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INSIDE TRACK with **Amarpal Khanna,** IMS General Chair | **33**

Cutting-Edge Technologies to Watch | **65**

GaN Performance Breaks Barriers | **133**

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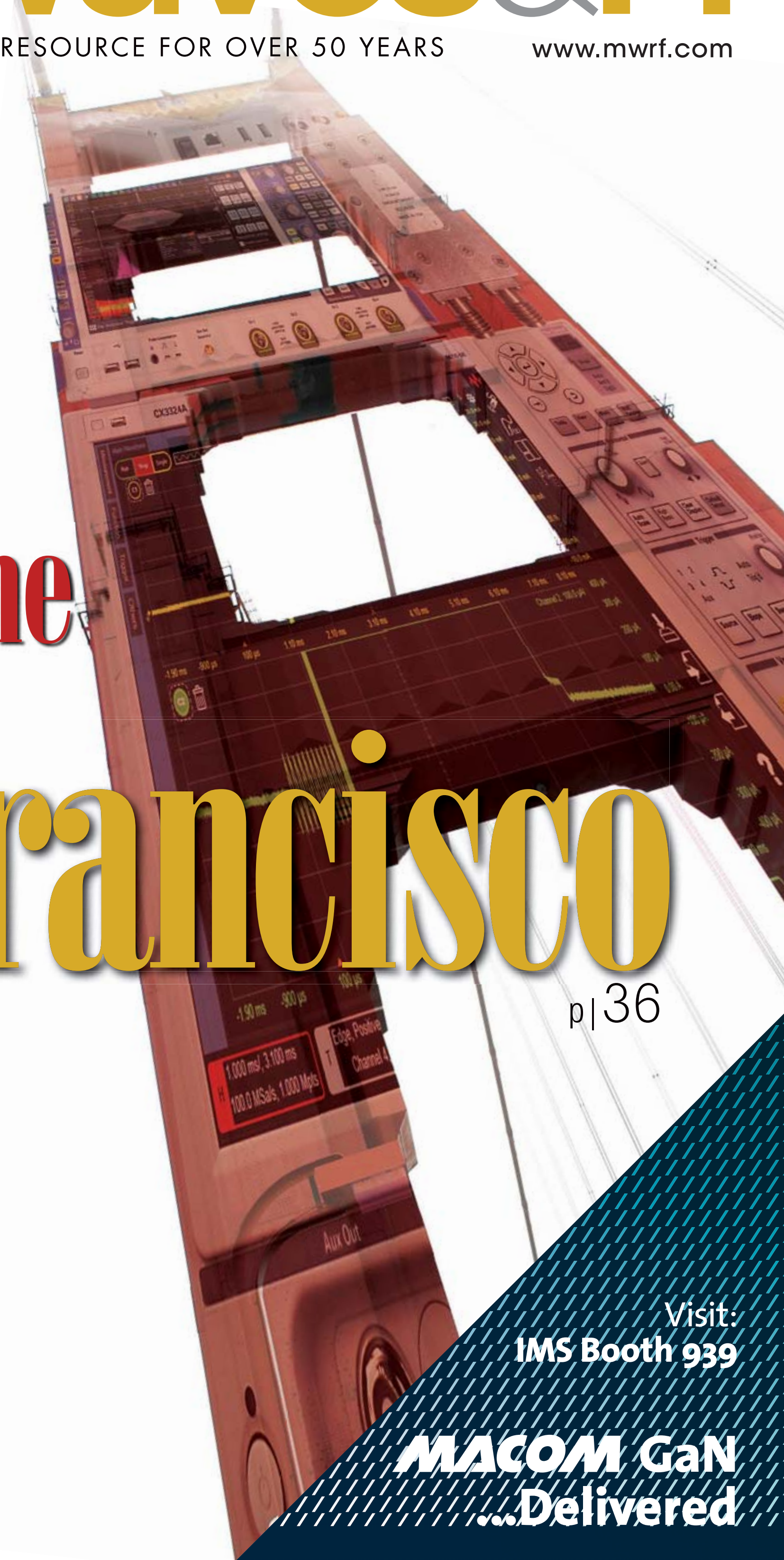

IMS PREVIEW:

Right at Home in San Francisco

p|36

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  13.5 dB (CH 7-16)
- Isolation: 60 dB minimum
- Amplitude Match: ±1.5 dB
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- Filters easily customizable to meet any other requirements.

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- **DC Voltage:** +5 V @ 1500 mA, -15 V @ 260 mA

4SFB-2G18G-CD-SFF
4 Channel Switch Filter Bank

- Frequency Range: 2 to 18 GHz
- Power Rating: +27 dBm CW maximum
- Harmonics: -65 dBc minimum, relative to RF Out, tested with +27 dBm @RF In
- Insertion Loss: 7.0 dB
- Isolation: 60 dB minimum
- Filter channels are centered at 2.75, 4.75, 8.2 and 14.2 GHz, 55% BW
- Integral TTL driver and offers fast switching speeds of less than 300 ns.

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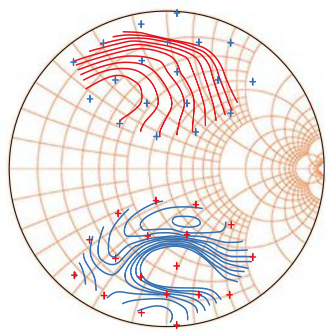
In This Issue

36

CONTOURS FOR FUNDAMENTAL AND SECOND-HARMONIC IMPEDANCES



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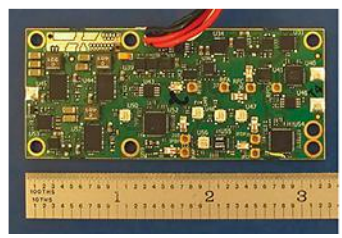
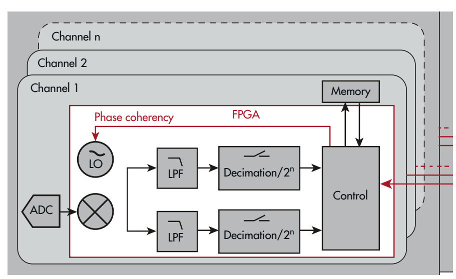
61



90

defense electronics
Starts on p. **103**



98

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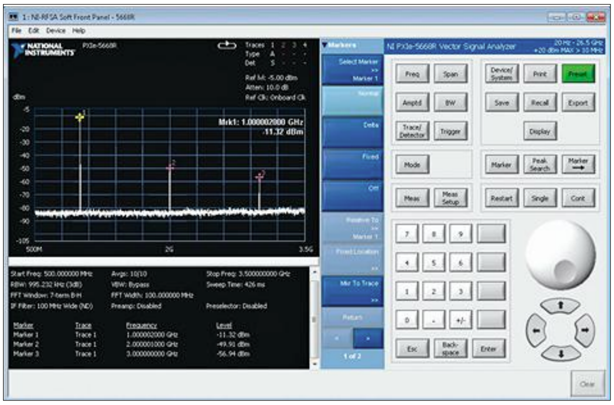

VSA SIMPLIFYING HARMONIC MEASUREMENTS

http://mwrf.com/test-measurement-analyzers/vsa-helps-simplify-harmonic-measurements

A vector signal analyzer is a powerful tool for measuring the harmonic signal levels of wireless communications standards with complex, wideband modulation formats. Using a VSA, several techniques are available for measuring the output power of signal harmonics. Using a VSA, several techniques are available for measuring the output power of signal harmonics. These involve either the frequency or time domain, with tradeoffs in simplicity, measurement time, and accuracy depending upon the choice of measurement approach.

PRACTICAL THz TECHNOLOGY

http://mwrf.com/mixed-signal-semiconductors/taking-steps-toward-practical-thz-technology

The potential for terahertz waves is enormous for imaging and communications applications—if practical semiconductor THz detectors and generators can be developed.

NEW-LOOK ANALYZERS SCOUR WIDE BANDWIDTHS

http://mwrf.com/test-measurement-analyzers/new-look-analyzers-scour-bandwidths-3-hz-50-ghz

Bandwidth is a precious commodity, with an increasing amount of applications, from commercial automotive safety systems to military radar systems, occupying RF and microwave bands. Keeping all of those signals straight can be a chore, but the job just got easier with the latest generation of X-Series signal analyzers from Keysight Technologies.

DIFFERENCES BETWEEN SAWs AND BAWs

http://mwrf.com/passive-components/what-are-filtering-differences-between-saws-and-baws

Components based on surface-acoustic-wave (SAW) and bulk-acoustic-wave (BAW) technology both employ acoustic waves but in different ways and with different performance levels, especially at higher frequencies. These technologies have found their ways into many applications, from automotive navigation systems and smartphones to military radar systems.

Editorial

CHRIS DeMARTINO
Technical Editor
chris.demartinol@penton.com

IMS 2016 To Shine in San Francisco

The IEEE International Microwave Symposium (IMS) and all that it has to offer is once again almost upon us. This year's event will take place May 22-27 at San Francisco's Moscone Center. For good reason, IMS is considered to be the most noteworthy event of the RF/microwave industry each year. The 2016 edition looks to be no exception to that rule.

Some of the buzzwords associated with IMS this year are 5G, the Internet of Things (IoT), automotive radar, and more. These topics will be discussed all week long via myriad keynote talks, panel sessions, and technical presentations. Those who attend will undoubtedly receive plenty of insight into these and other areas of interest.

IMS 2016 will also allow companies throughout the RF/microwave industry to showcase their latest products and technology. More than 600 companies are slated to participate this year. The latest and greatest of everything microwave will be on display, including components, subsystems, design software, test-and-measurement equipment, and much more. Of course, it is always easy to pay more attention to the larger booths occupied by some of the prominent companies in the RF/microwave industry. However, missing the smaller companies in attendance would be a mistake. This industry would not be what it is without the contributions from the smaller, innovative companies working hard day in and day out.

To encourage young people to consider pursuing engineering, a number of science, technology, engineering, and mathematics (STEM) activities are planned for IMS. A full day will be dedicated to education, as students will be introduced to RF/microwave technology through demonstrations and guided tours. This experience will allow students to interact with working engineers. In addition, the STEM Science Fair is an exciting opportunity for students to showcase their work.

Women in Microwaves (WIM) will also be a featured topic at IMS this year. Although the industry has historically beenbeen male-dominated, women play an increasingly important role as well. WIM will present a panel session on leadership for all technical professionals who wish to grow their leadership skills.

Of course, IMS is also an opportunity to connect with others who work in the industry. Opportunities to network with peers abound, as well as to possibly catch up with colleagues and industry contacts at other companies. For anyone who is a part of the RF/microwave industry, IMS is clearly an event that should be marked on the calendar. mw

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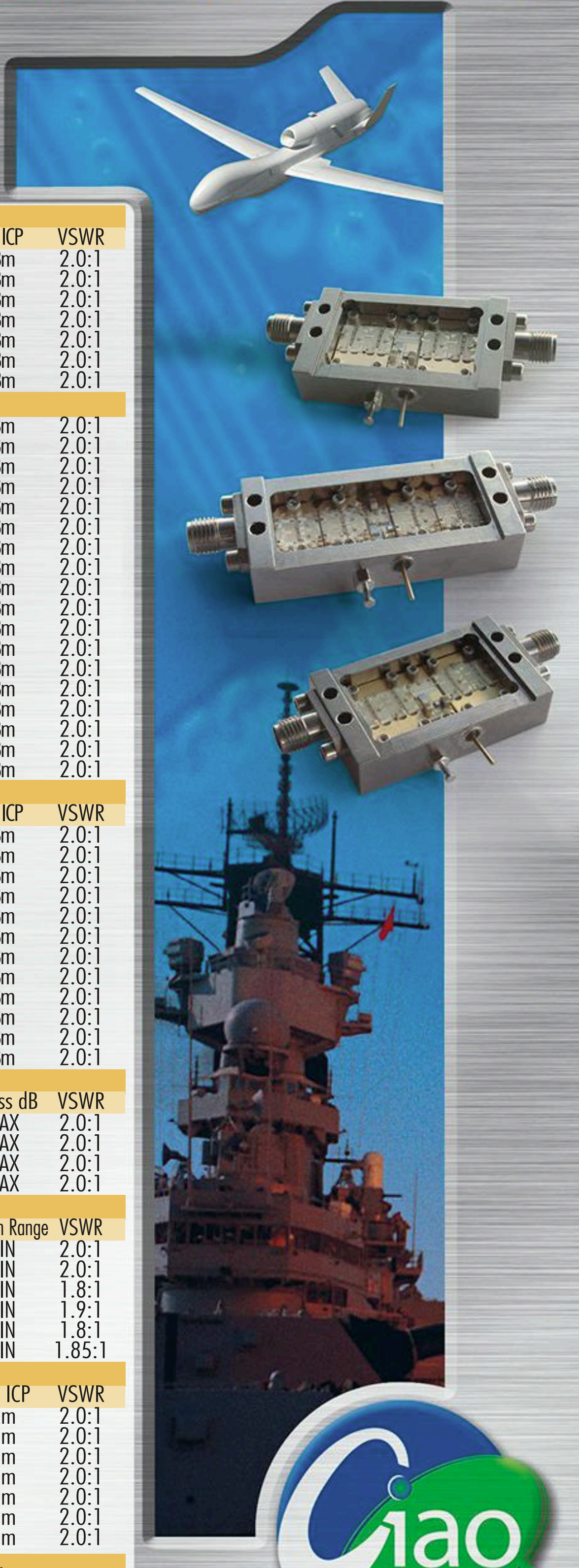

OCTAVE BAND LOW NOISE AMPLIFIERS

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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UNDERSTANDING THE MYSTERIES OF UWB

I found it curious that *Microwaves & RF* featured ultra-wideband (UWB) communications technology as a possible solution to the large amount of data that must be communicated over limited bandwidth *(see "UWB Comms Salvage Crowded Spectrum" on www.mwrf.com)*. UWB technology has often been considered a bit of RF/microwave hocus pocus by systems analysts and engineers for its seeming capability to communicate high-data-rate signals across bandwidths already occupied by conventional modulated and multiplexed signals.

Ironically, your choice of commercial product examples from Time Domain Corp. (www.timedomain.com) are for radio modules that act more like traditional radar systems in providing ranging and distance measurements, rather than as systems for high-data-rate communications. Will UWB technology be used for conventional mobile voice and data communications or just for these more specialized applications?

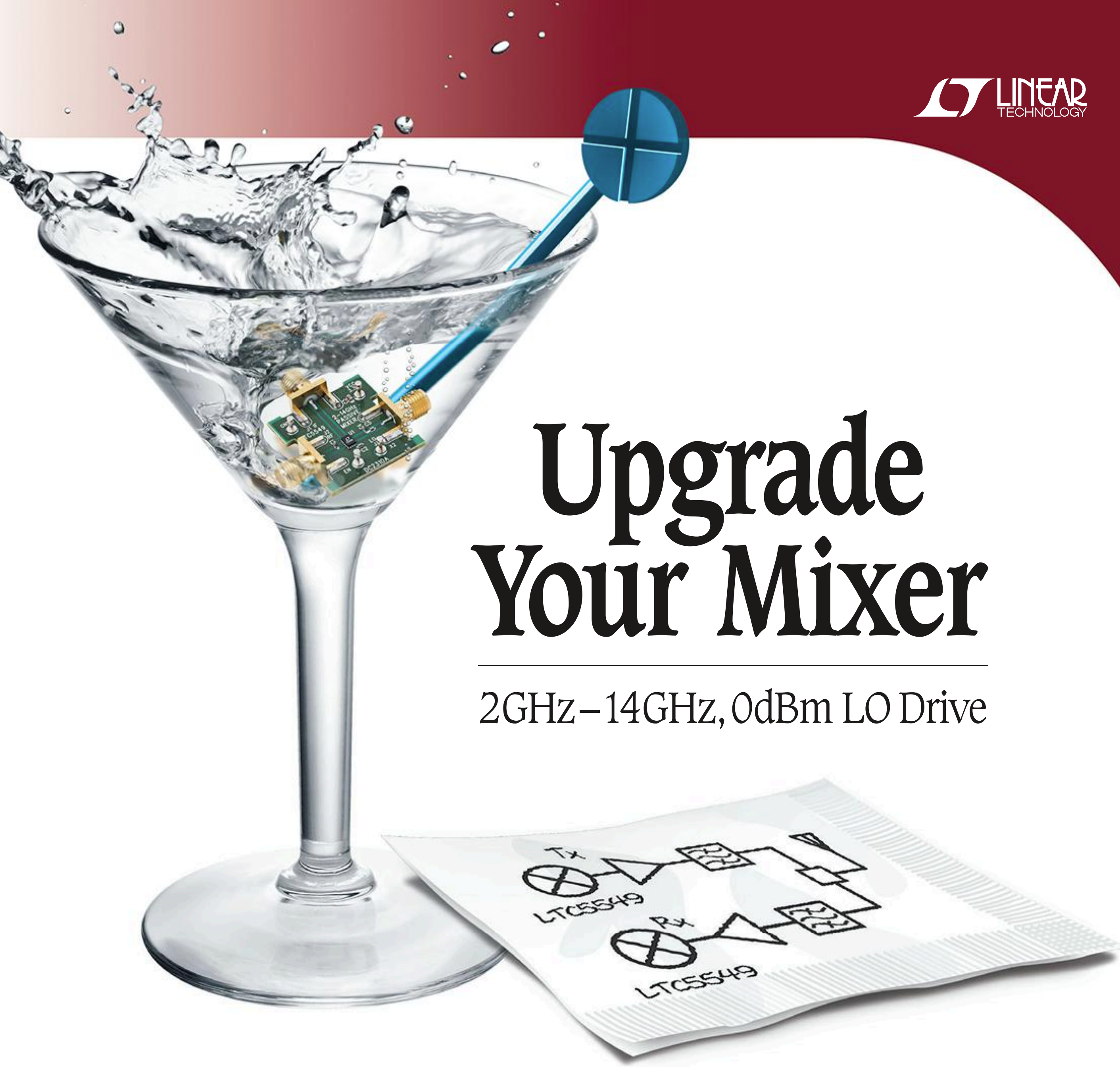
James Demshick

EDITOR'S NOTE

Thank you for reading the article and for your note. Admittedly, the Time Domain UWB radios do not function as traditional radios except for relatively low-data-rate communications *(for more on Time Domain's UWB technology, turn to p. 144 in this issue)*. The UWB report did reference additional companies, however, including Multispectral Solutions and Zebra Technologies Corp. (www.zebra.com), with radios that achieve high data rates for voice and data over low power levels, but at relatively limited distances (about 2 km). In addition, military researchers have explored the capabilities of UWB radios for battlefield communications when long running times on battery power are required. The low transmit power and low power consumption of UWB radios makes them ideal for use as tactical radios that can extend battery lifetimes by their low power usage.

