$

while f_c can be found from

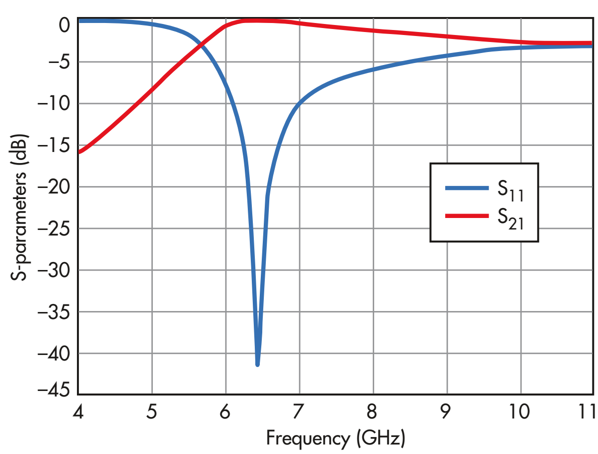
$f_c = C/[2(\varepsilon_r)^{0.5} a_{RWG}]$

Figure 3 shows the layout of an SIW circuit with CSSRs etched in the top layer of a PCB substrate. *Figure 4* depicts the layout of an SIW circuit with CSSRs etched in the bottom layer of the substrate. Since CSRRs are etched in the center of the top or bottom layers of the substrate—and they are mainly excited by the electric field induced by the SIW (as for TE10 mode)—this coupling can be modeled by connecting the capacitance of the SIW transmission lines to the CSRRs. Using this strategy, the lumped-element equivalent circuit for an CSRR-loaded SIW circuit is shown in *Fig. 5*.

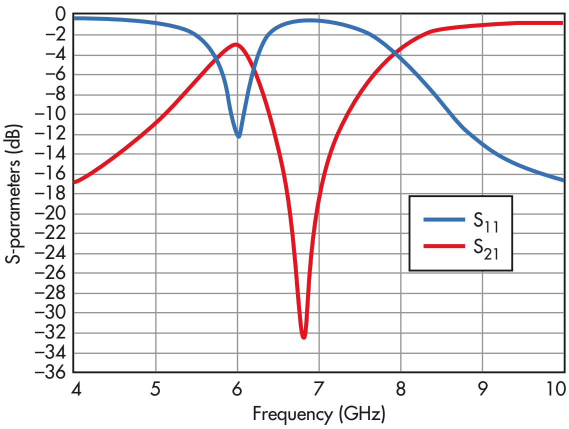
As long as the electrical size of the CSRRs is small, the structures can be described by means of lumped elements. In these models, L is the SIW inductance and C is the coupling capacitance



5. This equivalent-circuit model represents the CSRR-loaded SIW circuit shown in Figs. 3 and 4.



6. These simulated responses show the insertion loss (S_{21}) and return loss (S_{11}) for the basic CSRR cell depicted in Fig. 3.



7. These simulated responses show the insertion loss (S_{21}) and return loss (S_{11}) for the basic CSRR cell depicted in Fig. 4.

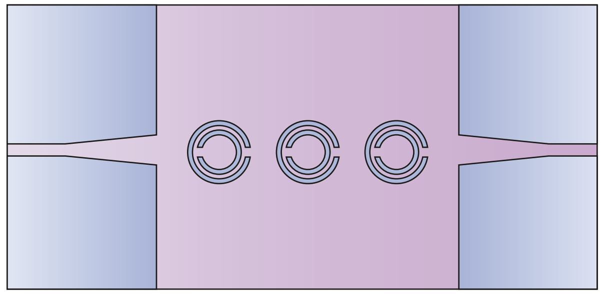
between the SIW and the CSRR. The resonator is described by means of a parallel tank,[7, 8] with L_c and C_c being the reactive circuit elements and R accounting for loss.

Using this model, the transmission-zero frequency which nulls the shunt impedance was determined through simulations and measurements. To demonstrate the viability of the proposed technique, it was applied to the determination of the electrical parameters of a single-cell CSSR-loaded SIW circuit.

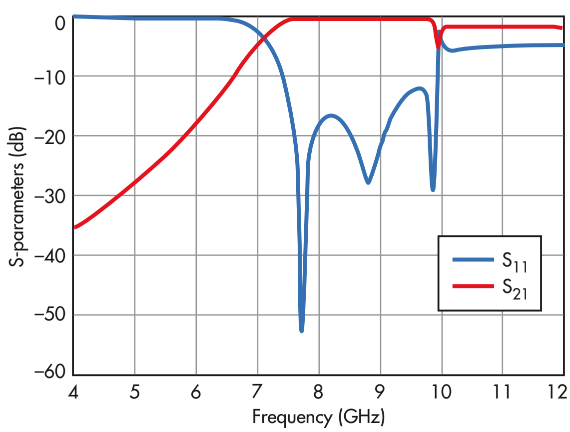
The structures of *Figs. 3 and 4* were simulated for fabrication on RT/duroid 5880 circuit laminate material from Rogers Corp. (www.rogerscorp.com). The PCB material has a relative dielectric constant, ε_r, of 2.22 at 10 GHz in the z axis (thickness) of the material. The material's thickness, h, is 0.254 mm, and dissipation factor (loss), δ, is 0.002. The width of the access lines is 0.76 mm.

Figures 6 and 7 show the simulated scattering (S) parameters for the circuits depicted in Figs. 3 and 4, respectively. The circuit structures show similar characteristics, except that the circuit of Fig. 3 achieves higher stopband attenuation.

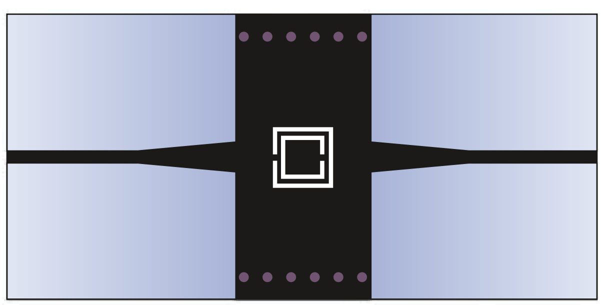
The single SIW CSRR cell shown in *Fig. 4* was designed using a cell with outer-circle radius of 1.8 mm and inner-circle radius of



8. A compact SIW bandpass filter was formed with three cascaded CSRR cells and tapered lines for interconnection with microstrip input and output transmission lines.



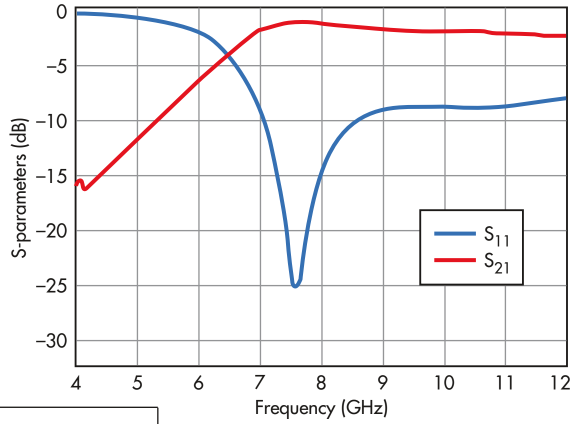
9. These simulated responses show the insertion loss (S_{21}) and return loss (S_{11}) for the SIW bandpass filter of Fig. 8.



10. This is an SIW transmission line with single CSRR cell etched in the top layer.

1.0 mm. To minimize losses, a microstrip feed was used to obtain maximum coupling between the SIW filter and the external feed line. By reducing the dimensions of the CSRR cell, the resonant frequency will increase.

The CSRR cell was loaded periodically onto the face of the SIW circuitry, but its edges were adjusted in size to achieve adequate bandwidth. As a result, their size has been slightly adjusted—to 1.7 mm for the outer-circle radius and 0.9 mm for the inner-circle radius—using the RT/duroid 5880 PCB substrate material.



11. These simulated responses show the insertion loss (S_{21}) and return loss (S_{11}) for the SIW circuit with single CSRR cell of Fig. 10.

Following simulation via the High Frequency Structure Simulator (HFSS) EM simulation software from ANSYS (www.ansys.com), the single cell CSRR was found to resonate at around 6.5 GHz, yielding negative effective permittivity at that frequency. *Figures 6 and 7* show simulated results for the CSRR-loaded SIW structures of Figs. 3 and 4, respectively, from 4 to 10 GHz.

When CSRR cells are cascaded, as shown in *Fig. 8*, the SIW circuit exhibits bandpass behavior from 7.2 to 10.0 GHz with very low return and insertion losses. When two CSRR cells are added and aligned with the central CSRR structure, the resulting structure achieves wide bandwidth from 4 to 12 GHz as part of a bandpass response *(Fig. 9)*.

A SIW circuit with square CSRR cell was designed using a width of 3.6 mm for the outer ring and 2.0 mm for the inner ring *(Fig. 10)*. A taper was employed to minimize losses by maximizing coupling between the SIW filter and the external line. Otherwise, the SIW circuit dimensions were the same as those for the SIW circuits with circular CSRR cells. The SIW circuit with square CSRR cell was simulated with HFSS software, with minimal reflections found around 7.4 GHz, when the effective permittivity of the CSRR cell is negative *(Fig. 11)*. mw

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NEW!	PWR-6RMS-RC	True RMS	50 to 6000	-35 to +20	USB & Ethernet	1595.00
	PWR-4RMS	True RMS	50 to 4000	-35 to +20	USB	1169.00
	PWR-2.5GHS-75 (75Ω)	CW	0.1 to 2500	-30 to +20	USB	795.00
	PWR-4GHS	CW	0.009 to 4000	-30 to +20	USB	795.00
	PWR-6GHS	CW	1 to 6000	-30 to +20	USB	695.00
	PWR-8GHS	CW	1 to 8000	-30 to +20	USB	869.00
	PWR-8GHS-RC	CW	1 to 8000	-30 to +20	USB & Ethernet	969.00
	PWR-8FS	CW	1 to 8000	-30 to +20	USB	969.00

*Measurement speed as fast as 10 ms for model PWR-8-FS. All other models as fast as 30 ms.

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Deciphering Between MIMO and MMICs

These abbreviations stand for two completely different things—antennas and semiconductors—although surprisingly some similarities exist between the two.

Modern wireless systems have long depended on monolithic microwave integrated circuits (MMICs) and are increasingly relying on the use of multiple-input, multiple-output (MIMO) antenna techniques. As much as these abbreviations seem similar, what exactly is each technology and what roles do each play in a wireless system? Knowing the differences between MMICs and MIMO systems can help avoid confusion when assembling the components for a modern wireless communications system..

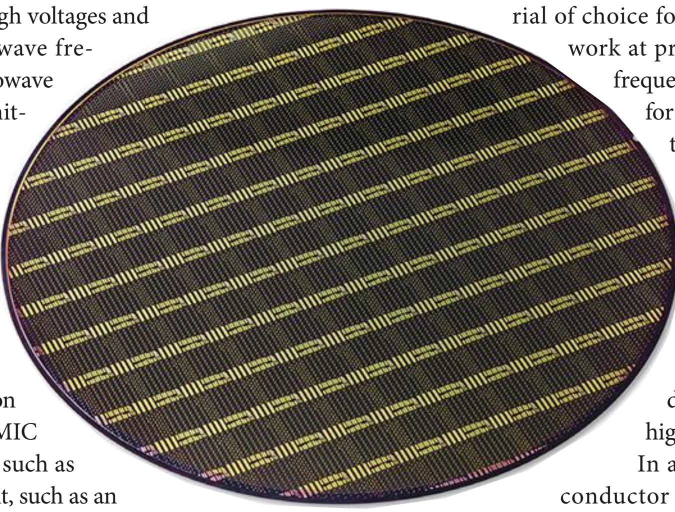
MMICs are integrated circuits (ICs), designed for use at microwave frequencies and, occasionally, as high as millimeter-wave frequencies. They were originally fabricated solely on gallium- arsenide (GaAs) semiconductor wafers. Now, though they are based on a wide range of semiconductor materials, including silicon (Si), indium phosphide (InP), silicon germanium (SiGe), and, increasingly, gallium nitride (GaN) for its capabilities of operating at high voltages and high power levels at microwave frequencies (as a basis for microwave amplification and for transmitter and transceiver circuits).

MMICs comprise a number of different high-frequency components on the same chip, supplied in semiconductor die form or in a package, such as a surface-mount-technology (SMT) package for ease of mounting on a printed circuit board. A MMIC can be a passive component, such as a filter, or an active component, such as an amplifier, rather than a transistor in a similarly small package.

As an example, the model CMD233C4 from Custom MMIC *(www.custommmic.com)* is a distributed amplifier in a low-profile package *(Fig. 1)* fabricated on GaAs semiconductor substrate material. It is extremely broadband, operating from 2 to 18 GHz with more than 9-dB small-signal gain, 4.5-dB noise figure, and +20.5-dBm output power at 1-dB compression. The MMIC is impedance-matched to 50 Ω and powered by a single bias supply of +3 to +6 V dc.

RF/microwave MMICs are available from a large number of suppliers, in die and packaged formats, which simplifies the task of adding component functions while shrinking the overall size of a system design. MMICs can be mass-produced from large semiconductor wafers *(Fig. 2)* and screened through automated testing to maintain proportionally lower cost for each component than the equivalent cost of each of the discrete component functions they replace.

While GaAs was once the semiconductor wafer material of choice for microwave MMICs, more work at present is being done at high frequencies on GaN wafers (at least for power amplifiers) because of the material's enhanced power capabilities compared to GaAs. Many military contractors, such as Northrop Grumman Corp. *(www.northropgrumman.com)*, maintain their own GaN and GaAs wafer/semiconductor foundries as a source of high-frequency semiconductors. In addition, commercial semiconductor foundries offer wafers and fabrication services that enable customers to submit design files



1. By using large semiconductor wafers, great numbers of MMIC devices can be fabricated and produced with high yields. *(Courtesy of MACOM.)*

in software to fabricate MMICs or discrete devices within the limits of a particular commercial semiconductor foundry's design guidelines. GaN is currently a widely accepted starting material for high-frequency MMICs, with many device designers in quest of filling one major gap between GaN and GaAs, and that is for a truly low-noise amplifier (LNA) based on GaN material.

BOOSTING CAPACITY WITH MIMO

MIMO antennas are similar to MMICs in that they integrate a number of antennas into a single package *(Fig. 2)*. These antennas take advantage of multipath propagation to improve the performance and capacity of a wireless communications system. Prior to the use of MIMO techniques, multipath effects were never considered a good thing. Signal multipath is caused by transmitted signals bouncing off objects between a transmit antenna and a receive antenna, such as buildings, towers, bridges, and any object with sufficient mass and material type to deflect electromagnetic (EM) energy.