While it is true that UWB communications may seem like something that a carnival magician whipped together, the technology is valid and feasible when matched with the right set of applications. One possible application for this technology will be in support of the growth of wireless sensor networks (WSNs), and the need to transfer the massive amount of data acquired by such devices as temperature sensors and motion detectors, moving them to the equivalent of a small base station for achieving Internet access to that compiled data. UWB communications technology provides the means to help manage that growing amount of data without "stealing" bandwidth from a licensed wireless standard, and without interfering with the proper operation of other wireless standards.

Jack Browne
Technical Contributor



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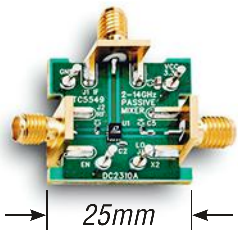
- –30dBm LO Leakage
- Tiny 3mm x 2mm Package

Demo Board



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News

MICROWAVE SOUNDERS
Mine Data for Long-Term Weather Models

The National Aeronautics and Space Administration (NASA) has lengthened its contract with Northrop Grumman to design satellite systems that sift the atmosphere for temperature and humidity data. The technology will be included on the next generation of the Joint Polar Satellite System, or JPSS, a satellite array that gathers data to assist scientists in forecasting weather patterns.

The advanced technology microwave sounders (ATMSs) scan the atmosphere with microwave signals, from which scientists extract high-resolution temperature and humidity data. Using 22 microwave channels, the ATMS measures the temperature within 1° Kelvin in one-kilometer slices of the atmosphere and moisture within 15% in two-kilometer layers. Combining data from an instrument called the cross-track infrared sounder (CrIS), which scans the atmosphere with infrared signals, scientists are able to build three-dimensional profiles of atmospheric temperature, water vapor, and other gases.

The Suomi-NPP satellite, the first satellite launched as part of the new JPSS system, being prepped for launch in a cleanroom in 2011. *(Image courtesy of NASA)*

The new scanners will be significantly more powerful than previous technology, combining the channels used by three different microwave sensors into one instrument, gathering much more detailed data. The raw data is processed in ground stations, which are operated by the National Oceanic and Atmospheric Administration (NOAA). Scientists from the National Weather Service and National Hurricane Center filter the data into weather models, helping them predict weather patterns, storm tracks, and precipitation.

The satellites in the JPSS constellation orbit the earth from pole-to-pole, as opposed to geostationary satellites that orbit around the earth's equator. The satellites fly over the equator 14 times every day, scanning the entire atmosphere twice a day. The satellite data is essential for taking the "pulse of the planet" and in recent years it has been helped scientists understand major climate shifts caused by greenhouse gas emissions.

Over the last few years, NASA has strengthened its ties with the NOAA to advance research into severe—but poorly understood—weather patterns. Last year, the space administration began testing a series of eight microsatellites that redirect GPS signals to track the evolution of hurricanes. The weather agency is also partnering with the RF industry to upgrade its systems. The National Severe Storms Laboratory, for instance, is building multi-function phased-array radars into a new weather surveillance system.

These efforts could assume a huge responsibility in the next few decades, when rapid changes in earth's climate could result in more unpredictable, erratic, and destructive weather patterns. Research from James D. Hensen, the retired NASA climate scientist and political activist, has recently argued that a period of extreme weather caused by climate change is only decades, not centuries, away.

The ATMS instruments will be placed on JPSS-3 and JPSS-4, the fourth and fifth satellites in the next generation of the JPSS constellation. An ATMS instrument is currently aboard the Suomi-NPP satellite, the first satellite that was launched as part of the new system. NOAA and NASA are planning to launch the second satellite, called JPSS-1, in early 2017. ■

WIRELESS CARRIERS STRETCH Toward 5G Digital Services

FROM AUGMENTED REALITY to industrial sensor networks, new digital services that could be possible with fifth-generation, or 5G, wireless technology was the overarching theme at Mobile World Congress in Barcelona last month. The keynotes from Mark Fields, chief executive of Ford, and Derek Aberle, president of Qualcomm, underlined the role of wireless networks in autonomous cars. And wireless carriers like AT&T and Verizon emphasized research into drones and data analysis.

Alex Jinsung Choi, chief technology officer of South Korea's SK Telecom, said that his company hopes to not only provide wireless service, but also develop digital and multimedia services. With higher throughput and other advanced features, 5G networks will function as an "infrastructure" for things like cloud computing and virtual reality. Partnering with Ericsson, the company has demonstrated a 3D hologram service that visualizes information about wireless networks in real-time.

(Image courtesy of Kārlis Dambrāns, Flickr)

These technologies have often been considered the territory of computing companies like Google and Amazon, but the line between them and wireless carriers are slowly blurring. AT&T, for instance, is training its workforce more in step with the demands of companies that gather and analyze data from its customers. On the other hand, Google is laying fiber-optic cables in cities and Amazon provides phone systems over the cloud.

Nevertheless, wireless carriers are in the unique position of being able to build wireless networks that lend themselves more to digital services. SK Telecom has demonstrated so-called "network slicing," which enables a single physical network into multiple virtual ones. These virtual networks can be distributed for different services—the low-power, low-bandwidth networks necessary for industrial sensors—to high-bandwidth connections for smartphones and tablets.

These concerns have not slowed advances into core 5G features. SK Telecom has partnered with Nokia Networks to demonstrate 20.5-Gb transmission speeds over the air. Both companies noted that 20.5 Gb/s was the target for 5G networks set by the International Telecommunication Union (ITU), the international standard bearer for wireless technology.

The companies had previously demonstrated speeds of 19.1 Gb/s using multiple-input multiple-output (MIMO) radios and 400 MHz of bandwidth. They wrung out more speed by adding data bits that prevent disturbances on wireless channels. SK Telecom had previously achieved 25 Gb/s in the laboratory with Ericsson in February, but this was the first test in real-world conditions.

At Mobile World Congress, SK Telecom also collaborated with Intel on a mobile platform that supports below-6-GHz frequency bands and above-6-GHz bands. The platform, which lays the groundwork for mobile phones that tap into everything from 2G to 5G, exhibited 1.5-Gb/s transmission speeds. SK Telecom worked with Samsung Electronics to demonstrate smooth millimeter-wave handovers.

5G wireless technology comes at an unusual time for wireless companies. The standards process has converged with a shift in how wireless carriers operate and where wireless chipmakers are selling their products. "Speed is not everything when it comes to 5G," said Choi. "5G cannot be achieved through the mere advancement of technology. Technologies, services, and the ecosystem must all work in concert and develop in lockstep." ■

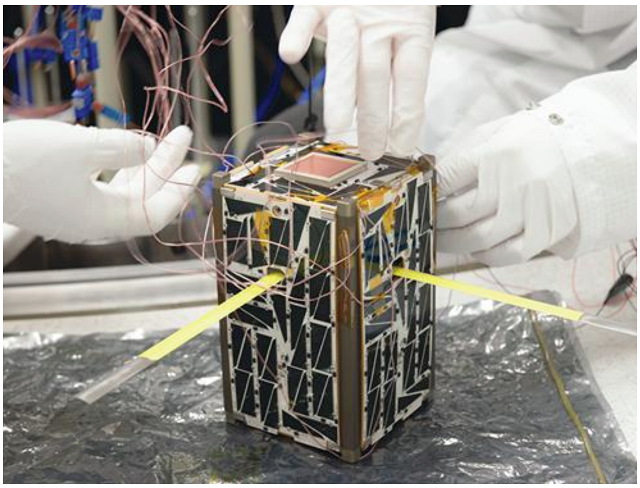
SMALL BROADBAND SATELLITES Pepper Low Earth Orbits

THE TIMES WHEN ROCKETS strained enormous broadband satellites into orbit are giving way to an era of miniaturization. Both commercial satellite companies and government agencies are now sending out smaller satellites, probes, and capsules that perform a narrow range of tasks and are cheaper to build.

The result is that during the next 20 years the majority of satellites scheduled for launch will be extremely small and placed in low-earth orbits, according to a report from aerospace research firm Teal Group. The report found that 5,095 payloads were scheduled to be built and launched between 2016 and 2035. More than four out of every five payloads will be positioned in low-earth orbits, carrying out tasks ranging from broadband and mobile communications to meteorological, imaging, and location services.

"It's going to get extremely crowded at low earth orbits," says Marco Caceres, senior space analyst at the Teal Group and author of the report. "During the 1990s, we started launching hundreds of mobile communications satellites to low earth orbits…but that's nothing compared to the potentially thousands of small low-earth-orbit broadband satellites aimed at expanding Internet connectivity worldwide."

For instance, Iridium Communications—which operates a constellation of 66 satellites in low earth orbit—is planning to launch new satellites to provide faster data coverage to satellite phones and integrated transceivers. The first 10 satellites in the Iridium Next constellation are scheduled for flights with SpaceX in late 2016. Iridium is also trying to expand service for customers using satellites for industrial sensor networks and the Internet of Things (IoT).



A tiny satellite is being built as part of NASA's Nodes project. Engineers are preparing the satellite for thermal vacuum testing at Ames Research Center in California. *(Image courtesy of NASA Ames)*

The report also says that around three-fifths of the payloads will be commercial equipment, while one-fifth will be government spacecraft.

Government agencies are also sending out small, low-cost satellites to perform a narrow range of simple research tasks. Next year, the National Aeronautics and Space Administration (NASA) plans to send eight microsatellites in low-earth orbit to monitor tropical storms, hurricanes, and typhoons throughout their lifecycle. Every year, the agency also sends out several tiny research satellites, or Cubesats, as auxiliary payloads on rockets carrying heavier cargo.

The smaller sizes and lower costs are making it easier to send satellites into orbit. The payload count for 2016 to 2035 reflects a 10% increase compared to the 4,607 payloads identified in 2015. It is also 36% and 38% higher than reports in 2013 and 2014, respectively. And yet the payloads built and launched over the next 20 years will total more than $245 billion.

About one-fifth of the satellites identified in the report are expected to be sent into deeper orbits. The next generation of Global Positioning System (GPS) satellites built by Lockheed Martin and commissioned by the United States Air Force could be launched into medium-earth orbits starting around 2017. Inmarsat, a satellite communications company, is planning to send new satellites into geostationary orbit to provide faster and more reliable television and mobile service. ■

LIQUID-COOLING SYSTEM BOOSTS Amplifier RF

AN ENGINEERING TEAM at Lockheed Martin has built an experimental cooling system that sprays tiny drops of water on the bottom of microchips, dissipating large amounts of heat that can hurt chip performance. In laboratory tests, the cold plate helped boost the RF output of power amplifiers six times higher than chips cooled with traditional heat sinks.

The new technology was designed to remove heat from the thousands of microchips contained in everything from radars to high-performance computers and data centers. Though the cold plate was designed to be general purpose, Lockheed Martin has targeted the project at gallium-nitride (GaN) power amplifiers, which are widely used in electronic-warfare (EW) and other military systems. Lower operating temperatures make these systems not only more powerful, but also vastly more efficient.

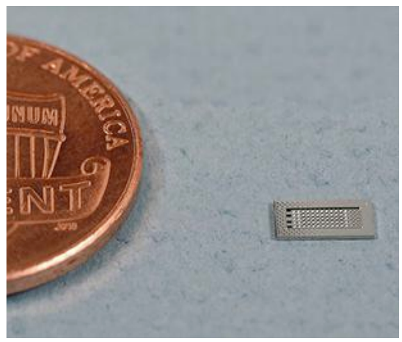
"Right now, we're limited in the power we can put into microchips," says John Ditri, the project's principal investigator. "If you can manage the heat, you can use fewer chips and that means using less material, which results in cost savings as well as reduced system size and weight. If you manage the heat and use the same number of chips, you'll get even greater performance."

Lockheed Martin notes that in recent demonstrations, its liquid-cooling system had vastly improved the thermal resistance of GaN monolithic microwave integrated circuits (MMICs). The company measured resistance four times higher than chips cooled with conventional, dry heat sinks. The cold plate dissipated 1,000 watts per square centimeter heat flex on the die. And in several local hot spots, it removed around 30,000 watts per square centimeter.

As computer processors and wireless amplifiers have grown more powerful, the microchips inside them have become smaller and more susceptible to heat build-up. That heat can impact chip performance and even raise the risk of failure. When your personal computer begins to overheat, for instance, you normally hear the fan underneath start whirring, and can notice a slight dip in the time it takes to load apps.

The most common way to remove heat from electronics is using fans or materials like copper that divert heat from the chip. The problem is that these heat sinks get larger as processors become more powerful, adding size and weight to the system.

But liquid-cooling systems are positioned closer to the chip than these more conventional heat sinks. Though these systems have long held promise, engineers have struggled to integrate practical designs into products. Lockheed Martin's cold plate was designed with that problem in mind. It measures a mere 250 µm thick, 5 mm long, and 2.5 mm wide.



Lockheed Martin's liquid-cooling system was designed to be a slight 250 µm thick, 5 mm long, and 2.5 mm wide. One of the major problems with conventional heat sinks is that they have to be enlarged as microchips get more powerful and susceptible to heat build-up. *(Image courtesy of Lockheed Martin)*

The cold plate was developed as part of the Interchip/Intrachip Enhanced Cooling (ICECool) program run by the U.S. Defense Advanced Research Projects Agency (DARPA). The program aims to bring liquid cooling right up against the chip, sending water through channels or pores etched into chip. ■

INTEL, AT&T Test Drones on LTE Network

THE REQUIREMENTS FOR fifth-generation (5G) wireless are forming around technologies that until recently have never been connected to cellular networks. That automobile companies like Porsche and Ford attended this year's Mobile World Congress in Barcelona signaled that wireless carriers had chosen new services over smartphones as the main target for 5G technology.

That was underlined again recently when Intel announced that it would cooperate with AT&T to test unmanned aerial vehicles (UAVs), or drones, using LTE networks. With the tests, both companies want to understand how reliable the high-speed wireless standard is for streaming live video and flight information—and in general, how it works with devices flying through the air.

"UAVs have great potential, from inspections [and] precision agriculture, to deliveries of consumer goods and providing emergency disaster relief," said Anil Nanduri, vice president of Intel's New Technology Group, in a statement. Their unique point of view has turned drones into a versatile tool for commercial companies like Skycatch, a startup that uses drones to map construction sites.

But once drones get out of range of Wi-Fi or radio signals, reliability becomes a serious concern—especially in situations like disaster relief or law enforcement. Both Intel and AT&T want to know whether the range and reliability of LTE can settle concerns like security, safety, and potential interference with manned aircraft.