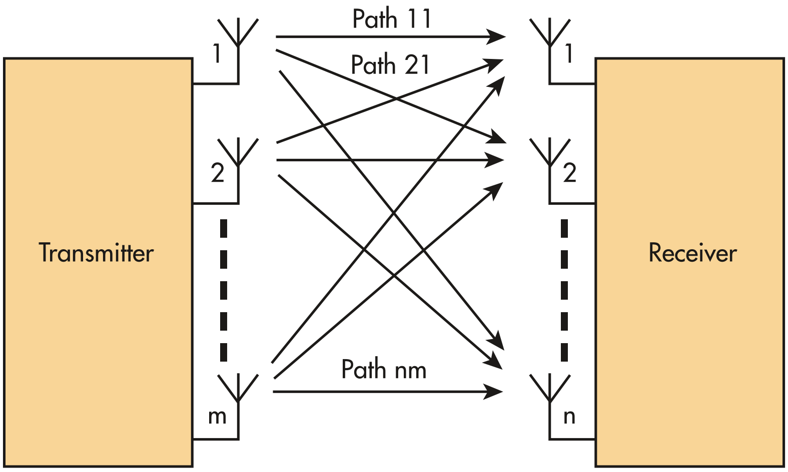
Legacy wireless communications systems have used what are known as single-input, single-output (SISO) antenna configurations. MIMO approaches employ multiple transmit and receive antennas or antenna elements to send signals along a number of different propagation paths *(Fig. 2)* rather than a single signal path and, in the process, enable increased data rates for a given frequency and bandwidth.

MIMO methods can increase channel capacity as a function of the increasing number of antenna elements or boost performance in terms of signal-to-noise -ratio (SNR) of a transmitter-receiver combination. Quite simply, more antennas in a MIMO system, such as a 4 × 4 MIMO system, with four transmit and four receive antennas, versus a 2 × 2 MIMO system, with two transmit and two receive antennas, means faster data rates and greater capacity.

MIMO techniques were developed in response to the ever-increasing number of wireless communications subscribers and limited amount of available bandwidth. MIMO is employed in a number of mobile communications standards, including IEEE 802.11 (Wi-Fi), IEEE 802.16 (WiMAX), Third-Generation (3G) wireless systems, and Fourth-Generation (4G) wireless systems, including Long Term Evolution (LTE) systems.

MIMO may be implemented in the form of polarization diversity systems, where antennas use adjustable feed systems to achieve dual polarization, such as vertical and horizontal polarization or X-polarization (with -45 deg. and +45 deg. polarization). Different diversity modes may also be used with MIMO antennas.

Diversity modes typically used in MIMO systems include time diversity, space diversity, and frequency diversity. In time diversity, data is transmitted at different times, using different time slots and different channel coding. In space diversity, antennas are positioned in different physical positions in order to make use of terrestrial characteristics and different radio paths available in a particular location. A reference signal (RS) is used in many MIMO configurations to allow for measurements of the spatial channel properties and facilitate coherent demodulation at the terminal. It can be an RS for a specific terminal or a common RS (CRS) that is shared among a group of terminals.



2. MIMO technology uses multiple antennas and multiple signal paths to boost the performance and/or data capacity of a wireless communications system, optimizing use of multipath propagation effects.

Spatial multiplexing may also be used in MIMO systems to increase system capacity. With spatial multiplexing, multiple spatial streams are sent through multiple transmit antennas; the spatial streams are separated at the receiver's multiple antennas by means of spatial signal processing.

In frequency diversity, information is communicated using different frequencies, such as the different channels on a commercial broadcast radio. It may also be implemented by means of frequency-agility techniques, such as frequency hopping or spread-spectrum communications, to divide transmitted data among available frequencies and bandwidth, as well as minimize the effects of interference and enhance communications security. mw

DEFEAT INTERFERENCE PROBLEMS WITH REAL-TIME SPECTRUM ANALYSIS

AS THE NUMBER of wireless technologies in communications networks expands, overcoming RF/microwave interference has become more of a challenge. Quality of service is determined by the extent of interference management. Real-time spectrum analysis (RTSA) enables users to detect challenging signals and solve network problems, making RTSA essential for field testing. In the application note, "Overcoming RF & MW Interference Challenges in the Field," Keysight Technologies discusses interference in various networks before delving into RTSA technology and its key performance indicators.

The note begins with a description of interference in commercial wireless networks, explaining both internal and external interference. LTE networks, which must have a sophisticated and efficient interference management scheme, are examined in detail. Microwave backhaul is then discussed, with the application note stating that approximately 50% of the world's base stations are connected to backhaul with a microwave radio. Microwave-radio network interference can be produced by reflection and refraction, as well as the usage of unlicensed frequency bands. The challenges associated with aerospace and defense communication systems and public safety systems are explained as well.

Keysight Technologies, 1400 Fountaingrove Pkwy., Santa Rosa, CA 95403; (707) 577-2663; www.keysight.com

Some of the shortcomings of traditional interference analysis are examined, too. Traditional swept-tuned and FFT spectrum analyzers can effectively detect a relatively constant signal. However, these analyzers are less effective when measuring random bursty signals, narrow pulses, or signals with duration based on network traffic conditions. Detecting such challenging signals can be achieved by utilizing RTSA, which is able to detect transient signals, dynamic signals, and RF pulses within a specific bandwidth.

The note mentions several important RTSA performance indicators, such as real-time bandwidth, minimum signal duration for 100% probability of intercept (POI), and dynamic range. Moreover, two types of challenging interference in the field—co-channel and uplink interference—are touched upon, along with an explanation of how RTSA can help detect both types. The application note also states that component failures lead to many instances of interference, with further discussion of how component-based problems can be prevented. The document concludes with a description of Keysight's FieldFox handheld analyzers.

DELIVER 125 W OF POWER USING A GAN TRANSISTOR

GALLIUM-NITRIDE (GAN) DISCRETE transistors have steadily improved in terms of performance, with manufacturers now offering devices with impressive gain, RF output power, and efficiency. In the white paper, "The Design of a 125W L-band GaN Power Amplifier," Plextek RFI demonstrates the design of a single-stage, 125-W power amplifier (PA). The PA, which is optimized for a frequency range of 960 to 1,215 MHz, is designed with a commercially available GaN transistor housed in a metal-based ceramic package.

Plextek RFI, London Rd., Great Chesterford, Saffron Walden, CB10 1NY, UK; +44 (0) 1799 533200; www.plextekrfi.com

The PA is designed using a 32-mil-thick Rogers 4360G2 laminate with 1-oz. metallization. By using this relatively thick substrate, the trace widths of the required characteristic impedance are wide enough to handle high RF power and dc current under large-signal drive conditions. The transistor operates with 260-mA quiescent current at a drain voltage of +50 V dc.

Large-signal load-pull data demonstrated the device is able to provide +51 dBm of output power at the 3-dB compression point at 1.1 GHz. The complete PA schematic is presented, with passive components carefully selected to handle high dc voltages and RF power levels alike. Both the gate and drain bias networks utilize printed transmission lines along with shunt surface-mount-technology (SMT) capacitors. Furthermore, the input and output matching networks are lowpass structures that transform the 50-Ω system impedance to the lower source and load impedances needed to achieve optimum power transfer.

Utilizing a SHaaS ecosystem can reduce redundancy and maintenance. For example, a single sensor can be used for a range of applications. A motion sensor could be used to control lighting, manage the home environment, and more.

The final assembly is mounted onto an aluminum alloy carrier that acts as a heat spreader. This carrier can also be attached to a heatsink. Small-signal S-parameters were measured at package-base temperatures of –40, +25, and +85°C. These measurements demonstrate a small-signal gain of approximately 19 dB across the frequency range, which varies by less than 2 dB over temperature. Large-signal measurements were performed over the same temperature range. Those results prove the PA can deliver 125 W of output power at the 3-dB compression point at midband. The document also details the PA's efficiency performance.

JACK BROWNE | Technical Contributor

PORTABLE TESTERS Add Real-Time Spectrum Analysis to 50 GHz

Covering a total frequency range from 9 kHz to 50 GHz, these portable, handheld test instruments now offer a 10-MHz real-time bandwidth to capture short-duration signals.

ON-SITE SPECTRUM ANALYSIS ONCE implied the use of a "portable" instrument with a battery almost large enough to start an automobile. But portable RF/microwave test instruments have come a long way, and lightweight units such as the FieldFox analyzers from Keysight Technologies *(www.keysight.com)* provide a number of measurement functions from a battery-powered package weighing just 7.1 lb. (3.2 kg).

Just added as an option to 16 models in the FieldFox line is real-time spectrum-analysis (RTSA) capability. Available over a total frequency range of 9 kHz to 50 GHz, it captures the most elusive signals—including multiple pulses, interference, and other signals occupying a band of interest. With outstanding efficiency, these portable analyzers can run for nearly four hours on a single battery charge for thorough, on-site RTSA measurements.

The FieldFox analyzers *(Fig. 1)* are compact and light in weight, yet quite rugged and lacking none of the power and accuracy of much larger, laboratory benchtop analyzers. They show captured signals on a bright 6.5-in. diagonal thin-film-transistor (TFT) display and are available with a variety of measurement functions, including as combination instruments with cable and antenna tester (CAT), spectrum analyzer, and vector network analyzer (VNA).

The 16 models available with RTSA option 350 *(see table)* include spectrum analyzers and combination analyzers with built-in power meters, frequency counters (with 1-Hz resolution), and a Global Positioning System (GPS) receiver for precise location of detected signals. The internal GPS receiver,

THE FIELDFOX ANALYZERS WITH OPTION 350 RTSA, AT A GLANCE

Model	Instrument type	Frequency range	RTSA range
N9913A	Combination	30 kHz to 4 GHz	100 kHz to 4 GHz
N9914A	Combination	30 kHz to 6.5 GHz	100 kHz to 6.5 GHz
N9915A	Combination	30 kHz to 9 GHz	100 kHz to 9 GHz
N9916A	Combination	30 kHz to 14 GHz	100 kHz to 14 GHz
N9917A	Combination	30 kHz to 18 GHz	100 kHz to 18 GHz
N9918A	Combination	30 kHz to 26.5 GHz	100 kHz to 26.5 GHz
N9935A	Spectrum analyzer	30 kHz to 9 GHz	100 kHz to 9 GHz
N9936A	Spectrum analyzer	30 kHz to 14 GHz	100 kHz to 14 GHz
N9937A	Spectrum analyzer	30 kHz to 18 GHz	100 kHz to 18 GHz
N9938A	Spectrum analyzer	30 kHz to 26.5 GHz	100 kHz to 26.5 GHz
N9950A	Combination	300 kHz to 32 GHz	9 kHz to 32 GHz
N9951A	Combination	300 kHz to 44 GHz	9 kHz to 44 GHz
N9952A	Combination	300 kHz to 50 GHz	9 kHz to 50 GHz
N9960A	Spectrum analyzer	300 kHz to 32 GHz	9 kHz to 32 GHz
N9961A	Spectrum analyzer	300 kHz to 44 GHz	9 kHz to 44 GHz
N9962A	Spectrum analyzer	300 kHz to 50 GHz	9 kHz to 50 GHz

Note: Combination analyzers include cable and antenna tester (CAT), vector network analyzer (VNA), and spectrum analyzer.

which has a female SMA connector for attachment of a GPS antenna, can also be used as a frequency reference.

Although battery powered, these analyzers perform very much like larger benchtop instruments, with frequency resolution of 1 Hz for signals to 5 GHz, 1.34 Hz for signals to 10 GHz, 2.68 Hz for signals to 20 GHz, 5.36 Hz for signals to 40 GHz, and 8.04 Hz for signals to 50 GHz. The dedicated reference oscillator is accurate to ±0.7 ppm plus the aging rate, which is ±1 ppm/year for 20 years.

When locked to a GPS signal, the frequency accuracy improves to ±0.010 ppm. The nominal zero-span sweep time can be set from 1 µs to 1000 s, with 100-ns resolution. The zero-span 3-dB RBW is settable from 10 Hz to 5 MHz in a 1-3-10 sequence. Video bandwidth range is 1 Hz to 5 MHz. The amplitude accuracy at center frequency ranges from ±0.8 to ±1.4 dB depending on frequency.

1. The FieldFox portable, battery-powered RF/microwave signal and spectrum analyzers are now available with optional real-time-spectrum-analyzer (RTSA) capability across bandwidths as wide as 9 kHz to 50 GHz.

AN RTSA EXAMPLE

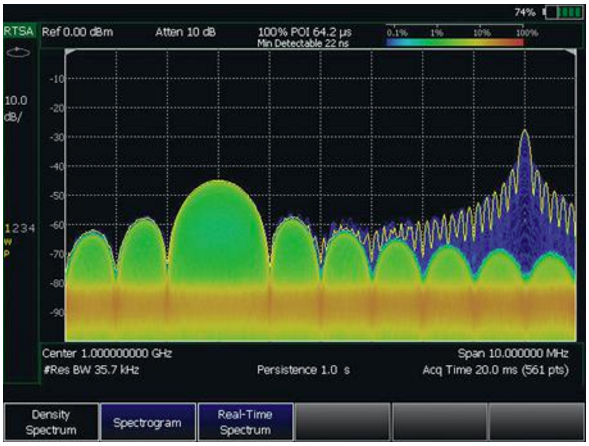
One of the widest-frequency analyzers, model N9952A, has a real-time bandwidth of 10 MHz that can be swept across a total frequency range of 9 kHz to 50 GHz. It features a wide dynamic range of 105 dB and spurious-free dynamic range (SFDR) of 63 dB. It can capture and display as many as four separate signal traces with a total of 561 points, using density spectrum, spectrogram, and real-time-spectrum displays. The N9952A FieldFox with RTSA capability can detect pulses as narrow as 22 ns even amidst surrounding signals and noise.