Whether drones can access LTE networks will ultimately be subject to the approval of the Federal Communications Commission (FCC) and Federal Aviation Administration (FAA), both of which have enacted strict rules governing drone use. But successful tests could help ease concerns about autonomous drones employed for commercial uses, like Amazon's plans for a drone shipping service.

Intel has regarded drones as a symbol for the kind of technologies that will proliferate around 5G networks. Sensors, for instance, will be embedded in everything from cargo-ship containers to parking spaces in a garage, transmitting data and sending it wirelessly.

AT&T has started giving businesses access to services like managing and storing data gathered by drones. Also known as M2X, the platform also extends to the industrial Internet of Things (IIoT), wearables, and other industries that want automatic status reports on their equipment. AT&T is betting that 5G will make these kinds of services even more valuable. ■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• Cable Assemblies
• Attenuators / Terminations
CAPABILITIES:
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• Wedge dielectric interfaces to prevent multiplication
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TERAHERTZ SPECTROSCOPY TRACKS H_2O VAPOR TEMPERATURES

TERAHERTZ SIGNALS AND radiation (typically considered from 0.1 to 10.0 THz) may seem beyond the range of practical applications, but it has many uses for otherwise difficult measurements. For instance, when using the relatively "low" terahertz frequencies from 0.5 to 0.8 THz, terahertz spectroscopy systems can measure water (H_2O) vapor temperatures in power plants..

Researchers at the University of Toronto (Ontario, Canada) teamed with engineers at Betterfrost Technologies (also in Toronto) and Arrow Grand Technologies (Covina, Calif.) to demonstrate high-temperature measurements of the H_2O vapor volume mixing ratio (VMR) at three absorption peaks for comparison with computer simulations. Use of terahertz energy and terahertz spectroscopy makes it possible to perform direct measurements of H_2O vapor temperatures without sample preparation, and to differentiate those measurements from ambient room-temperature water vapor.

The spectrometer test system includes a tunable continuous-wave terahertz source and analyzer, gas cell, heating system, and purging system. Tunable frequency ranges from 0.1 to 1.8 THz with frequency resolution of 100 MHz. Data are collected at a scanning step of 1 GHz. Emitted terahertz waves propagate through the gas cell and are detected by a terahertz receiver. The gas cell is enclosed in an air-tight chamber to eliminate ambient water vapor. See "High-Temperature H_2O Vapor Measurement Using Terahertz Spectroscopy for Industrial Furnace Applications," *IEEE Transactions on Terahertz Science and Technology*, Vol. 6, No. 1, January 2016, p. 26.

WEARABLE ANTENNAS WORK AT VHF AND UHF

WEARABLE ANTENNAS WERE once considered a novelty. But now, with more wireless sensors finding their way into Internet of Things applications, they are increasingly necessary. Professors from the University of Pisa (Italy) and the University of Ghent (Belgium) explored the materials and design configurations needed to use wearable antennas at VHF and UHF bands.

The research team points out that conventional VHF antennas are somewhat bulky and require miniaturization techniques to adapt them at VHF and UHF bands for use in wearables. The design should also consider the postures and movements of the wearer and how they will affect the radiation pattern and impedance of the wearable antenna.

To minimize the effects of mismatches due to body movements, many body-worn antennas are designed with broadband responses to overcome dielectric-constant effects of skin and muscle tissue on antenna patterns and responses. Several successful instances of helmet-worn antennas at VHF and UHF for public-safety professionals were detailed.

Much of the team's research focused on designing wideband antennas at VHF and UHF that are compact enough to be wearable, when compared to average human body size, without sacrificing electrical performance. One example is a vest-worn, flexible double-loop for use in the 30- to 80-MHz VHF range.

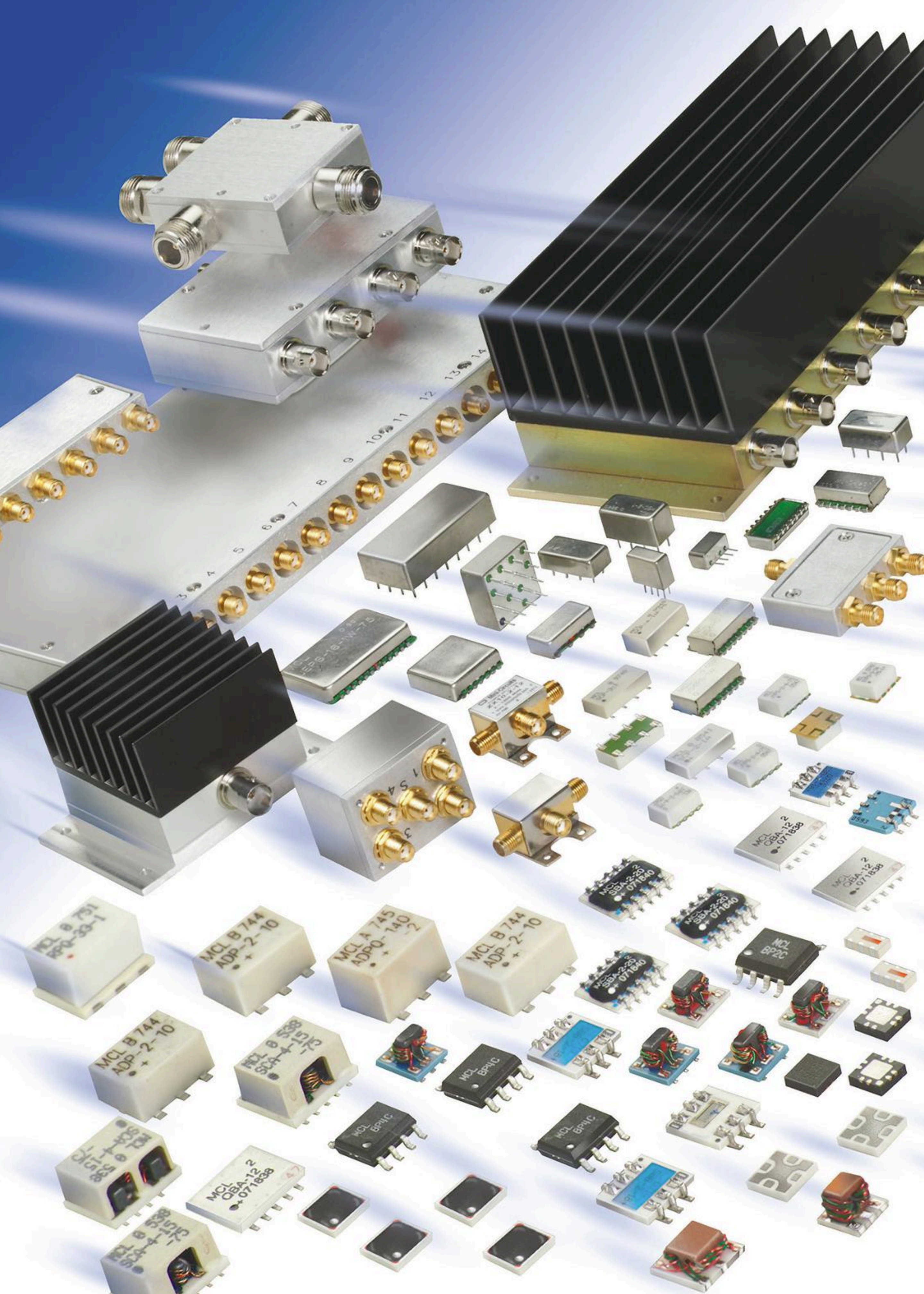
Other efforts involved wearable antennas for radio-frequency-identification (RFID) applications at UHF from 840 to 960 MHz, and how the RFID tags can be made with antennas small enough to be worn unobtrusively on wrists or over different clothing. See "Wearable Antennas for Off-Body Radio Links at VHF and UHF Bands," *IEEE Antennas & Propagation Magazine*, October 2015, p. 30.

SEEKING MM-WAVE ANTENNAS FOR RFID TAGS

ONE APPLICATION PROJECTED to move higher in frequency—radio-frequency-identification (RFID) tags—may fit numerous applications at millimeter-wave frequencies. First, though, compact RFID reader antennas with high axial ratios and fan-shaped radiation patterns need to be developed for use at frequencies between 57 and 64 GHz. In pursuit of such RFID antennas, a team from Monash University (Clayton, Australia) investigated the design of compact array antennas for use with chipless RFID tags.

The researchers considered the effects of different structural configurations as well as different substrate materials (including properties such as relative dielectric constant and substrate thickness) on the size and performance of various antenna designs with wide bandwidths at 60 GHz. Their candidate antennas were double-sided, printed-dipole (DSPD) antennas, which yielded wider bandwidths compared to the single-sided printed-dipole types

Commercial electromagnetic (EM) simulation software was used to refine the mechanical dimensions of the antennas and optimize performance prior to actually fabricating an antenna. In addition to the mechanical dimensions of the dipole antenna array, the design of the feeding network is critical to achieving the performance needed for the RFID reader application. It led to the development of a feedline extension using standard printed-circuit-board (PCB) substrate materials. See "Chipless RFID Reader," *IEEE Antennas & Propagation Magazine*, October 2015, p. 18.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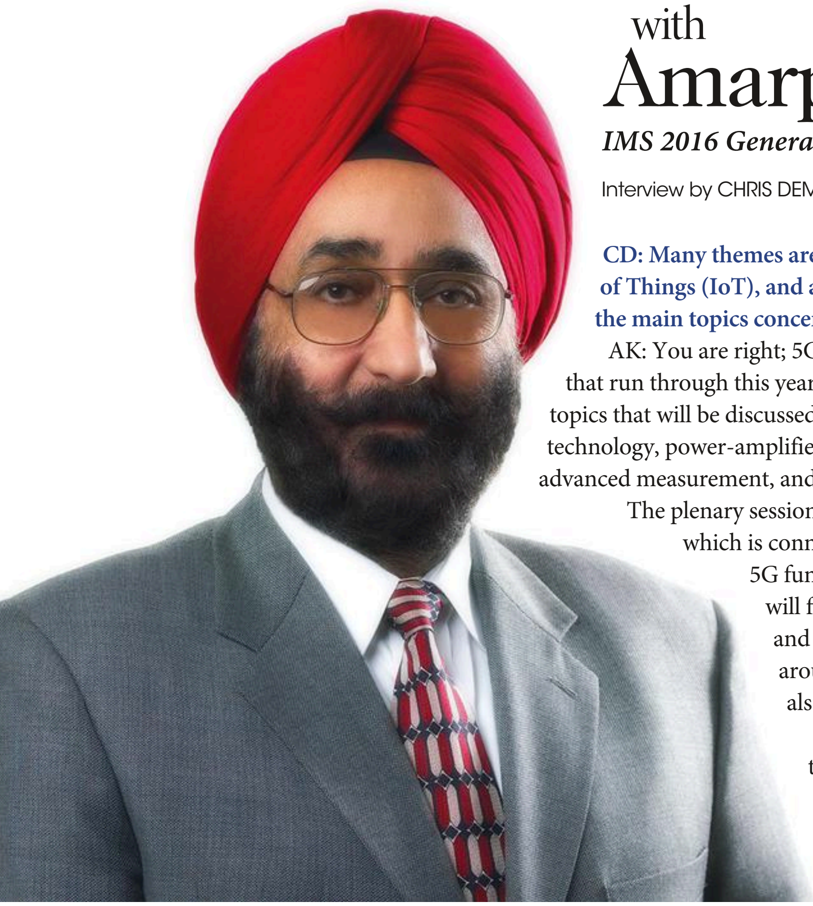
Inside TRACK with Amarpal Khanna, IMS 2016 General Chair



Interview by CHRIS DEMARTINO

CD: Many themes are associated with IMS 2016, such as 5G, the Internet of Things (IoT), and automotive radar, among others. What are some of the main topics concerning these themes that you believe will be discussed?

AK: You are right; 5G, IoT, and automotive radar are some of the themes that run through this year's IMS presentations and discussions. Related main topics that will be discussed concerning these themes include millimeter-wave technology, power-amplifier designs, multi-band radio and synthesizer designs, advanced measurement, and IC technologies.

The plenary session on Monday is about the future of smartphones, which is connecting us with IoT and is expected to provide us with 5G functionality in five years. Closing ceremony keynotes will focus on the role of software 5G microwave systems and evolution of IoT and wearable devices in, on, and around the human body. Out of 36 workshops and tutorials, a large number is related to these themes.

A tutorial on 5G technologies and a workshop on automotive radar for autonomous vehicles are designed to bring the attendees up to speed rapidly. Many other networking and discussion events will center on these themes. A good number of technical paper sessions are also related to these hot topics.

"With an antenna and sensors on every consumer and industrial device, the opportunities to improve our lives and businesses are endless."

CD: You have been a part of the RF/microwave industry for many years. Did you ever imagine that wireless communications would be as deep-rooted in our lives as it is today?

AK: Not really. It is true that I have watched the RF/microwave industry since the early '70s, and at the beginning of my career this technology use was really focused on military and aerospace applications. Satellite communications was one of the first applications that impacted our lives by providing a reliable means of long-range communications. Today's smartphone is obviously a lot more than a phone. The combination of Wi-Fi, GPS, RFID, NFC, Bluetooth, wireless charging, and millions of apps has made the smartphone a "superman" of gadgets, and this was hard to imagine even in fiction in the '70s.

Today we enjoy smart watches, wireless-controlled home thermostats, home lights, wireless key and phone finders, wearable health monitors, Bluetooth-enabled hearing aids, wireless monitored homes, cars, etc. With the emerging advances in IoT, 5G, and automotive applications, the interesting thing is that we are essentially only in the beginning stages at this point.

CD: What do you think are some of the most notable technological advances we have seen in the last 10 years?

AK: Number one for me is the smartphone for its wide-ranging capabilities to handle voice, data, and video in a user-friendly way. It is literally a computer in your pocket. The millions of apps on smartphones seem to be keeping the world dancing on its little fingers. Today there are 2 billion smartphones throughout the world, and that number is expected to grow rapidly for the foreseeable future. Other notable technological advances, as I see, include:

- The transition to digital TV, which is enabling high-definition TV in homes;
- Massive MIMO and the modern OFDM-modulation schemes for allowing non point-to-point communications, including enabling robust Wi-Fi;
- GPS for numerous consumer applications. My favorites are precision location finding and real-time traffic information;
- Bluetooth and NFC for short-range communications;
- Advances in sensor technology, which is a key enabler for IoT revolution;
- Wireless charging; and
- The fast-growing technological advance: electric vehicles with driver-assist features.

Let us not underestimate the significance of software's role in all of these applications. Developments in the software field are enabling newer applications every day.

CD: Millimeter-wave technology has become more of a focus now. What applications do you believe will benefit the most as a result of utilizing these higher frequencies?

AK: Millimeter-wave technology has finally found its place in the commercial and consumer world. This technology offers large bandwidth, ease of frequency use, smaller size, and reduced interference. Even though millimeter-waves theoretically cover 30 to 300 GHz, the present focus is limited from 28 to 86 GHz, as benefiting most applications in the near future. These frequency ranges were once considered too exotic for commercial use. Today, the wireless world is becoming millimeter-wave-centric. At this point, we are looking at four major applications of this technology, which in the order of priority as I see it, are:

- Next-generation Wi-Fi based on IEEE 802.11ad, using the license-free band of 57 GHz to 67 GHz;
- 5G access for high-speed data using smartphones at potential frequencies of 28 GHz, 38 GHz, and 71 GHz to 76 GHz;
- Automotive radars for adaptive cruise control and auto-braking using frequencies in the 76 GHz to 81 GHz range; and
- Short-range, low-cost, high-speed point-to-point data links around 60 GHz, 73 GHz, and 83 GHz.

CD: The IoT continues to be a major talking point. How do you see it taking form in the near future?

AK: In five short years, it is anticipated that connectivity across devices, or "Things," and the expansion of wearables and nearables will disrupt a number of consumer and industrial markets. Presently, there are about 2 billion connected devices, and are expected to cross 50 billion in five years. The impact we already see today in smart homes will be seen repeating in home entertainment, healthcare and insurance industries, agriculture, and manufacturing. The requirements to make 5G and IoT a commercial success are very demanding, while the potential and opportunities are huge.

IoT, in fact, is converting "Things" to "Smart Things." Increased information bandwidth and faster response times with minimal power consumption are challenging all engineers, from semiconductor technology to infrastructure. Explosion of connected devices is a sure thing. With an antenna and sensors on every consumer and industrial device, the opportunities to improve our lives and businesses are endless.