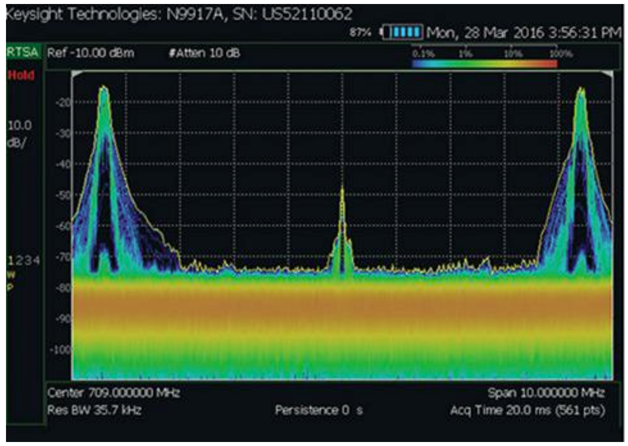
The analyzer achieves 100% probability of intercept (POI) with full amplitude accuracy for pulses as narrow as 12 µs. As with the other analyzers featuring the RTSA option, the N9952A provides flexible triggering, with free-run, external, video, and RF burst triggers using positive- or negative-edge trigger slopes. Trigger delay times can be set from 150 ms to 10 s with 100-ns resolution. The built-in power meter in the N9952A covers a frequency range of 300 kHz to 50 GHz.

For a given frequency range, these FieldFox portable analyzers with RTSA option can capture multiple simultaneous pulses or short-duration signal events within a channel of interest. The two pulses shown in *Fig. 2* were acquired within a 20-ms acquisition time for a center frequency of 1 GHz, using a spectrum- analyzer resolution bandwidth (RBW) of 35.7 kHz and real-time bandwidth of 10 MHz. The pulse traces are formed from 561 points with display persistence set at 1 s.

When working with the firm's new RTSA software, one of these FieldFox analyzers can capture and identify multiple simultaneous pulses within the capture bandwidth; work with a directional antenna to identify interference signals; and even verify wireless communications network operations, such as Long -Term -Evolution (LTE) uplink control and traffic signals *(Fig. 3)*.

These portable analyzers with optional RTSA capability are compliant to MIL Class 2 requirements and are as home in





2. The portable FieldFox analyzers with optional RTSA capability can capture two simultaneous pulses and show traces on a bright, 6.5-in. diagonal TFT display screen.

3. When using available software, the portable FieldFox analyzers with optional RTSA capability can measure and display LTE commercial communications control signals.

commercial and industrial applications as they are in military test situations. They are well- suited for monitoring interference on two-way radio links, checking signals at satellite- communications (satcom) ground stations, capturing frequency-hopped signals, and verifying pulse sequences in military radar systems.

With their multiple display modes, such as spectrogram and real-time-spectrum displays, these FieldFox analyzers with optional RTSA capability can show small signals "hiding" within or in the presence of larger signals. They can serve as effective tools for checking on wireless communications signal carrier quality or for detecting the small signals emitted by improvised explosive devices (IEDs), even in the presence of much larger signals at airports.

The FieldFox microwave and spectrum analyzers with optional RTSA capability measure just 11.5 × 7.4 × 2.8 in. (292 × 188 × 72 mm). They are software-enabled and field-upgradable for keeping pace with changing measurement requirements. In addition to the many integral measurement functions already mentioned, these portable instruments also feature a built-in interference analyzer for the frequency range of the instrument, with included record and playback capability for analyzing captured interference.

Finally, the analyzers offer a number of different options, including for characterizing pulses found in radar and electronic-warfare (EW) systems, use of an external Universal Serial Bus (USB) power sensor, and remote control of the analyzer using smartphones or other wireless devices. mw

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Wi-Fi's Future Up in the Air

As competing technologies emerge, Wi-Fi must adapt over the next few years to maintain its position in the wireless arena.

IN MANY WAYS, WI-FI is a victim of its own success. Some 12 billion Wi-Fi products have been shipped and another 3 billion will be shipped in 2016, according to the Wi-Fi Alliance. Wi-Fi will continue to be one of the most prolific technologies around the world, with 38 billion products touching nearly all aspects of our lives by 2020.

As device makers and consumers see Wi-Fi as a key technology in everyday life, the wireless spectrum is becoming more congested and impacting performance. This is especially true in dense urban areas, where dozens of access points can overlap. Another factor is the growth of high-bandwidth applications, such as video streaming and multi-user gaming. To keep up with demand, Wi-Fi and the equipment used to test Wi-Fi devices must continue to evolve.

WI-FI EVOLUTION

Modern Wi-Fi took root when the IEEE formed the 802.11 working group back in 1990 to promote the standard. The initial release, 802.11 Wireless LAN, was approved in 1997. Since then, several advances to the Wi-Fi standard have occurred, perhaps the most significant being 802.11n. Released in 2009, 802.11n is considered a fourth-generation wireless-LAN technology standard, operating in both the 2.4- and 5.0-GHz bands.

Users had already begun migrating to 802.11n, based on the Wi-Fi Alliance's certification of products conforming to a 2007 draft of the 802.11n proposal. This version of the standard improved Wi-Fi in two major ways:

- It opened up the 5-GHz band. Although support for 5 GHz is optional under 802.11n, many users found this feature desirable because it relieved the congestion that users were experiencing on the 2.4 GHz band.
- It offered better throughput, as the maximum net data rate increased from 54 to 600 Mb/s. This was accomplished by increasing the channel width from 20 MHz to 40 MHz. Incorporation of multiple-input-multiple-output (MIMO) technology also enhanced performance. MIMO is made possible by devices utilizing multiple antennas. The antennas enable data to be transmitted over multiple streams, which significantly increases and accelerates overall data throughput.

Through the years, the evolution of 802.11 continued with the publishing of the 802.11ac standard in December 2013. Compared to 802.11n, it features wider channels (80 or 160 MHz versus 40 MHz) in the 5-GHz band, more spatial streams (up to eight versus four), higher-order modulation (up to 256-QAM versus 64-QAM), and the addition of multi-user MIMO (MU-MIMO). Generally, 802.11ac's rollout is distinguished by two "waves":

- "Wave 1" implementations support 80-MHz channels, three spatial streams, and 256-QAM, yielding a data rate of up to 433.3 Mb/s per spatial stream, 1,300 Mb/s total, in 80-MHz channels in the 5-GHz band.
- "Wave 2" devices include support for 160-MHz channels, four spatial streams, and MU-MIMO. Device makers began shipping Wave 1 devices in late 2013 and are starting to ship Wave 2 devices this year.

Today, 802.11ax is touted as the next-generation Wi-Fi standard. It promises to deliver even higher throughput than 802.11ac by using a more-efficient modulation scheme called orthogonal frequency division multiple access (OFDMA). OFDMA is a huge benefit of the 802.11ax standard. The primary goal is to increase the data rate per user by a factor of 4 and enable 10X more capacity over 802.11ac.

The current official release date of the 802.11ax standard is sometime in 2019. Like the rollout of 802.11n, though, we should begin to see devices that support the draft standard

before then. It is absolutely essential for 802.11ax to keep progressing, considering that another technology is beginning to compete for bandwidth.

ON YOUR MARK

Wi-Fi is in a horse race with two Long Term Evolution (LTE) technologies: LTE in Unlicensed Bands (LTE-U) and LTE Licensed-Assisted Access (LTE-LAA). LTE-U is quietly emerging in 4G/LTE wireless networks specific to North America that use unlicensed spectrum—the same unlicensed 5-GHz spectrum currently being used by Wi-Fi.

Some studies have shown that LTE technology—originally used in cellular phones in licensed bands—offers performance advantages over Wi-Fi when operating in unlicensed bands, such as:

- Better link performance
- Medium access control
- Mobility management
- Excellent coverage

These benefits, combined with the vast amount of available spectrum (>400 MHz) in the 5-GHz band, make LTE-U a promising radio access technology in the unlicensed arena. Mobile operators are hot to implement this technology, as it will enable them to offload data traffic onto unlicensed frequencies and reduce the load on their wireless networks that use licensed spectrum. Devices that employ LTE-U are being field tested now, and commercial devices will be available to consumers starting this year.

Some of the industry's biggest players are behind LTE-U. In 2014, Verizon, in cooperation with Alcatel-Lucent, Ericsson, Qualcomm Technologies Inc. (a subsidiary of Qualcomm Inc.), and Samsung, formed the LTE-U Forum. The LTE-U Forum is a consortium, much like the Wi-Fi Alliance. In March 2015, the group published technical specifications, including minimum performance specifications for operating LTE-U base stations and consumer devices on unlicensed frequencies in the 5-GHz band as well as coexistence specifications.

The coexistence specifications are meant to address concerns that LTE-U devices will interfere with Wi-Fi networks. The FCC requires that devices using unlicensed spectrum do not interfere with the operation of other devices using those frequencies, but that's easier said than done.

The LTE-U Forum has conducted tests and published a report that shows that LTE-U will not cause interference to Wi-Fi. The study concludes that, "With a set of well-designed coexistence algorithms, the level of protection that LTE-U nodes provide to nearby Wi-Fi deployment can be better than what Wi-Fi itself provides."

Not surprisingly, Wi-Fi companies aren't quite so optimistic. Google issued a report that LTE-U would seriously interfere with Wi-Fi. Fortunately, we're at a point where these issues can be worked out before the widespread sale and implementation of devices that could cause harmful interference to one another. Consumers will benefit greatly if the Wi-Fi Alliance and the LTE Forum work out these issues.

One possible scenario is that devices support both 802.11ax and LTE-U. This is certainly possible because the 802.11ax spec describes some of the same mechanisms found in LTE-U. For this to happen, chipset manufacturers will have to make chipsets that support both standards. Another scenario is that the IEEE 802.11ax committee will continue to improve the Wi-Fi specification, so that when it is released, it will be competitive with LTE-U.

INCREASED TESTING CHALLENGES

Of course, new technologies mean new testing challenges. Range and battery life will continue to be a concern. Higher data rates can reduce range and battery life, and manufacturers will have to make sure that their new designs don't fall short in these two areas. Comprehensive testing during the design phase is important to ensure that the customer experience isn't degraded.

Chipset calibration is another issue. As opposed to cellular, many device manufacturers do not perform Wi-Fi calibration in order to minimize test time and reduce cost. However, failing to do so can adversely affect range and battery life.

Another test challenge is that consumer devices are supporting more cellular and connectivity technologies. For example, smartphone manufacturers need to support 2G, 3G, and 4G cellular technologies today to ensure worldwide operation. Manufacturers need test equipment that can cover all of the communications protocols supported by a particular device.

More standards, in general, means increased test times. More test time in turn impacts the test process, and often becomes a financial quandary. Balancing new test methodologies and managing reasonable test times, while ensuring a high level of quality, deserves a fresh look. Test methodologies or test strategies should be periodically reevaluated, keeping mindful of the impact on the economies of test.

CONCLUSION

Without a doubt, Wi-Fi technology and the equipment needed to test it must adapt over the next few years. On the one hand, consumers are demanding more from their Wi-Fi in terms of more devices, users, and bandwidth. On the other hand, competing technologies, such as LTE-U, are looking to grab a share of the market, if not dominate it.

The next two years are crucial. The longer it takes manufacturers to develop and test LTE-U consumer devices, the better for 802.11ax, as it gives the standards committee time to make the standard more competitive. And, chances are that the groups supporting Wi-Fi and LTE-U will make concessions to allow for coexistence. mw

JACK BROWNE | Technical Contributor

Multiport VNA Tests to 20 GHz

With outstanding measurement speed, accuracy, and 16 test ports, this RF/microwave vector network analyzer supports high-throughput production testing to 20 GHz.

VECTOR NETWORK ANALYZERS (VNAs) are so essential for higher-frequency testing of transmission characteristics that they might be thought of as "microwave voltmeters." Most commercial VNAs are equipped with two or four ports for measuring the forward and reverse transmission characteristics of RF/microwave devices and components one at a time.

In production testing, however, more ports are needed, and the R&S ZNBT20 VNA from Rohde & Schwarz is designed for that purpose, with 16 integrated test ports and a frequency range of 100 kHz to 20 GHz. Each of the 16 ports provides high performance, allowing for high-volume S-parameter measurements under high-speed production conditions. The multiport analyzer can drive all of its test ports in parallel without compromising performance, for simultaneous testing of multiple devices under test (DUTs).

The R&S ZNBT20 (*see figure*) provides generous test port power through 20 GHz, with -30 to +6 dBm to 1 MHz, -30 to +8 dBm to 10 MHz, -30 to +10 dBm to 1 GHz, -30 to +8 dBm to 10 GHz, and -30 to +5 dBm to 20 GHz. The source power accuracy is better than 2 dB to 10 GHz and better than 3 dB to 20 GHz, with power resolution of 0.01 dB.

The multiport analyzer tunes frequency with 1-Hz resolution and can perform measurements on as few as 2 and as many as 100,001 points. The measurement bandwidth can be set from 12 Hz to 1 MHz in standard models and from 1 Hz to 10 MHz in instruments with an increased bandwidth option. The typical dynamic range at all ports is high, as good as 115 dB to 1 MHz, 130 dB to 2 GHz, 125 dB to 10 GHz, and 120 dB to 20 GHz.

The measurement accuracy is a function of frequency and test-port power, with amplitude accuracy at the lowest frequencies ranging from 0.30 dB for test-port power of -50 to -60 dBm to 0.06 dB for test port power from -35 to +5 dBm. From 1 MHz to 10 GHz, the amplitude accuracy is 0.10 dB for test port power from -50 to -60 dBm, improving to 0.06 dB for more robust test-port power from -35 to +5 dBm. At the highest test frequencies, from 10 to 20 GHz, the amplitude accuracy is 0.20 dB at the lowest test-port powers, improving to 0.06 dB for test-port power of -50 to -35 dBm and topping out at 0.05 dB for test-port power from -35 to +5 dBm.

The phase measurement accuracy is similarly well controlled, falling as low as 2 deg. at the lowest frequencies (100 kHz to 1 MHz) and power levels but typically 0.8 deg. or better for all power levels and for all frequencies above 1 MHz. Test signal harmonics are well controlled for the R&S ZNBT20. When tested for a 0-dBm test output level, harmonics are typically -20 dBc from 100 kHz to 10 MHz, -30 dBc from 10 to 100 MHz, -35 dBc from 100 MHz to 8 GHz, and -25 dBc from 8 to 15 GHz.


This multiport RF/microwave vector network analyzer (VNA) provides 16 parallel test ports for production S-parameter testing to 20 GHz.

The R&S ZNBT20 20-GHz multiport VNA can achieve fast sweep times in support of production testing. Data transfers and measurement times were evaluated with a PC running 64-b copy of the Windows 7 operating system (OS) from Microsoft Corp. For a 900-MHz center frequency, the sweep time is less than 2.5 ms with a full test cycle time of less than 5 ms. For a 5.1-GHz center frequency, the sweep time is less than 2.0 ms and the full cycle time is less than 5 ms. The compact VNA is supplied with 3.5-mm male connectors on its RF/microwave ports and includes two USB 2.0 ports on front panel and two more on the rear panel to help with data transfers.