But, this revolution will only happen if it can be done reliably and economically, and a big part of that challenge is keeping the cost of not only devices, but also the test solutions, low. Among the serious challenges, I find a lot of work still needs to be done to handle privacy and security issues. We are still in the early stages and these issues should be easier to deal with now than years later. I am also concerned that some of us may not feel comfortable to be a part of a persistent and perpetual connection to all "Things" like a node on the IoT network.

CD: Do you think the industry is doing enough to encourage young people to pursue engineering?

AK: No, I think the industry needs to wake up and set aside a budget for this purpose. Recently, efforts like STEM are stepping in, but schools are still operating in the past. Some countries are better than others, and we can learn from each other. However, due to the lack of engineering infrastructure and focus, young people in most countries—including the United States—are being lured by non-engineering fields. There is a need to develop courses using modern tools to make it easier for students. Particularly, in the RF/microwave field, it is not uncommon for students to switch to other subjects when they are exposed to electromagnetics and Maxwell's equations. In light of this, IMS is paying special attention to the needs of students, and a number of programs and events are being held to inspire and guide students at various levels, from middle school to graduate students as well as young professionals. mw

CHRIS DeMARTINO | Technical Editor

Welcome to IMS2016

Microwave Week comes to San Francisco this year, showcasing the very best of the RF/microwave industry.

This year's Microwave Week is set to take place May 22-27 at the Moscone Center in downtown San Francisco. The IEEE International Microwave Symposium (IMS) is clearly the main spectacle, as the flagship event of the RF/microwave industry each year. Attendees will be able to learn about a vast number of topics concerning RF/microwave technology.

In addition, the IMS exhibition will have over 600 participating companies, including 67 first-timers. Microwave Week also consists of the IEEE Radio Frequency Integrated Circuits (RFIC) Symposium and the 87th Automated RF Techniques Group (ARFTG) conference, which are both co-located with IMS.

IMS will offer technical sessions, interactive forums, panel sessions, workshops, short courses, and application seminars. A number of STEM activities are planned for the event, allowing young people to gain access to the RF/microwave world. The RF Bootcamp, which is a 3/4-day course for newcomers to the microwave arena, will be held on Wednesday, May 25. A variety of topics will be discussed during this workshop, with the goal of providing the basics of RF to those who attend.

MESSAGE FROM THE GENERAL CHAIR

According to Amarpal Khanna, who is the IMS 2016 general chair, a large number of themes will be discussed at IMS. Topics include 5G, automotive radar, wearable electronics, the Internet of Things (IoT), wireless high-definition multimedia interface (HDMI), medical applications, and satellite communications (satcom). The themes will be discussed during keynote talks, panel sessions, and technical presentations—beginning with the opening plenary session on Monday and running until the closing ceremony on Thursday.

KEYNOTE SPEAKERS

This year's keynote speakers are Dr. Martin Cooper, Dr. James Truchard, and Prof. Jan M. Rabaey. Dr. Cooper will present the plenary session, "The Birth and Death of the Cell Phone." He

San Francisco's famed Moscone Center will be home to this year's Microwave Week, which includes the IEEE International Microwave Symposium. *(Courtesy of Moscone.com)*

is recognized for leading the development of the first handheld mobile telephone, which was introduced in 1973. Expect plenty of insight into the future of wireless technology in this session.

Truchard will present the closing address, "Software's Role in Next-Generation 5G RF and Microwave Systems." This discussion will explore the vital role of a software-based approach to enable wireless communications. For those interested in a possible sneak-peek at next-generation RF/microwave systems, this presentation is a must.

EXHIBITION

Of course, the exhibition is always a very exciting part of the IMS experience. Over 600 companies will be exhibiting this year, showcasing the latest and greatest state-of-the-art technology. Everything from materials, devices, components, subsystems, design/simulation software, and test-and-measurement equipment will be on display. Industry leaders will be ready and willing to answer any purchasing and technical questions.

Microwave application seminars, or MicroApps, will be conducted in conjunction with the exhibition. These 20-minute technical seminars give IMS exhibitors the opportunity to present the technology behind their products. A large number of state-of-the-art products and processes will be discussed by various industry professionals.

STUDENTS AND YOUNG PROFESSIONALS

IMS will also include a number of events for both students and young professionals. Student design competitions will allow registered student teams from around the world to apply RF/microwave engineering design principles. Students have the opportunity to present their own work in competition. Young professionals will also be represented at IMS, notably at this year's special session and complimentary reception.

IEEE RFIC SYMPOSIUM AND ARFTG CONFERENCE

Both the IEEE RFIC Symposium and the ARFTG conference will be co-located with IMS. These two events have a great deal to offer attendees, including technical sessions, workshops, and much more.

The RFIC Symposium will demonstrate some of the latest developments in RF, microwave, and millimeter-wave integrated-circuit (IC) technology and innovation. The symposium begins Sunday, May 22, with workshops and short courses. These will be followed up with two plenary talks and a reception. On May 23 and 24, there will be presentations of contributed papers, in addition to lunchtime panel sessions.

The 87th ARFTG conference, "Measurements for Emerging Communications Technologies," will take place May 27, with a range of topics related to RF/microwave test-and-measurement on tap.

Enjoy the show!

The iconic Golden Gate Bridge will welcome visitors from all over the world to this year's IMS.

(Courtesy of Thinkstock.com)

Interview with SHERRY HESS

For Women, the Industry Presents New Opportunity

Interview by CHRIS DeMARTINO | Technical Editor

At IMS 2016, Women in Microwaves (WIM) will be presenting a panel session that focuses on leadership. Sherry Hess, who is widely known for her contributions to the RF/microwave industry, spoke to *Microwaves & RF* about diversity in the RF/microwave industry. Sherry is vice president of marketing at National Instruments, AWR Group.

The RF/microwave industry here in the U.S. is obviously a male-dominated arena. Do you think the industry is doing its part to encourage women to enter the field?

Nearly a year ago now, I had the chance to attend the WIE (Women in Engineering) Leadership Conference that was held in Silicon Valley. Intel CEO Brian Krzanich restated his "Diversity Challenge" to his company, which stated that Intel would reach full representation by 2020.

While I've not seen a firm in our own microwave space issue a similar challenge, I do know that our own IEEE MTT society is actively seeking to improve diversity and taking direct action to embrace and grow female representation within our society.

To be specific, over the past few years our Women in Microwaves group, a subset of IEEE Women in Engineering (WIE), has grown and expanded its footprint to include activities at IEEE-sponsored conferences worldwide. For the first time last year at IMS, the traditional WIM networking cocktail party was expanded to include an all-female track on the topic of 5G, as well as a panel discussion on "Diversity in Microwaves."

This is clearly a start at placing a spotlight on the women in our industry, and hopefully encouraging networking and support among us all so that we can inspire and attract more women into technical professions—in particular our RF/microwave industry.

How do you think that diversity can benefit the RF/microwave industry?

Many sources say diversity is good for business. One that I've cited prior is *The New York Times* "Women at Work" series, written by Facebook COO Sheryl Sandberg and University of Pennsylvania Wharton School Professor Adam Grant. This article cites research that shows women bring different knowledge, skills, and networks to the table. It further states that raising women's participation in the workforce to the same level as men could raise the GDP by 5% in the U.S. and 9% in Japan.

Intel's Krzanich says data suggests that best-in-class companies with the highest level of racial diversity generate 15 times more sales that those with the lowest levels. Diversity in the work force is not just a matter of fairness: Diversity is good for business. As such, it is a vital part of the future success of our high-tech industry.

With technology playing such a major role in our lives, do you think this will lead to girls gaining an interest in STEM at an earlier age?

Absolutely. The key is for girls to believe that STEM careers are cool and exciting, and solve real-world life problems. We need to lose the stigma that being smart is a synonym for "nerd" or "geek." I do see great strides toward doing this across industry, academia, and even social media in recent years.

One data point is back in 2013, when I remember watching (and loathing) the Teen Choice Awards with my daughter. But in the end I was stunned and excited when Ashton Kutcher made his now famous speech about "the sexiest thing in the world is being really smart…" This is exactly what young people contemplating a future in STEM need to hear, and especially those thinking about RF/microwave engineering.

My own theory is that in order to encourage more young minds to become engineers and scientists, we need to work toward inspiring them (here both men and women can help) through a concerted communications program to foster awareness and camaraderie, as well as focus on programs that tap into the "wonderment" of our career choice. If you've not yet heard of Makerspace, check it out (makerspace.com). It is an active program doing exactly this…adding "wonderment" into young people in elementary schools and beyond.

Why would you personally recommend a career in the RF/microwave industry to a young woman?

When I am asked what I do for a living, I say "my company makes the products that allow you to use all the wireless gadgets you love." This is true, and I find being in the forefront of technology both exciting and fulfilling. Does this speak more to women vs. men? I'm not sure. But if being able to see the output of your efforts in the real world and its importance in shaping the future of our "connected lives" matters to anyone reading this, then a career in the RF/microwave industry is a great choice for you. mw

JACK BROWNE | Technical Contributor

Previewing the Parade of Products Invading IMS 2016

A large portion of a small industry is set to show its hardware, software, and test equipment at this year's IMS exhibition in San Francisco's Moscone Center.

THOUSANDS OF ENGINEERS from the RF/microwave industry will once again gather at this year's *IEEE's annual International Microwave Symposium (IMS) and Exhibition.* They get to indulge in a healthy diet of high-frequency technology on the symposium side and a broad range of products on the exhibition side, from the smallest semiconductors and integrated circuits (ICs) to complete systems and test instruments. It offers a chance for designers to complete a bill of materials (BOM) for a new circuit, or track down the test equipment needed for the new wing of a manufacturing facility—or to simply catch up with old friends and competitors.

The IMS 2016 Exhibition is scheduled for May 24-26, 2016 in the Moscone Center, San Francisco, Calif. *(Go to www.ims2016.org for a complete exhibitors' list and exhibition floor plan.)* Over 600 companies are planning to exhibit, providing visitors with a chance to "wander the aisles" in search of a particular product or browse and learn about the latest product offerings from this diverse group of electronic hardware and software manufacturers. Attendees can compare products and performance levels in real time, without a computer or the Internet, moving from booth to booth and meeting representatives from each company in quest of a spectrum analyzer with a particular frequency range and analysis bandwidth, or an oscillator with unbeatably low phase noise.

For example, want to know more about the latest gallium-nitride (GaN) discrete transistors or ICs? Numerous suppliers will be available to discuss the merits of this popular high-frequency, high-power semiconductor technology, and vendors will be on hand to compare power amplifiers (PAs) and offer details about their own GaN products *(see p. 133 for more on GaN and p. 139 for more on new GaN products from* **QORVO**, *Booth 839, www.qorvo.com)*. Similarly, for a hands-on demonstration of the versatile new Universal Serial Bus (USB) spectrum analyzers from **TEKTRONIX** (www.tektronix.com, *see p. 128)*, time at Booth 2449 will be well spent.

Many manufacturers use the annual IMS Exhibition as a launching point for a new product. For instance, **KEYSIGHT TECHNOLOGIES** (Booth 1239, www.keysight.com), which earlier in the year had expanded its UXA series of signal analyzers for coverage from 3 Hz to 50 GHz *(see Microwaves & RF, March 2016, p. 64)*, plans to introduce an innovative new family of device current analyzers—the company's first such product line *(see "Analyzers Measure Device Microcurrents," p. 46)*.

TEST MEASURES UP AT IMS

The exhibition will be a showcase for many of this industry's leading test-and-measurement equipment developers. **ANRITSU CO.** (Booth 949, www.anritsu.com) tackles remote spectrum monitoring with a family of portable, modular spectrum analyzers, including the model MS27101A *(Fig. 1)*. The instruments are very much the image of modern high-frequency test equipment, in compact, modular form, working with optional Vision software on a Windows-compatible PC and the computer's display screen via a USB connection. It integrates a web server that allows access anywhere in the world via Internet browser for truly remote, off-site monitoring.

They can be used to find and identify interference signals. Given the growth of wireless services, including the growing wave of Internet of Things (IoT) devices in the vicinity of wireless networks, remote spectrum monitoring helps locate unlicensed or interfering signals at sweep rates to 24 GHz/s. The IP67-rated instrument operates on 11 W of power, enabling it to be powered by solar cells in remote applications. Three or more units can be used together to triangulate the location of an interference signal.

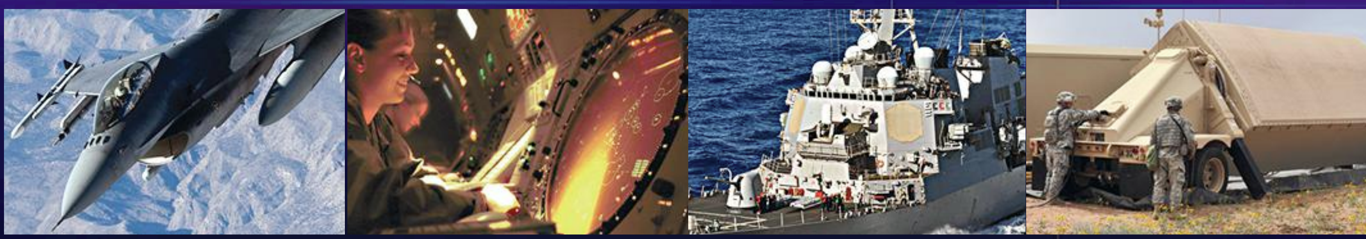
1. A growing number of test instruments are becoming modular, such as this portable USB spectrum analyzer designed for use with a portable computer for remote spectrum monitoring. *(Courtesy of Anritsu Co.)*

Conference Hotel Locations

1. **W San Francisco Hotel** - *181 3rd St.*
2. **San Francisci Marriot Marquis (HQ)** - *780 Mission St.*
3. **The Mosser Hotel** - *54 4th St.*
4. **Palace Hotel** - *2 New Montgomery St.*
5. **Hotel Zelos** - *12 4th St.*
6. **Pickwick Hotel** - *85 5th St.*
7. **Abri Hotel** - *127 Ellis St.*
8. **King George** - *334 Mason St.*
9. **Handlery Union Square Hotel** - *351 Geary St.*
10. **Parc55 A Hilton Hotel** - *55 Cyril Magnin St.*
11. **Hotel Nikko** - *222 Mason St.*
12. **Hilton Union Square** - *333 O'Farrel St.*
13. **Sir Francis Drake** - *450 Powell St.*
14. **Hotel Griffon** - *155 Steuart St.*
15. **Hotel Zeppelin** - *545 Post St.*
16. **Hilton Financial District Hotel** - *750 Kearney St.*
17. **Hotel Triton** - *342 Grant Ave.*
18. **InterContinental Mark Hopkins Hotel** - *999 California St.*

Enabling wideband frequency agility

GaN and GaAs Solid-State Power Amplifiers for Multi-Function, Radar and EW System Design



Whether your application is narrowband, wideband or ultra-wideband, operating in pulsed or CW mode, CTT's power amplifiers are an especially attractive choice for new multi-function frequency-agile systems that effectively conserve weight, space and power consumption.

The characteristics of the portion of the electromagnetic spectrum selected for any of these particular system designs are undoubtably the most important to the end user, as it has the greatest impact on the type of information required and received.

Engineered specifically to meet the stringent requirements imposed by many modern system designs, CTT's family of GaN and GaAs-based solid-state power amplifiers excel in a wide range of applications.

CTT has delivered production quantities of amplifiers with power levels from 10 through 200 Watts – and higher – for a variety of multi-function, radar and EW applications.

- AMDR
- Shipboard Radar
- AESA Radar
- VLO/FLO Threats
- New Land Radar
- EW
- UAVs

More than thirty years ago CTT, Inc. made a strong commitment to serve the defense electronics market with a simple goal: quality, performance, reliability, service and on-time delivery of our products.

Give us a call to find out how our commitment can support your success.

It's that simple.

Microwave Technology Leadership

- ❖ **Power Amplifiers**
  - **NEW GaN and GaAs Models**
  - Radar Bands up to 400W
  - EW Bands up to 200W
  - Pulse and CW
  - Solid-State Microwave Power Modules
  - Rack-Mount Configurations
- ❖ **Low-Noise Amplifiers**
- ❖ **Up and Downconverters**
- ❖ **Subsystems**
- ❖ **Custom Engineered Options**

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BOONTON ELECTRONICS (Booth 1830, www.boonton.com) will show its RF power meters/sensors and modulation analyzers, including the completely redesigned model 4500B peak power analyzer. It works with different sensors for peak power measurements from 1 MHz to 40 GHz. Depending on the choice of sensor, the 4500B can deliver a 70-dB power measurement range, reading pulsed signal levels from –50 to +20 dBm and modulated signal levels from –60 to +20 dBm.

2. The measurement power of this 20-Gsample/s oscilloscope can be harnessed with the control provided by a capacitive touchscreen. *(Courtesy of Rohde & Schwarz)*

The analyzer provides a video bandwidth of 65 MHz with better than 7-ns risetime. It can measure the power levels of pulses as narrow as 6 ns and at pulse repetition frequencies (PRFs) to 50 MHz. And to view the statistical analysis, a 8.4-in. thin-film-transistor (TFT) color liquid-crystal-display (LCD) screen shows as many as four measurement channels, two memory channels, and one math channel simultaneously.

MAURY MICROWAVE CORP. (Booth 1139, www.maurymw.com) provides high-accuracy hardware and software tools for performing various noise-parameter and load-pull measurements through microwave and millimeter-wave frequencies. For example, the firm's MT97x and MT98x series automated impedance and load-pull tuners, respectively, are based on slide-screw designs. With that design, they can position a slab-line transmission structure so that it will precisely match a device under test (DUT) to a terminal impedance. These tuners have long been essential tools in measuring and modeling active devices, especially for optimum performance at high-power and low-noise-figure levels. The firm also offers a series of software tools for the automated control of these PC-based tuners.

NATIONAL INSTRUMENTS (Booth 1529, www.ni.com), in addition to demonstrating its popular LabVIEW test software, will showcase many of its modular test instruments, including power meters, signal generators, vector network analyzers, and vector signal analyzers (VSAs). These feature PXI Express (PXIe) modules operating from 20 Hz to as high as 26.5 GHz, and instantaneous bandwidths as wide as 320 MHz for frequencies to 3.6 GHz and to 765 MHz for frequencies above 3.6 GHz.

Specifically, the NI PXIe-5668R combination VSA and spectrum analyzer is available in versions operating from 20 Hz to 14.0 or 26.5 GHz with 765-MHz analysis bandwidth. It features –129 dBc/Hz phase noise offset 10 kHz from an 800-MHz carrier and –168 dBm/Hz average noise floor at 1 GHz. The instrument digitizes input signals at 2 Gsamples/s and 12-b resolution.

ROHDE & SCHWARZ (Booth 1827, www.rohde-schwarz.com) will also exhibit its radio-monitoring test gear, including the R&S UMS12-OEM Monitoring System, a modular test system capable of monitoring signals from 100 kHz to 6 GHz. The system, which can be powered by ac or dc sources, will integrate into vehicular test systems for mobile spectrum monitoring and interference direction finding. It employs an open programming interface for operating flexibility, and is ruggedly constructed for use in outdoor environments. The system, which includes AM and FM demodulators, offers 1-Hz tuning resolution and two female Type-N connector input ports for antennas.

Furthermore, the firm will show its latest high-performance oscilloscope—the model RTO2000 laboratory scope *(Fig. 2)*—that's able to display correlations between time and frequency via analog input channels and advanced digital signal processing. A new zone trigger permits graphical separation of events in the time and frequency domains, defining as many as eight zones on screen and activating a trigger signal when a signal either does or does not intersect the zone. This can greatly simplify the most challenging measurements, such as searching for EMI disturbances in a circuit.

3. These programmable USB attenuators are handy "add-on" components for test systems operating to 20 GHz. *(Courtesy of Vaunix Technology Corp.)*

The instrument captures 1 million waveforms per second and operates at rates to 20 Gsamples/s with as much as 16-b vertical resolution to capture the most intermittent signals for display on a 12.1-in. capacitive touchscreen. Users can view all saved signals and analyze them with tools such as zoom, measurement, math, and spectrum-analysis functions. The oscilloscope comes in two- and four-channel versions with bandwidths of 0.6, 1.0, 2.0, 3.0, and 4.0 GHz.

ROOS INSTRUMENTS (Booth 2452, www.roos.com) will display examples of its automatic-test-equipment (ATE) hardware and software, including its Cassini configurable instrument system with its capability of holding multiple instruments and measurement functions in a tight space. The ATE system is available for a number of different test applications, including for characterizing power amplifiers, 3G cellular devices, base stations, backhaul equipment, and even devices for millimeter-wave automotive radar systems. For example, the automotive test system is available for testing at 40 and 77 GHz with full S-parameter coverage and for automated testing of parameters like fixed output power, leakage current, and third-order intermodulation (IM3).

TELEDYNE LECROY (Booth 1739, www.teledynelecroy.com), just one of a number of Teledyne companies at IMS, will exhibit its high-performance LabMaster 10-100Zi 100-GHz-bandwidth oscilloscope. With a 240-Gsamples/s real-time sampling rate, the instrument is able to detect short-duration transient signal events occurring over extremely wide bandwidths from 20 to 100 GHz.

4. This C-band frequency synthesizer achieves low phase noise when working with an external reference. *(Courtesy of Z-Communications)*

AN ACCESSORY TO TEST

In addition to the many attention-grabbing test instruments at IMS 2016, the exhibition floor will include a generous sampling of test accessories for making RF/microwave measurements, including the "Lab Brick" line of programmable attenuators from **VAUNIX TECHNOLOGY CORP.** (Booth 523, www.vaunix.com). The model LDA-023 programmable attenuator *(Fig. 3)* will target applications from dc to 20 GHz. Supplied with graphical-user-interface (GUI) to run on a PC or in a system with a self-powered USB hub, the attenuator's range spans 0 to 63 dB, controllable in 0.5-dB steps. With a response time of 100 ns, very little time will be wasted changing signal power levels in a test system.

AR RF/MICROWAVE INSTRUMENTATION (Booth 1711, www.ar-worldwide.com) will display some of its high-power amplifiers for assisting with EMC/EMI testing, including the classic 16,000A225. This self-contained, solid-state amplifier, which pumps out 16,000 W CW power from 10 kHz to 225 MHz, uses liquid cooling to dissipate heat from the active devices and maintain long-term reliability. The amplifier can be controlled locally or under remote GPIB or RS-232 control for use in ATE systems.

Featuring one of the more diverse product lines in the industry, **MINI-CIRCUITS** (Booth 2029, www.minicircuits.com), will show a cross-section of its wares at 2016 IMS. The PMA3-83LN+ low-noise amplifier (LNA), for instance, has a noise figure of 2 dB or less from 0.5 to 8.0 GHz, and provides generous 21-dB gain within a 3.00- × 3.00- × 0.89-mm, 12-lead MCLP.

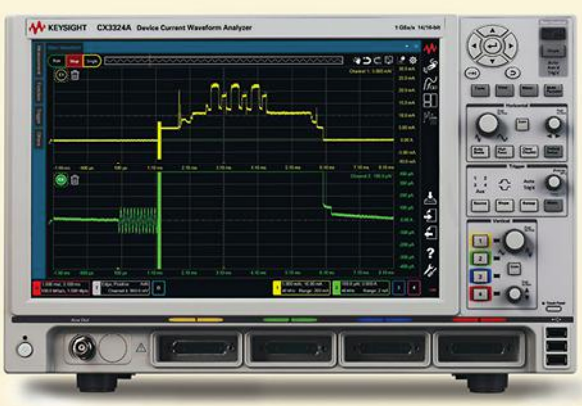
Mini-Circuits will also display larger components for test-and-measurement applications, including programmable attenuators that handle 1 MHz to 8 GHz. Ideal for use in path-fade simulators and ATE systems, the attenuators provide values from 0 to 120 dB in 0.25-dB steps under computer control

ANALYZERS MEASURE DEVICE MICROCURRENTS

VISITORS TO THE KEYSIGHT TECHNOLOGIES booth (Booth 1239, www.keysight.com) at the 2016 IMS Exhibition will see an impressive array of high-frequency test instruments. However, they will also come upon something never seen before: the Keysight CX3300 Series of device current waveform analyzers.

For the instrument maker, this new category of analyzer has never before been available. The instruments provide transient current measurements at extremely low levels—100 pA and less across maximum analysis bandwidths of 200 MHz. Device designers and researchers will embrace these new analyzers for their ability to provide accurate analysis of semiconductor device behavior in quest of improved performance, including reduced power/current consumption in low-power devices.

Existing measurement tools are challenged to detect low levels of dynamic device current (below 1 μA) due to limited bandwidths and dynamic ranges. The CX3300 Series of device current waveform analyzers *(see figure)* captures input current information at a sampling rate of 1 Gsample/s with 14- or 16-b resolution.



In fact, a single instrument is able to simultaneously measure wideband and low-level current waveforms, as well as provide advanced signal analysis, via an intuitive graphical user interface (GUI). All of the functionality is visible on a 14.1-in. multi-touch display screen.

The CX3300 analyzer can measure transient current even at pulse durations as short as 100 ns or less. Masaki Yamamoto, general manager of Keysight's Wafer Test Solutions in Industrial Solutions Group, says, "The CX3300, with its ability to measure wideband and low-level dynamic current, represents a significant breakthrough in meeting our customers' needs. In addition to complementing the existing Keysight instrument portfolio, the new analyzer provides our customers with a more complete solution for device analysis."

Visitors to the Keysight Technologies booth at IMS can see a demonstration of the new analyzers and learn more about the different current probes available for use with them. (Note: Don't miss the next issue of *Microwaves & RF* for the full-length review of the new CX3300 Series analyzer.)

using RS-232, Ethernet, or USB interface.

The firm will also show its lines of USB- and Ethernet-controlled synthesized signal generators for use from 0.25 MHz to 6.4 GHz. These compact, modular test signal sources include the model SSG-6400HS with frequency range from 0.25 to 6400 MHz and output-power range of –75 to +10 dBm.

In addition, Mini-Circuits will spotlight its growing numbers of test products, including the ZTM Series of modular test systems that fit different function modules into a 19-in. rack-mount chassis. These are typically analog signal-processing functions, such as switches and attenuators that can operate under USB or Ethernet control. Test functions include switches to 18 GHz qualified to 100 million switching operations.

L3 NARDA-MITEQ (Booth 1811, www.miteq.com), which represents the joining of two of the industry's most long-running and influential companies, will showcase its many active and passive component solutions. They include the recently introduced model 4792 variable attenuator for applications from 8 to 18 GHz. Part of a family of variable attenuators with different coaxial connectors that covers 0.8 to 18.0 GHz, the 4792 is equipped with female SMA connectors and provides as much as 30-dB attenuation with only 0.5-dB insertion loss and attenuation flatness of ±0.5 dB. It handles 5 W average power and 3 kW peak power in a compact enclosure.

SERVING UP SIGNALS

For those in need of stable signal sources, **SYNERGY MICROWAVE CORP.** (Booth 1615, www.synergymwave.com) has an array of free-running and phase-locked options. High-performance oscillators and frequency synthesizers on display at the company's booth will be the recently introduced model DXO10701095-5 surface-mount VCO for X-band use from 10.5 to 11.0 GHz. It tunes across its 500-MHz bandwidth by means of 0.5 to 15.0 V and draws 25-mA maximum current from a +5-V dc supply. The VCO delivers at least +2-dBm output power with low phase noise of –82 dBc/Hz offset 10 kHz from the carrier. The miniature VCO is ideal for satellite-communications (satcom) systems.

In addition to its passive components, Synergy will show its award-winning combination of a phase-locked oscillator (PLO) and frequency synthesizer (a *Microwaves & RF* "Top Product of 2015"), a frequency source with a proprietary application-specific integrated circuit (ASIC) for wideband frequency tuning from 100 MHz to 15 GHz. The microwave source achieves outstanding phase noise of –118 dBc/Hz offset 1 kHz from the carrier and –123 dBc/Hz offset 10 kHz from the carrier.

VECTRON INTERNATIONAL (Booth 1028, www.vectron.com) will feature some of its latest stable oscillators, including oven-controlled crystal oscillator (OCXO) model OX-208 for use at frequencies from 5 to 20 MHz. Supplied in a surface-mount package measuring just 25.4 × 25.4 × 12.7 mm, the OCXO boasts temperature stability of ±0.4 ppb from 0 to +70°C and ±0.8 ppb from –40 to +85°C. With phase noise of –155 dBc/Hz offset 10 kHz from the carrier and aging rate of 0.15 ppb/day, it is a good fit for frequency synthesizers, military communications equipment, and test equipment.

BLILEY TECHNOLOGIES (Booth 1548, www.bliley.com) supplies low-noise oscillators for space and military applications. The firm "made noise" at the Satellite 2016 show with its new Apollo series of miniature OCXOs, which are also sure to capture lots of attention at IMS. Measuring 26.16 × 26.16 × 11.68 mm and with standard frequency of 100 MHz and +10 dBm or more output power, these sine-wave sources are available for factory-set frequencies from 30 to 130 MHz. Initial frequency accuracy is ±0.25 ppm. The OCXOs exhibit worst-case harmonics of –30 dBc and worst-case spurious content of –80 dBc. Worst-case aging is ±5.0 ppb/day. These extremely well characterized sources have a number of options for phase noise, and available performance is as good as –172 dBc/Hz offset 10 kHz from the carrier.

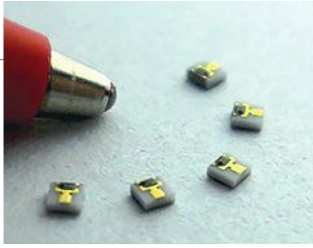
CRYSTEK CORP. (Booth 1733, www.crystek.com) will demonstrate some of its latest high-frequency sources, including the recently announced model CVCO55CC-2275-2290 coaxial resonator oscillator (CRO) for tuning signals from 2275 to 2290 MHz. It tunes that range by means of +0.5 to +4.5 V dc and provides signal output levels of +4.5 dBm (typ.) with ±2.5-dB flatness (typ.). Typical phase noise is –115 dBc/Hz offset 10 kHz from the carrier, while second harmonics are –25 dBc (typ.). In its surface-mount package, the CRO measures just 0.5 × 0.5 in.

Z-COMMUNICATIONS (Booth 711, www.zcomm.com) will offer visitors a look at its lines of miniature frequency sources, such as the model SFS6265A-LF fixed-frequency synthesizer for C-band use at 6265 MHz. The low-cost, PLL-based source *(Fig. 4)* works with an external 100-MHz reference oscillator to achieve –89 dBc/Hz phase noise offset 1 kHz from the carrier and –90 dBc/Hz phase noise offset 10 kHz from the carrier (second harmonics and spurious suppression are –20 dBc and –65 dBc, respectively). The synthesizer operates at temperatures from –40 to +85°C and is well-suited for radar applications. Based on a VCO running at +5 V dc and 35 mA, it is capable of +3-dBm typical output power. Its RoHS-compliant, surface-mount housing measures 0.6 × 0.6 × 0.13 in.

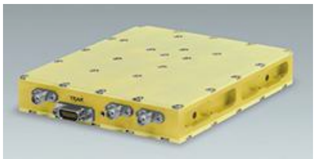
5. Broadband passive components such as this two-way stripline power divider for applications from 1 to 18 GHz are essential in high-frequency systems design. *(Courtesy of MECA Electronics)*

For higher-frequency signal sources, **MICRO LAMBDA WIRELESS** (Booth 1110, www.microlambdawireless.com) will present examples of its YIG-oscillator-based devices, such as the MLMS Series of miniature frequency synthesizers for applications from 500 MHz to 16 GHz. Available in standard frequency bands of

0.6 to 2.5 GHz, 2 to 8 GHz, 6 to 13 GHz, and 8 to 16 GHz, these low-noise synthesizers provide output levels from +10 to +13 dBm and programmable 1-kHz tuning steps. They can be equipped with a five-wire SPI or USB control interface and with internal crystal oscillator reference, external crystal oscillator reference, or both. The miniature sources measure 2.5 × 2.5 × 0.5 or 0.65 in. and suit single-slot PXI chassis.



6. Circuit designers will take note of these types of chip resistors, which can support applications through dc to 60 GHz. *(Courtesy of Barry Industries)*



7. Many integrated subsystems will be on display at the 2016 IMS Exhibition, including this C-band transceiver with GaN-fired transmitter. *(Courtesy of TRAK Microwave Corp.)*

CONSTRUCTION MATERIALS

Visitors to the 2016 IMS exhibition hall will also find the electronic materials they need that are essential to electronic design, including those for electromagnetic-compatibility (EMC) shielding and printed-circuit boards (PCBs). Engineers from **ROGERS CORP.** (Booth 2039, www.rogerscorp.com) will be on hand to discuss circuit materials and how different material parameters relate to the final performance of RF/microwave circuits.

The Rogers' booth will feature examples of the company's many high-quality circuit laminates, including its popular RO4000 hydrocarbon ceramic laminate materials for use at microwave frequencies. These materials can be processed much like low-cost FR-4 circuit boards without need of special processing steps like polytetrafluoroethylene (PTFE) circuit materials, and yet still deliver low loss at high frequencies plus outstanding stability with temperature.