The analyzer is available with a sizable list of options, including extended bandwidth. An additional option, the R&S ZNBT-K20 option for extended time-domain analysis, makes it possible to perform signal-integrity tests on high-speed transmission standards, allowing displays of plots useful for such analysis, including eye diagrams, rise time, and skew. The R&S ZNBT20 is supported by a number of different ATE test programs to speed and simplify setup of production test systems. mw

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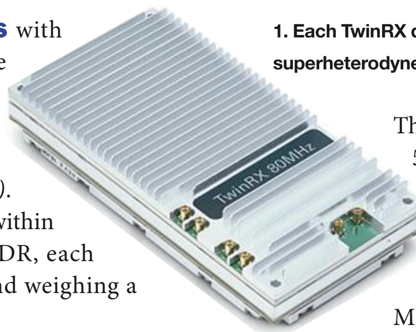
JACK BROWNE | Technical Editor

Board Packs Pair of Superhet Channels

This low-power, wideband receiver module provides as much as 80 MHz for each of two superheterodyne channels with wide dynamic range from 10 MHz to 6 GHz.

MODULARITY OFTEN IS SYNONYMOUS with flexibility—a trait exemplified in the TwinRX daughterboard for the USRP X Series of software-defined radios (SDRs) from Ettus Research, a National Instruments company *(www.ettus.com)*. Two of the TwinRX daughterboards fit within a model USRP X300 or USRP X310 SDR, each measuring just 27.7 × 21.8 × 3.9 cm and weighing a mere 1.7 kg.



1. Each TwinRX daughterboard contains two independently tunable superheterodyne receiver channels for use from 10 MHz to 6 GHz.

The TwinRX boards deliver 80-MHz bandwidth per receiver channel across a total frequency range of 10 MHz to 6 GHz. Each compact daughterboard *(Fig. 1)* is actually a full-fledged dual-channel receiver. They are capable of local-oscillator (LO) sharing with other receiver daugterboards in a system to create multichannel receiver systems or even massive MIMO system solutions. Each TwinRX is a low-power subsystem, with stable preselection filters *(Fig. 2)*, attenuators, and two frequency mixer stages with tightly controlled phase synchronization.

BROAD FUNCTIONALITY

The TwinRX achieves a 110-dB dynamic range at 2.4 GHz, 5.5-dB minimum noise figure at the same frequency, and only 10-W power dissipation. Each of the daughterboard's receiver channels has instantaneous bandwidth of 80 MHz that can be tuned independently across the full frequency range from 10 MHz to 6 GHz to capture and analyze signals in multiple-frequency bands of interest.

As an example, a single TwinRX daughterboard can simultaneously monitor uplink and downlink communications signals across a combined bandwidth of 80 + 80 = 160 MHz. By sharing LO signals across multiple TwinRX daughterboards, it is possible to achieve the phase-aligned operation needed for multichannel phased-array systems. In addition to the tight phase control, the dual-channel receiver is also capable of high-speed frequency-hopped tuning to detect frequency-agile emitters.

The TwinRX exhibits noise figure of better than 5 dB from 10 MHz to 3 GHz, better than 4 dB from 3 to 5 GHz, and better than 8 dB from 5 to 6 GHz. Image rejection is –70 dBc from 0.5 to 6.0 GHz. Phase noise is –88 dBc/Hz offset 10 kHz from a 900-MHz carrier, –86 dBc/Hz offset 10 kHz from a 2.4-GHz carrier, and –82 dBc/Hz offset 10 kHz from a 5.8-GHz carrier. And phase noise is –105 dBc/Hz offset 100 kHz from a 900-MHz carrier, –107 dBc/Hz offset 100 kHz from a 2.4-GHz carrier, and –103 dBc/Hz offset 100 kHz from a 5.8-GHz carrier.

In addition, non-input-related spurious levels are –95 dBc from 10 MHz to 3 GHz, –92 dBc at 3.2 GHz, –98 dBc at 4.8 GHz, and –98 dBc at 5.4 GHz. The third-order-intercept point is –8 dBm for a full scale of –45 dBm from 10 MHz to 1.8 GHz, –2 dBm for a full scale of –30 dBm from 10 MHz to 1.8 GHz, and +16 dBm for a full scale of –20 dBm from 10 MHz to 1.8 GHz, with similar readings at higher frequencies. mw

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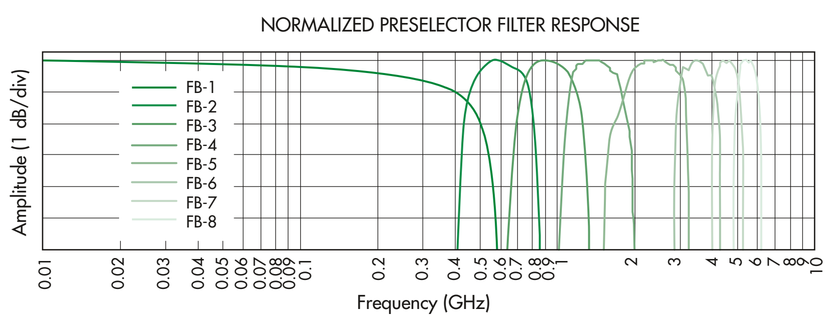

2. Powerful preselector filter capability within each TwinRX dual-channel receiver allows for detection and isolation of signals from interference from 10 MHz to 6 GHz.

JACK BROWNE | Technical Contributor

YIG Oscillators Offer 20-MHz FM Bandwidth

YIG-based RF/microwave oscillators have been enhanced with 3-dB frequency modulation capabilities of 20 MHz or more.

MICROWAVE OSCILLATORS BASED ON yttrium-iron-garnet (YIG) resonators have long been prized for their low phase noise and linear tuning capabilities. The performance has always come at the cost of limited frequency-modulation (FM) 3-dB bandwidth—typically just a few MHz—which challenged synthesizer designers attempting to stabilize these sources with a phase-locked loop (PLL).

But those limits are no more: Micro Lambda Wireless has introduced YIG oscillator technology with FM 3-dB bandwidths of 20 MHz and higher, applicable to both electromagnetic and permanent-magnet (PM) type YIG oscillators. The firm designs and manufactures PM YIG sources from 2 to 20 GHz *(Fig. 1)* and electromagnetic YIG oscillators *(Fig. 2)* from 0.5 to 40.0 GHzs.

Smaller YIG oscillators, such as the TO-8-packaged MLSMO series of PM YIG oscillators and the mini and PCB lines of sources, are currently available with the wideband FM to 16 GHz. Larger oscillators, such as 1-in. and 1.25-in. cubes and 1.75-in. cylinders, will be available shortly with the wideband FM capabilities. These exceptional FM capabilities are available as options meeting specific customer requirements.

The firm's various YIG oscillators are available for narrowband and wideband frequency tuning ranges. The MLSMO series, for example *(see "YIG Oscillators Fit Surface-Mount Packs" at mwrf.com)*, covers a variety of frequency bands, including 3.0 to 6.0 GHz, 4.0 to 9.0 GHz, and 6.5 to 13.0 GHz. The output power for all models is +8 dBm across each frequency range, with phase noise as good as -128 dBc/Hz offset 100 kHz from carriers to 9 GHz.

The electromagnetic and PM YIG oscillators differ in their approaches to the resonant magnetic structure within each oscillator, as well as with their resulting performance levels. While both approaches are capable of linear tuning low noise, electromagnet YIG oscillators offer extended frequency coverage with wider tuning ranges than PM YIG oscillators based on a magnet tuned at the factory according to a customer's requirements.