For applications requiring extremely low insertion loss, the company also offers LoFoil conductive foil with the RO4000 dielectric materials; the smooth copper surfaces assist in forming low-loss circuits and high-frequency transmission lines such as microstrip, stripline, and coplanar waveguide. Rogers offers a range of RO4000 material configurations, including RO4350B laminates that employ RoHS-compliant, flame-retardant technology for applications requiring UL-94V-0 certification.

TACONIC (Booth 1511, www.4taconic.com) and the firm's Advanced Dielectric Div. (www.taconic-add.com) will be exhibiting its laminate materials for high-frequency analog and high-speed digital circuits. The firm will unveil its low-loss, ceramic-filled PTFE laminates and woven-glass-reinforced PTFE laminates in a range of dielectric-constant values to accommodate a wide range of frequencies and transmission-line circuits. In addition, Taconic will show a sampling of its specialty materials, which includes fastfilm flexible thin-film RF material.

CRANE POLYFLON (Booth 915, www.polyflon.com) will present its PTFE-based circuit-board materials, including the popular CuFlon microwave substrates. The firm uses a proprietary plating process to create laminates with low-loss characteristics and outstanding dielectric strength. The material exhibits a dielectric constant of 2.05 at 18 GHz in the z-axis (thickness), held to a tolerance of ±0.05.

PASSIVE BUT POWERFUL

WEINSCHEL ASSOCIATES (Booth 2214, www.weinschelassociates.com), one of the longest-running developers and suppliers of high-quality passive components, will show its many product lines at IMS 2016. These include power dividers/combiners, terminations, dc blocks and, perhaps the components the company is best known for, attenuators, both fixed and variable. Fixed attenuators are available as individual units or in calibrated sets for test and measurement applications, and for low-, medium-, and high-power applications.

As an example, model WA35 is a rugged coaxial attenuator with customer-specified attenuation values from 10 to 40 dB that is usable at 5 GHz. It comes with Type-N or DIN connectors and can handle 300 W average power and 10 kW peak power (for a 5-μs pulse). The attenuation accuracy of these high-power components is ±0.75 dB for attenuation values of 10 through 30 dB and ±1 dB for 40-dB attenuation.

MECA ELECTRONICS (Booth 818, www.e-MECA.com) will be one of many small but capable engineering firms at the exhibition with high-performance passive components. On display will be low-distortion terminations and attenuators as well as the latest addition to its N-way power dividers, with weatherproof six-way coaxial power dividers/combiners featuring Type-N and SMA connectors for applications from 5 to 500 MHz. These six-way dividers maintain low insertion loss and VSWR in addition to high isolation between channels from 5 to 50 MHz.

The firm will also offer its new model 802-2-9.500, two-way stripline power divider for applications from 1 to 18 GHz *(Fig. 5)*. The low-loss splitter, which is available with SMA coaxial connectors, features typical VSWR as low as 1.20:1 and tight matching of amplitude and phase between ports. The isolation between ports is typically 25 dB. MECA will also present its model 80X-X-3.250WWP power divider available for broadband applications in 2-, 4-, 8-, 16-, and 32-way configurations (with Type-N and SMA connectors) for use from 0.5 to 6.0 GHz. Units are available with BNC and TNC connectors as well. These rugged, IP67-rated power splitters are suitable for both indoor and outdoor applications.

KRYTAR (Booth 1426, www.krytar.com) will show samples of its many directional couplers, directional detectors, coaxial adapters, terminations, and 3-dB hybrids for applications from dc to 67 GHz. The product lineup includes directional couplers from 300 MHz to 67 GHz with coupling values of 6, 10, 13, 16, 20, and 30 dB, as well as dual directional couplers from 1 to 40

GHz with coupling values of 10, 16, and 30 dB. The couplers are suit many applications in commercial and military systems, and test equipment for channeling signals of interest.

BARRY INDUSTRIES (Booth 1217, www.barry-ind.com) will offer its many lines of high-quality thick-film resistors along with a new chip termination for extremely broadband applications. Model TV0404FA-50R0JN-91 *(Fig. 6)* exhibits impressive typical return loss of 18.5 dB or more from dc to 60 GHz with a maximum VSWR of 1.27:1. The 0404 termination measures a mere 1.016 × 1.016 mm and consists of thick film on alumina substrate with wire-bondable input pad. The 50-Ω termination is RoHS/REACH-compliant and rated at 250 mW. It comes in bulk or tape-and-reel packaging.

COILCRAFT (Booth 1826, www.coilcraft.com) provides straightforward guidance on selecting inductors for applications beyond 40 GHz by means of handy software tools. Among them are the Coilcraft LC Filter Designer software and RF Inductor Finder, available for free download from the company's website.

8. These monolithic phase and amplitude controllers (MPACs) are designed for use with Doherty amplifiers from 2.3 to 2.7 GHz and from 3.4 to 3.8 GHz. *(Courtesy of Peregrine Semiconductor Corp.)*

INTEGRATED SOLUTIONS

For system integrators, IMS has always been an opportunity to find multiple-function subsystems and integrated assemblies needed for systems in development. One such subassembly is the model T001291 C-Band transceiver from **TRAK MICROWAVE CORP.** (Booth 931, www.trak.com) *(Fig. 7)*. The 4.0- × 4.6- × 0.8-in. module combines a receiver with 3-dB noise figure and a GaN-based transmitter capable of 4-W minimum transmit power at C-band frequencies. It employs surface-mount-technology (SMT) components for small size and incorporates all necessary filters for C-band communications systems, suiting it for airborne environments.

TRAK will also show its recently announced model MFC147 block upconverter for civilian and military aviation Ku-band satcom systems. The module translates inputs from 950 to 1,700 MHz to outputs from 13.75 to 14.50 GHz. It employs a GaN power amplifier to achieve low-noise Ku-band outputs of +12 to +17 dBm, and includes built-in test (BIT), temperature monitoring, and forward/reverse power detectors for protection.

For small-signal applications, many essential system functions can be found in IC form. The good news is that the IMS Exhibition will have a full lineup of IC suppliers, including **ANALOG DEVICES** (Booth 1519, www.analog.com) with its many analog, digital, and mixed-signal circuits. Visitors to the booth can size up various analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) for processing everything from audio and video through microwave frequencies. These include 12- and 14-b ADCs capable of sampling rates to 1 Gsample/s and four-channel, 16-b DACs with update rates to 2.8 Gsamples/s. The company, which turned 50 last year, offers IC solutions ranging from attenuators, amplifiers, and clock oscillators to frequency mixers, phase shifters, PLLs, and switches.

MACOM (Booth 939, www.macom.com) should draw a good number of visitors with its GaN-based solutions, both at the device and component levels. The firm offers GaN-on-silicon and GaN-on-silicon-carbide discrete transistors as well as complete amplifiers based on the devices. Transistors are available for high-power pulsed applications, as in radar systems, and for CW amplification.

For example, model MAGX-001090-600L00 is a GaN-on-SiC high-electron-mobility transistor (HEMT) capable of 600 W pulsed output power at 2% duty cycle from 1030 to 1090 MHz. For CW use, model MAGX-000245-014000 is a GaN-on-SiC HEMT that delivers 14 W output power from dc to 2.5 GHz. For system integration, the firm offers fully matched, hybrid GaN power-amplifier modules with more than 25 W CW output power through 3.5 GHz

AMPLEON (Booth 2149, www.ampleon.com) will also be on hand with GaN products, including devices and amplifiers for high-power applications. As an example, model CLF1G0035S-50 is a general-purpose GaN HEMT amplifier for commercial and military use from dc to 3.5 GHz. It delivers 50 W output power from a +50-V dc supply and can handle operation into a 10.0:1 VSWR load mismatch. The GaN amplifier, which comes in a ceramic flange package, offers typical drain efficiency of 54% with 11.5-dB typical gain at 3 GHz and +50 V dc.

PEREGRINE SEMICONDUCTOR CORP. (Booth 2129, www.psemi.com) plans to showcase several new products, including its PE46130 and PE46140 monolithic phase and amplitude controllers (MPACs) for Doherty amplifiers *(Fig. 8)*. The PE46130 is designed for amplifiers from 2.3 to 2.7 GHz while the PE46140 operates from 3.4 to 3.8 GHz. The controllers, based on the firm's UltraCMOS semiconductor technology, hold current consumption to 0.35 mA with excellent amplitude and phase accuracy. They provide a phase-control range of 87.2 deg. in 2.8-deg. steps and attenuation-control range of 7.5 dB in 0.5-dB steps. Packaging is an RoHS-compliant 6- × 6-mm QFN.

SKYWORKS SOLUTIONS (Booth 1611, www.skyworksinc.com) will provide examples of its many monolithic-microwave-integrated-circuit (MMIC) component solutions, including the model SKY65605-21 low-noise amplifier (LNA) for Global Navigation Satellite System (GNSS) and Global Positioning System (GPS) receiver front-end applications. The LNA achieves 0.6-dB typical noise figure and 19-dB typical gain at 1575 MHz with typical input third-order-intercept point (IIP3) of –5 dBm. It is extremely compact, coming in a six-pin housing measuring 0.7 × 1.1 mm, and operates at +1.80 to +2.85 V dc and 3.6 mA.

CUSTOM MMIC (Booth 1950, www.custommmic.com) will unveil its model CMD230 GaAs MMIC single-pole, double-

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STANDARD DETECTORS

Omniyig Model No.	Frequency Range (GHz)	k Factor	TSS (dBm)
Zero-Bias Schottky			
ODZ0004A	0.1 - 18.0	1200	-52
ODZ0328A	2.0 - 18.0	1200	-52
ODZ0441A	6.0 - 26.0	1000	-51

STANDARD COMB GENERATORS

Omniyig Model No.	Input Frequency (MHz)	Output Frequency (GHz)	Output Power (dBm)
OHG10118	100	0.1 - 18.0	-40
OHG20218	20	0.2 - 18.0	-35
OHG51026	500	0.5 - 18.0	-28
OHG81026	1000	1.0 - 18.0	-18

Let Omniyig help with any special Limiter or Detector requirements you may have - Zero Bias Schottky Detectors, Limiter-Detectors, Comb Generators and a broad line of YIG-tuned Filters, Oscillators and Multipliers.

STANDARD LIMITERS

Omniyig Model No.	Frequency Range (GHz)	Insertion Loss (dB)	Leakage Power (dBm)
Pin			
OLP2645A	8.0 - 18.0	2.0	+19
OLP2726A	2.0 - 18.0	1.2	+19
PL473	0.5 - 12.0	1.8	+19
OLP2652	2.0 - 18.0	2.5	+20
Schottky Turn-on			
SL048	2.0 - 26.0	2.5	+14
OLD2635A	4.0 - 18.0	2.5	+14
OLD2733A	0.4 - 18.0	2.5	+14

Leakage Power Measured at P(in) = +30 dBm

YIG MULTIPLIERS

Omniyig Model No.	Input Frequency (GHz)	Output Frequency (GHz)	Output Power (dBm)
YM1001	1.0 - 2.0	2.0 - 13.0	6
YM1002	0.1	1.0 - 12.0	-33
YM1003	0.2	1.0 - 12.0	-28
YM1004	0.5	1.0 - 12.0	-10
YM1026	1.0 - 2.0	2.0 - 18.0	-4
YM1027	0.1	1.0 - 18.0	-40
YM1028	0.2	1.0 - 18.0	-33
YM1029	0.5	1.0 - 18.0	-22
YM1087	0.1 - 0.2	1.0 - 12.0	-25

RF input power on all models 0.5 to 1.0 watts.
Fast switching, MIL-Spec Hi-Reliability and units integrated with drivers, oscillators or amplifiers also available.

YIG BAND REJECT FILTERS

Omniyig Model No.	Frequency Range (GHz)	Ins. Loss (dB)	Bandwidth at 40 dB (MHz)
M107RX	8.0 - 18.0	1.5	20
M104RX	4.0 - 18.0	2.0	8
M105RX	2.0 - 8.0	1.5	10

MIL-SPEC and High Reliability!
Integrated with Analog and 12 Bit Digital Drivers.
MANY other Multioctave designs available.

WIDEBAND YIG FILTERS

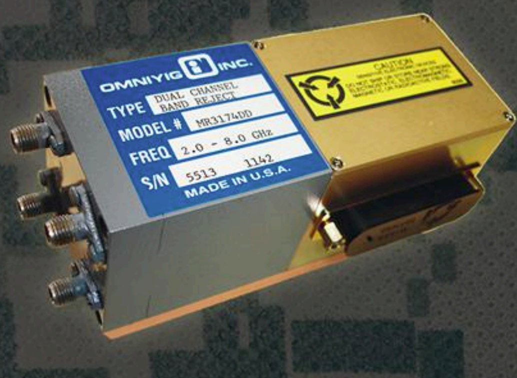
Omniyig Model No.	Frequency Range (GHz)	Ins. Loss (dB)	Bandwidth at 3 dB (MHz)
4-STAGE			
M3064	6.0 - 18.0	6.5	500 min
M2997	6.0 - 18.0	6.0	400 min
M3513	8.0 - 18.0	6.5	500 min

Industry-leading bandwidths in multi-octave, YIG units providing the widest 3dB bandwidth available!

LOW PHASE NOISE YIG OSCILLATORS

Omniyig Model No.	Frequency Range (GHz)	RF Power Output (mW)	Second Harmonic (dBc)
YOM1517	0.5 - 2.0	20-60	16
YOM1518	1.0 - 4.0	20-60	16
YOM1514	4.0 - 12.0	10	15
YOM3719-5	2.0 - 15.0	20	13
YOM1679	2.0 - 12.4	20	13
YOM83	2.0 - 6.0	20	12
YOM137	2.0 - 8.0	20	12
YOM3719-4	8.0 - 18.0	20	14
YOM3719-2	6.0 - 18.0	20	14
YOM3719-1	4.0 - 18.0	20	13
YOM3719	3.0 - 18.0	10	12
YOM3676	2.0 - 18.0	20	15

We offer other models with Second Harmonic -60 dBc and Oscillators integrated with 2-stage YIG Filters.



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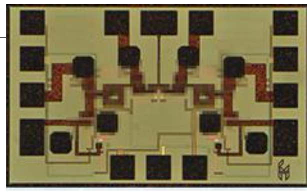
throw (SPDT) for use from dc to 26 GHz *(Fig. 9)*. Available in die form, the switch achieves low 1.4-dB insertion loss and high 40-dB isolation between ports at 13 GHz. It requires no bias supply and operates with 0/–5-V logic levels. The reflective switch also boasts fast switching speed of 3.4 ns. In addition, the firm will show the model CMD231 GaAs MMIC driver amplifier, with 14.5-dB gain and +13.5-dBm output power at 1-dB compression at 4 GHz. It runs on a supply from +3 to +6 V dc and has an output IP3 of +23.5 dBm at 4 GHz.



9. This GaAs MMIC SPDT reflective switch is available in die form for applications from dc to 26 GHz. *(Courtesy of Custom MMIC)*

MAKING CONNECTIONS

Cables, connectors, and waveguide help route high-frequency signals from one point in an RF/microwave system to another. Like many high-frequency components, size is a function of frequency, with smaller dimensions supporting transmission of smaller wavelengths prevalent at higher frequencies. As interest grows in the use of millimeter-wave frequencies for point-to-point communications and automotive safety systems, the exhibition is sure to have its share of visitors seeking more details on cables and connectors for use above 30 GHz.

10. Coaxial connectors in the pSeries meet military test requirements for applications from dc through 30 GHz. *(Courtesy of San-tron Inc.)*

One of the suppliers in this arena will be **DYNAWAVE CABLE** (Booth 1011, www.dynawavecable.com), which plans to flex its new DynaTest Series test cable assemblies for broadband use from dc through 26.5 GHz. Suitable for research and development (R&D) as well as production testing, these phase-stable cable assemblies come in standard lengths of 24 in. (609 mm), 36 in. (914 mm), and 48 in. (1,219 mm), with SMA connectors for use from dc to 26.5 GHz and Type-N connectors for applications from dc to 18 GHz. The cable assemblies are 100% RF tested to meet specifications. They feature polyurethane cable jackets terminated with electro-polished, stainless-steel connectors, and are designed for an operating temperature range of –45 to +85°C.

EZ FORM CABLE CORP. (Booth 1122, www.ezform.com) will display semirigid and flexible coaxial cable assemblies, including the low-cost EZFLex test cables with SMA connectors for applications through 18 GHz and other connectors for applications through 40 GHz. The rugged cable assemblies, available in custom lengths, feature a steel-wire-reinforced PVC outer jacket with PTFE dielectric and stainless-steel connectors for low loss and durability. Minimum bend radius is 1 in.

HUBER + SUHNER'S (Booth 846, www.hubersuhner.com) revolutionary SUCOFLEX 400 cable assemblies will be on hand. They maintain extremely low loss for medical, military, and test applications from dc through 26.5 GHz, depending on choice of connector. Attenuation is nominally 0.99 dB/m at 18 GHz. Available with a variety of coaxial connectors, including Type-N and SMA, these cable assemblies feature excellent phase stability with temperature, and can be used across operating temperature ranges as wide as –55 to +125°C. **IW INSULATED WIRE MICROWAVE PRODUCTS** (Booth 2020, www.insulatedwire.com) will also feature its cables and cable assemblies at IMS, with low-loss assemblies available for use through 60 GHz.

For frequencies from dc through 30 GHz, **SAN-TRON INC.** (Booth 1514, www.santron.com) will serve up its pSeries coaxial connectors *(Fig. 10)*. They offer low loss through 30 GHz, and are manufactured to exceed the requirements of MIL-STD 202 Method 212, Condition D test conditions. The connectors' simplified three-piece design, with body, center contact, and dielectric, meets the IP68 standard with a proprietary insulator that has excellent thermal stability. Various connector interfaces are available.

LOADING SOFTWARE

One of the industry's most trusted simulation software tools, the Sonnet Suites of planar electromagnetic (EM) simulation programs from **SONNET SOFTWARE** (www.sonnetsoftware.com), will be demonstrated at booth 1939. These simulators provide 3D EM analysis of planar circuits and antennas based on Maxwell's equations for precise modeling of material and circuit effects. The software works with a physical description of a circuit and predicts the behavior of EM fields around different transmission lines to improve the impedance matching in antennas, filters, and other high-frequency circuit designs.

In terms of electronic-design-automation (EDA) software, the 2016 IMS Exhibition is a virtual "supermarket" of design and test tools. For instance, along with its many instruments, Keysight will provide demonstrations of the Advanced Design System (ADS) suite of design software tools, including its SystemVue system-level design software. **APPLIED WAVE RESEARCH** (Booth 1529, www.awrcorp.com) and parent company National Instruments will show its popular AWR Microwave Office design tools. **MATHWORKS** (Booth 130, www.mathworks.com) will offer applications on its mathematics-based MATLAB program, and **CST OF AMERICA** (Booth 739, www.cst.com) will show its CST Studio Suite. Not to be outdone, **ANSYS** (Booth 1539; www.ansys.com) will offer demonstrations of its popular ANSYS High-Frequency Structure Simulator (HFSS) 3D EM simulation software and ANSYS Simplorer system simulation software.

Simulation models will also be available at the exhibition from **MODELITHICS** (Booth 1138, www.modelithics.com). The firm has worked with many device and component suppliers to develop an extensive library of models for use from RF through millimeter-wave frequencies. mw

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Engineering Essentials

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Wireless Standards Ensure Connectivity

Wireless standards have steadily evolved toward a worldwide wireless network—one that is capable of handling the massive amounts of data generated by modern users.

SO PERVASIVE HAS wireless communications become in daily life, most people take for granted the effective operation of multiple wireless devices each day (including their cell phones and Internet-connected computers). But bandwidth is limited, and without wireless standards to set limits and guidelines, all of these different wireless devices would compete for their "wireless space." And only the highest-level signals would make the connection.

Fortunately, with the aid of regulatory organizations such as the Federal Communications Commission (FCC; www.fcc.gov), frequencies and bandwidth are managed for effective coexistence of many different wireless communications devices and functions. By organizing frequencies into licensed and unlicensed bands and using different strategies for signal transmissions, order is maintained.

In theory, even devices with extremely low signal levels will function in the presence of much larger signals from broadcast stations if wireless standards are carefully designed and implemented. As the number of wireless devices and functions increases, they must fit comfortably within relatively limited bandwidth. This requires the use of radio transmission methods that will make the most efficient use of the available bandwidth.

In considering how commercial frequency-modulated (FM) radios are designed, with channels assigned to bandwidths from 88 to 108 MHz, the broadcast scheme is relatively inefficient for its number of "users" (channels) versus the number of modern cellular telephone users at higher frequencies. Early cellular communications systems were based on the analog (AMPS) technology, which was also applied to shorter-range products such as cordless telephones.

As the popularity of the communications format became apparent, more efficient cellular standards were needed for a rapidly growing number of users. The result has been a fast sequencing of new generations of cellular communications formats based on digital modulation techniques, allowing for more efficient use of available bandwidth and more users per cell site.

There has been a rapid succession of new cellular standards, extending from first-generation (1G) analog technology, through second-generation (2G), third-generation (3G), and the current fourth-generation (4G) cellular standards, including Long Term Evolution (LTE) and Long Term Evolution-Advanced (LTE-A).

As mobile telephones themselves evolve into all-in-one tools for voice, data, and video communications over the Internet, service providers must scramble to enhance their wireless networks with increased capacity and performance—or at least, to the degree that service providers and component/system designers are now debating with regard to the performance requirements necessary for a fifth-generation (5G) global cellular communication standard *(see "What Will It Take for 5G?," p. 62)*.

Each cellular communications generation has included its own set of wireless standards, which isn't always compatible with the previous generation's standards. 2G cellular systems included the specifications detailed in the Global System for Mobile Communications (GSM) standards developed by the Third-Generation Partnership Program (3GPP) and the first generation of the novel code-division-multiple-access (CDMA) networking technology developed by Qualcomm (www.qualcomm.com), known as cdmaOne.

Typically, an advance to the next cellular communications generation has involved a transition, with the "2.5G" transition employing wireless communications networks based on the next generation of CDMA, or cdma2000. Along with the Universal Mobile Telephone System (UMTS) based on the earlier GSM standard, they served as wireless network standards for the growth of 3G cellular services.

Both would also help bolster the growth of cellular services through the 3.5G transition to current 4G systems, along with such other wireless standards as mobile WiMAX (IEEE 802.16e, EVDO-B, HSPA, HSPA+, and LTE). Critics of the original LTE standard pushed for the development of LTE-A during the adoption of 4G cellular services as a "true 4G cellular standard."

In essence, all of these wireless standards have dealt with the same sets of tradeoffs: working to provide as much performance as possible within limited bandwidths, and for the lowest cost possible. The standards have differed in terms of multiplexing schemes, modulation, and waveform types, making use of the Internet Protocol (IP) in later generations of cellular communications standards for the fastest data rates possible.

Much infrastructure tuning has been necessary along the way. Picocells and microcells, for example, have been added inside buildings and other areas where coverage from a cell's main base station might have been blocked, weak, or nonexistent.

The evolution of cellular communications standards has occurred alongside of their closer-range wireless companions, the wireless-local-area-network (WLAN) standards. The most notable of these are the IEEE 802.11 standards established by the International Institute of Electrical and Electronic Engineers (IEEE; www.ieee.org). As the development of the IEEE 802.11 Wi-Fi standards makes apparent, the trend in all wireless communications standards is to achieve higher data rates without increasing the consumption of bandwidth.

Perhaps the simplest way to think of different wireless communications standards is by how far they allow a communications link to effectively operate (at some established data rate) between a sender and receiver. Cellular radio standards support voice, video, and data communications around the world, while WLAN standards support communications in a small area.

As formulated by the IEEE, the earliest version of IEEE 802.11—for WLANs in the unlicensed 2.4-GHz band—was expanded to two different-frequency versions in 1999: IEEE 802.11a at 5 GHz and 802.11b at 2.4 GHz. The difference in frequency and bandwidth for the two versions translated into differences in maximum data rate, at 54 Mb/s for IEEE 802.11a and 11 Mb/s for IEEE 802.11b.

For cellular or wireless network communications, no one standard has ever been enough, especially considering the different frequency assignments in different countries and the many varied requirements for different wireless applications. The current dominant 4G standard, LTE, is based on GSM/EDGE and UMTS/HSPA wireless network technologies that were developed by the 3GPP.

To improve upon the initial LTE standard, the ITU-R organization developed the higher-performance LTE-A version for 4G cellular systems. The goal of LTE, which is a trademark owned by the European Telecommunications Standards Institute (ETSI), was to improve upon 3G cellular standards with increased capacity and data-transmission speeds. It uses digital signal processing (DSP), advanced modulation, and a packet-switched, IP-based approach to reduce data latency.

LTE, which is incompatible with the earlier cellular standards, uses both frequency-division-duplex (FDD) and time-division-duplex (TDD) techniques as UMTS did before it, either sending or receiving at different frequencies or at the same frequency and at different times. It achieves peak uplink rates to 75 Mb/s and peak downlink rates to 300 Mb/s, with data-transfer latency of less than 5 ms. It operates on scalable bandwidths from 1.4 to 20.0 MHz on licensed frequency bands.

Standard LTE comes in several versions, including LTE-TDD (which uses a single frequency, downloading and uploading data at different times) and LTE-FDD (which uses pairs of frequencies for uploading and downloading data). In addition, LTE Direct is a device-to-device wireless technology developed by Qualcomm for use in many countries.

Ultimately, the public's appetite for wireless services has made clear the need for 5G technology and a new set of wireless standards—perhaps even looking to millimeter-wave frequencies for available bandwidth. mw

WHAT WILL IT TAKE FOR 5G?

TO BE ECONOMICALLY FEASIBLE, a new cellular standard such as 5G must have much greater capacity and much higher peak data rates than 4G in order to make the investment in a new wireless standard (and its infrastructure equipment) worthwhile by service providers. The 5G focus will be on providing more broadband services on portable wireless devices. To accomplish the improvements in performance, network design may involve reducing the sizes of cells to create more dense cellular networks compared to earlier cellular networks.

Various market forecasts call for a build-out of 5G cellular networks from 2017 through 2025. For example, the ITU-R announced plans to release its IMT-2020 5G standard sometime around 2020. During this time, 5G will have moved far beyond the functionality of earlier cellular networks and will include the Internet and Cloud-based data storage as essential parts of the network, along with Internet of Things (IoT) networking, and communications between both humans and machines and machines to machines (M2M).

It is clear that 5G cellular networks will rely heavily on cognitive radio technology, such as software-defined radios (SDRs), to employ communications devices that can shift function and performance according to data rates and operating conditions. These networks may use duplex systems that vary the use of frequency or time, rather than just FDD or TDD, and they will no doubt use multiple antennas in multiple-input, multiple-output (MIMO) configurations to improve distance, coverage, and data rates.

Finally, 5G cellular standards will most likely need to reach beyond the traditional frequency ranges of about 800 through 3,800 MHz for transmission and reception, and secure such links as backhaul connections within the network by means of millimeter-wave frequencies (around 50 GHz). With data growing through wireless services and additional applications such as IoT devices, bandwidth is invaluable.

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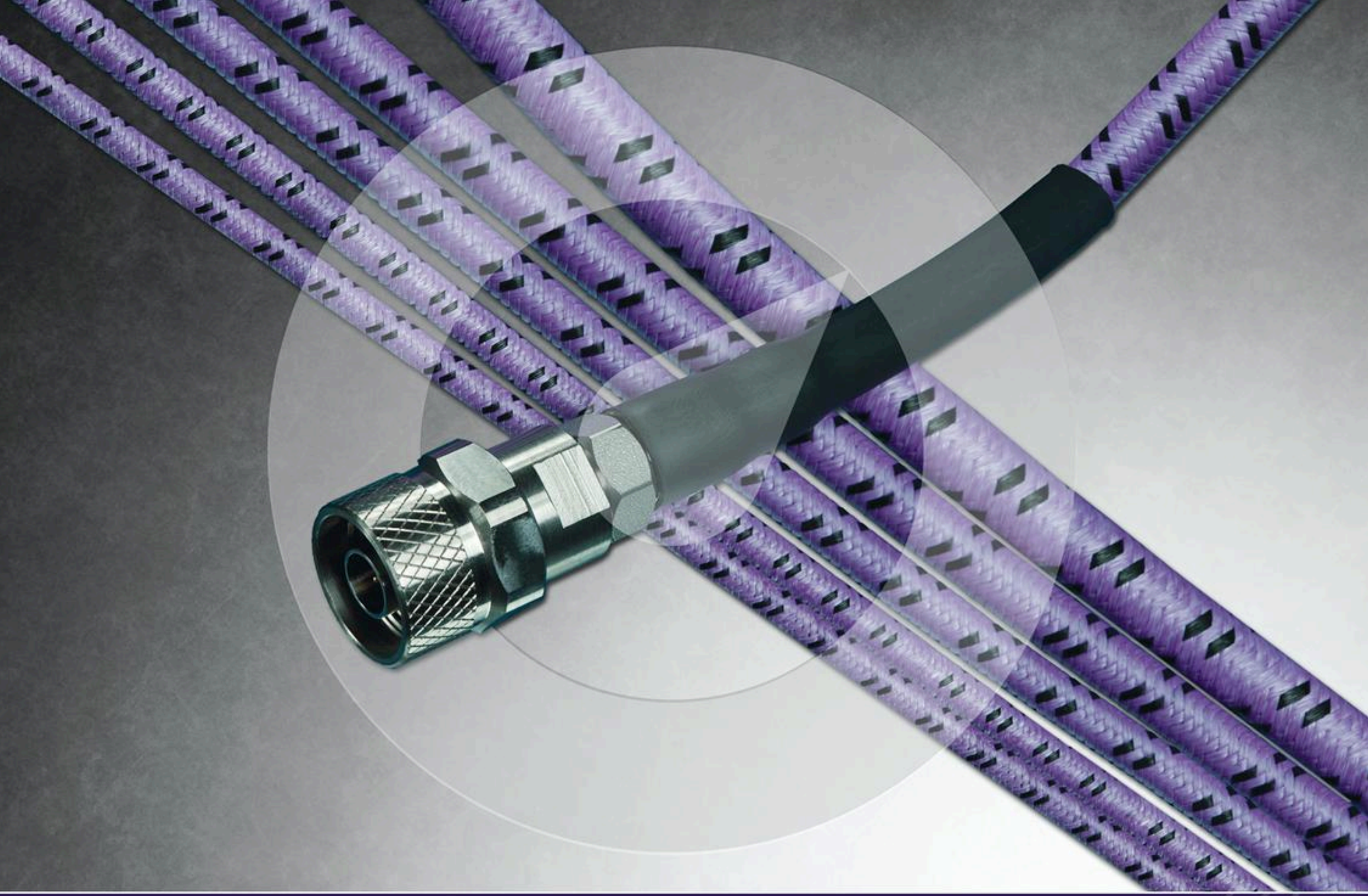


JACK BROWNE | Technical Contributor

Cutting-Edge Technologies Primed to Break Out

As microwave signals expand into automotive-safety and IoT remote-sensing types of applications, advanced technologies will be needed at reasonable performance/price ratios.

MICROWAVE COMPONENTS AND SYSTEMS have long depended on developments within many different technology areas to sustain the evolution of the industry as a whole. Take gallium arsenide (GaAs). For many years, it was viewed as "the semiconductor technology of the future" for its capabilities in broadband, high-gain field-effect transistors (FETs). But because engineers by nature are always striving for better ways to do things, new technologies are constantly under the microscope.

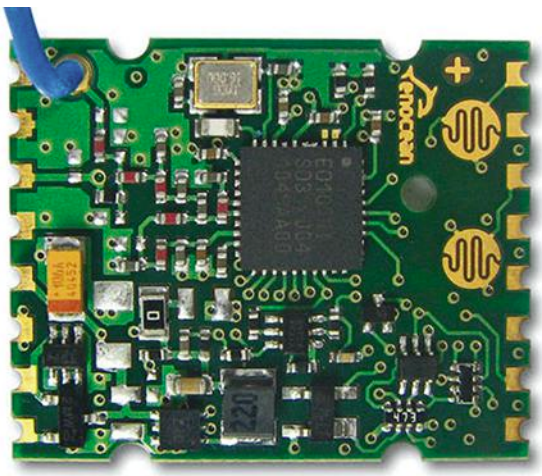
Gallium nitride (GaN) is currently the industry's "darling" semiconductor technology for a wide range of applications—from commercial through military uses, and even emerging industrial RF energy applications in heating and cooking, to replacing one of the more time-honored of this industry's technologies (the vacuum tube). It takes quite a few technologies to keep this industry going and growing. GaN represents just one of the many worth watching in the years ahead.

Dwindling bandwidth has been a consistent concern for wireless service providers, as they attempt to provide additional capacity for an increasing number of wireless subscribers. In addition, machines and things will require bandwidth in growing numbers, with industrial applications embracing machine-to-machine (M2M) wireless connections to the Internet and Internet of Things (IoT) devices helping automate our world.