The PM approach yields a tuning bandwidth of typically ±2 GHz, while the electromagnet approach can achieve tuning bandwidths in excess of an octave (albeit with higher power consumption, owing to the additional power needed to energize the electromagnet).


1. The MLTO series of PM YIG oscillators are supplied in 0.625-in.-diameter TO-8 housings.


2. The MLMB series of electromagnetic YIG oscillators are housed in PCB-mount enclosures.

To accomplish wideband FM with these different magnet structures, different design approaches and different FM driver configurations were required. For an end user, the results are the same, with FM tuning coils capable of 3-dB bandwidths in excess of 20 MHz and with standard FM coil sensitivity the same for the two YIG oscillator types, at 150 kHz/mA. For either type of oscillator and FM coil, the minimum frequency deviation is ±15 MHz.

To verify the wideband capabilities of the FM coils and drivers in both YIG oscillator types, swept-frequency hands-on testing was performed by Micro LambdaVice President of Engineering Dave Suddarth and President John Nguyen. Testing was performed with the aid of a swept-function generator capable of 30-MHz bandwidth, an FM discriminator, the various FM coil drivers under test, and a digital storage oscilloscope (DSO).

Test results were impressive. By way of example: Both oscillator types were studied at an RF/microwave frequency of 6.662 GHz using different five-turn FM coils in custom test fixtures. A 2-to-8-GHz TO-8 PM YIG oscillator was characterized by means of a linear FM sweep from 1 Hz to 30 MHz, exhibiting a 3-dB FM bandwidth of 28 MHz. Similarly, an electromagnet-based 3-to-8-GHz YIG oscillator was evaluated with a linear FM sweep from 1 Hz to 25 MHz, yielding a 3-dB FM bandwidth of 21 MHz.

This new wideband FM capability should make these YIG oscillators candidates for any designer seeking low phase noise, but put off by the relatively narrow 3-dB FM bandwidth. The 3-dB FM bandwidth of 20 MHz or more clears the way for a wide range of applications to 40 GHz and beyond—whether in terrestrial and satellite receivers, test equipment, or military electronic systems. mw

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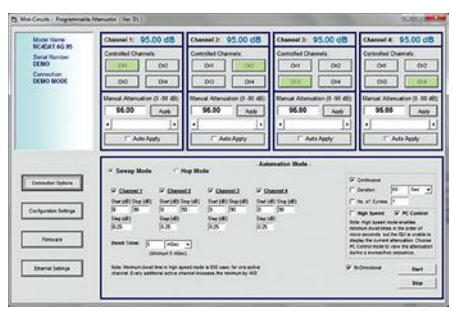

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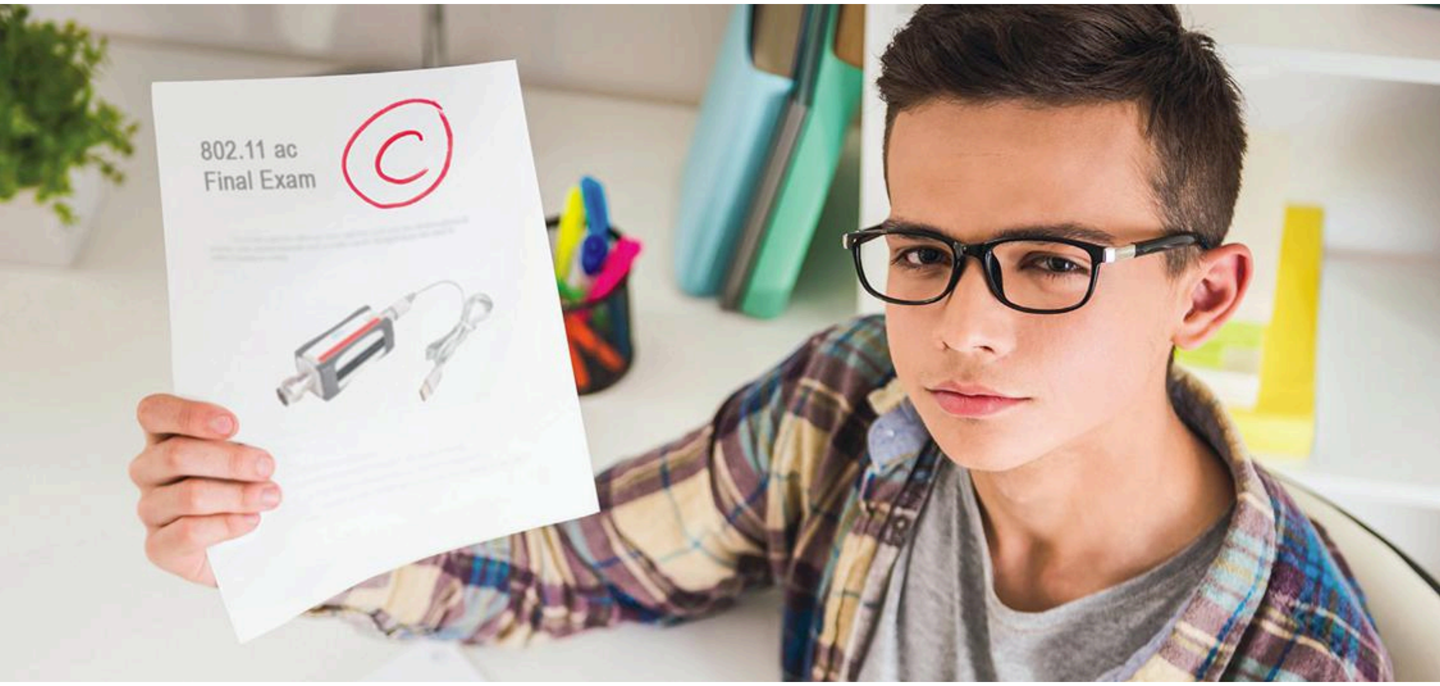

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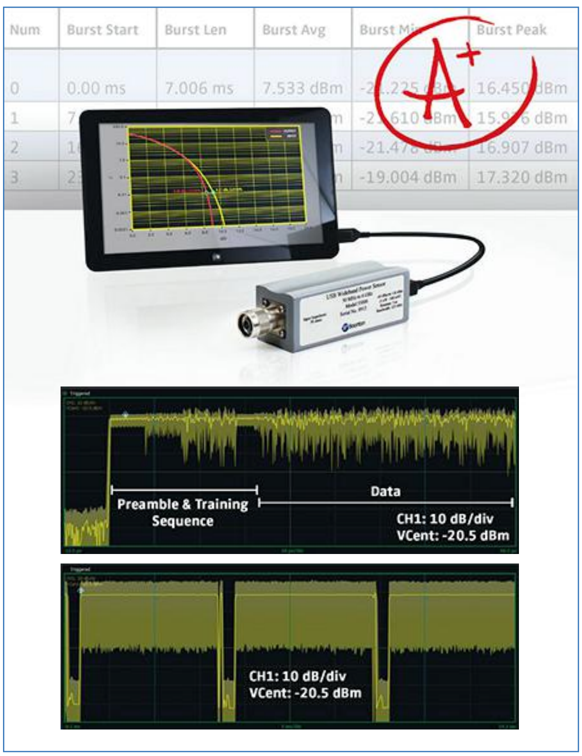

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