HIGHER IN FREQUENCY

New standards and specifications for fifth-generation (5G) cellular services *(see p. 61)* hope to address limited bandwidth not only by investigating different multiplex and modulation formats, but also by exploring frequency spectra once considered out of reach for practical use: millimeter-wave frequencies of 30 GHz and higher. In recent years, for example, automobile manufacturers have been integrating forward- and reverse-looking radar systems designed as one or more integrated circuits (ICs) at 77 GHz and various other frequencies.

The challenge of emerging 5G cellular systems to manufacturers of millimeter-wave components will be whether they can produce these components less as specialty items for space and military applications and more as commodity items for commercial and industrial application. With the coming of 5G cellular systems throughout the next decade, it appears that opportunities will be many for practical millimeter-wave technology.

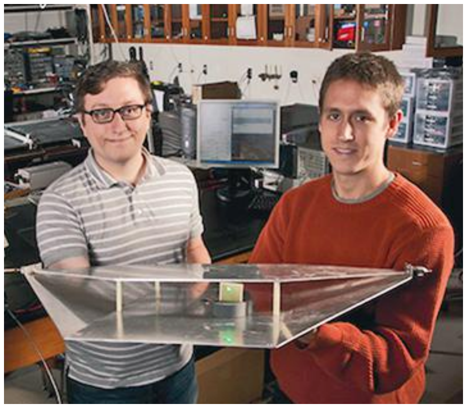


1. This module can transmit captured energy to wireless sensors over unlicensed frequency bands, such as 902 MHz. ***(Courtesy of EnOcean)***

Some firms are well aware of the growing opportunities for applications at these higher frequencies and have gone about refining the technologies needed to make millimeter-wave devices more practical. A long-time supplier of precision millimeter-wave components, Spacek Labs (www.spaceklabs.com), for instance, has been dedicated to supplying high-quality components for military and space-based systems. This includes its recently introduced model MVU-10 double-balanced mixer.

When fed with local-oscillator (LO) signals from 40 to 60 GHz, the mixer can convert RF signals from 50 to 75 GHz to an intermediate-frequency (IF) range of dc to 20 GHz with 7-dB typical conversion loss. It is built for reliability, with waveguide flanges for the millimeter-wave ports, but admittedly larger than an IC solution. The expansion of millimeter-wave technologies into commercial markets will require smaller, lower-cost components.

A step in this direction is being taken by Anokiwave (www.anokiwave.com). The firm has applied its experience in semiconductor device design and works with outside semiconductor foundries to create radio and amplifier ICs for radar and communications systems at RF through millimeter-wave frequencies. The firm's use of on-chip, active electronically steerable antenna (AESA) structures has made possible complex radio front-end designs for receive and transmit functions in devices small enough to fit in SMT packages.



2. Students at Duke University demonstrated an experimental antenna for converting RF/microwave energy in the environment to electricity. *(Courtesy of Duke University)*

An example of the possibilities with silicon-germanium (SiGe) semiconductor materials can be seen in Anokiwave's AWS-0102 quad-core satcom receiver IC, which is intended for K-band use from 17.7 to 20.2 GHz. It incorporates a blend of digital and analog circuitry to include 5-b phase control and the ability to achieve right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP).

At millimeter-wave frequencies, the company's model AWP-7176 is a five-stage power amplifier for use from 71 to 77 GHz. It is fabricated on a 0.1-μm pseudomorphic-high-electron-mobility-transistor (pHEMT) semiconductor process and achieves 26-dB gain. The chip even includes a forward power detector to reduce the need of adding a component to a system design.

HARVESTING ENERGY

Lots of publicity lately has been given to the market potential for IoT devices over the next decade, and how all of these Internet-connected "things" will enhance quality of life. Whether or not this holds up as true, these things will also significantly contribute to the enormous amount of data that must be transferred to the Internet, mainly through wireless means like wireless sensor networks (WSNs). That will eventually mean furnishing billions of electronic sensors and other devices with a source of power.

Possible solutions to the growing power drain include creating more energy-efficient IoT circuits, or even finding ways to recap-

ture or reuse energy from an electronic device or other nearby energy sources (e.g., optical or thermal energy). Some firms, such as Linear Technology (www.linear.com), have already made great strides in this arena. One example is Linear's LTC3107 dc-dc converter, which extends the battery life in a low-power wireless device. The converter, which provides +2.2-V dc output, automatically shifts from running on battery power to using harvested power whenever available from a thermal source.

Energy-harvesting circuits are actually subsystems, with antenna, ac-to-dc conversion, energy storage, sensors, and microcontroller to balance charging and discharging of energy. Among the companies at the forefront of this field is EnOcean (www.enocean.com). Its circuits and modules for capturing and transferring energy (e.g., transmitters, sensors, and receivers) can be used at standard frequencies around the world. For instance, the model PTM 33x transmitter module *(Fig. 1)*, with variants at 315, 868, and 902 MHz, permits the use of wireless sensors and other devices without batteries. .

Companies like Powercast Corp. (www.powercastco.com) have made significant progress on wireless transfer of power. The firm developed components for sending power to battery-free wireless sensors using its Powercaster transmitter to sense energy by means of direct-sequence spread spectrum (DSSS) modulation (at a center frequency of 915 MHz) to a model P2110 Powerharvester receiver. The receiving antenna is a low-cost, printed-circuit directional design with gain of 6.1 dB fabricated on FR4 circuit material.

By transferring energy from the transmitter to the receiver and the sensors it powers, a WSN can be achieved without batteries in each sensor. The next step will be for each sensor to recapture enough energy from the environment to be self-powered.

DEEPER RESEARCH INTO HARVESTING

Energy harvesting is certainly not a mature technology, but much research is being directed at improving the technology in conjunction with metamaterials or composite materials. For example, more than three years ago, students at Duke University (www.duke.edu) demonstrated how metamaterials could be used to form a power-harvesting cell capable of harvesting enough excess environmental microwave energy into the 7.3 V dc needed to power a light-emitting diode *(Fig. 2)*.

Georgia Tech's Strategic Energy Institute (www.energy.gatech.edu/) has developed methods for recovering energy, including a two-stage power-management and storage system that harvests energy from human motions, such as walking. The system is based on a capacitor for energy storage, a power-management circuit, and a larger capacitor or battery for more long-term energy storage. For instance, a triboelectric generator embedded in a shoe would produce electricity as a person walked, and that energy would be stored and consumed as needed. mw

Design Feature

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Load-Pull Methods Yield Improved Base-Station PAs

The latest version of an EDA software tool works directly with device load-pull data to develop the impedance-matching networks needed to obtain specific power-amplifier performance points.

Load-pull measurements are a powerful aid in identifying impedance matches for RF/microwave components. In a load-pull simulation of an active device, the impedances presented to the source and load of the device are swept across a range of values, and the effects on performance are measured. Performance contours are then plotted on a Smith chart *(Fig. 1)* to show how the changes in impedance impact device performance. By knowing how active-device performance relates to the input and output impedance of a power amplifier (PA), for example, attributes like output power and linearity can be fine-tuned to optimize performance.

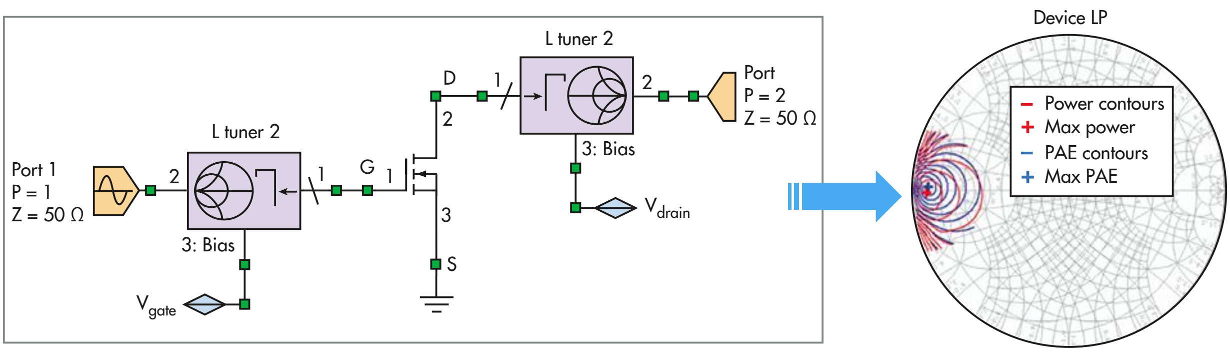
Recent advances in data-file formats by load-pull measurement system vendors, such as Maury Microwave (www.maurymw.com) and Focus Microwaves (www.focus-microwaves.com), have significantly expanded the utility of load-pull characterization within the simulation environment used to develop the input/output impedance-matching circuitry. These new file formats support a sweep of an independent variable such as input power, DC bias, temperature, or tone spacing (in the case of two-tone load-pull characterization), in addition to the swept source or load impedances.

The capability to import and manipulate these load-pull data sets in an electronic-design-automation (EDA) circuit-simulator software program greatly simplifies and speeds the design process. It also gives designers a broader design space to explore the performance impact of different design options.

EDA software tools such as the NI AWR Design Environment (www.awrcorp.com/products) V12 from National Instruments enables designers to take full advantage of these new load-pull file features in an intuitive manner by offering important load-pull measurements and graphing control. To address the high-performance requirements of PAs used in modern wireless communications working with analysis of swept input power, the NI AWR V12 load-pull capability supports studying amplifier responses to input power sweeps. However, it also allows any design parameter to be swept and the data manipulated in the design environment.

TRADITIONAL DESIGN FLOW

A traditional circuit design flow for a PA typically involves developing a nonlinear model of the active device to be used in a design circuit, and then performing a load-pull simulation of the

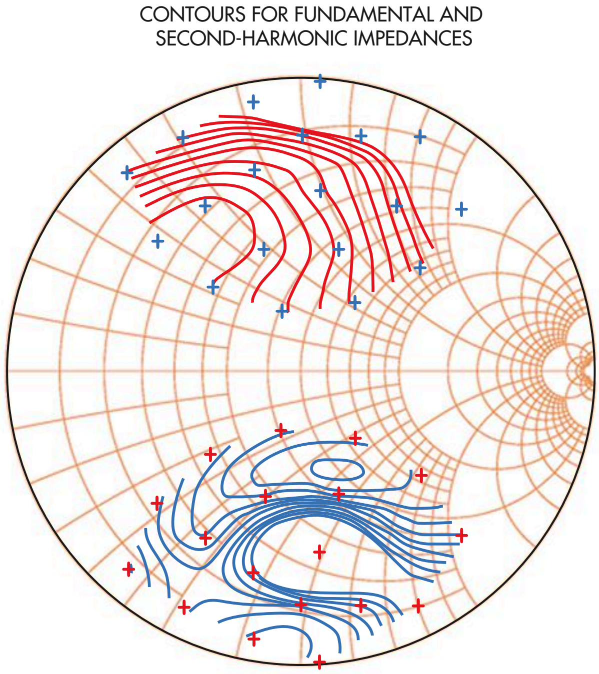


1. In load-pull approaches, the load or source impedance of an active device is measured under swept-frequency conditions. Performance contours are plotted on a Smith chart as a guideline to the development of impedance-matching networks for the load or source of the active device.

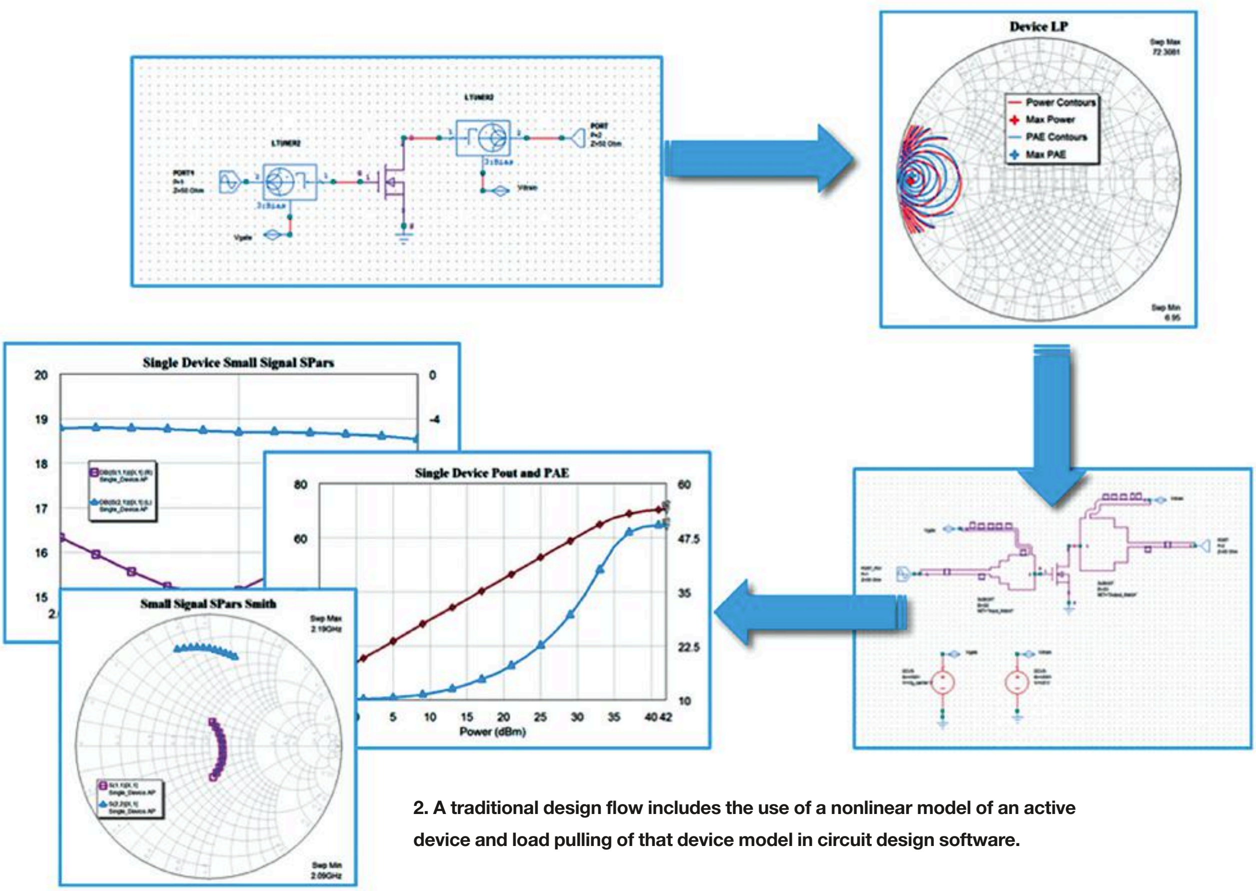
device model in a commercial circuit-simulation program *(Fig. 2)*. The input and output impedance-matching networks are then designed based on load-pull contours. The idea is to find a terminating impedance that will yield performance criteria most important for realizing system requirements. By comparing simulated results with design results, designers can adjust the matching network to achieve the performance goals or optimized performance levels for that particular device model.

Nonlinear models help predict how a device will behave under a set of operating conditions. While effective in many cases, the nonlinear-model approach has a number of limitations that can adversely impact overall product development. Standard nonlinear empirical models are based on curve-fitting characterization equations to various measurement data, including S-parameters, dc IV curves (often pulsed), and, in some cases, large-signal responses.

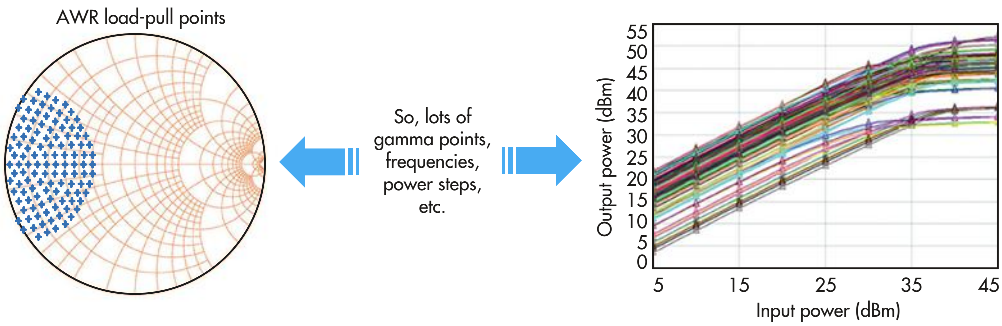
Creating accurate nonlinear device models absorbs a considerable amount of time, effort, and expertise in active device characterization. The process often requires a significant investment in measurement equipment and large-signal modeling/optimization routines, which must continually evolve to keep up with changes in technology. As a result, it's difficult to collect enough test data to create a nonlinear device model that predicts the performance of an active device under all operating conditions, such as bias point, frequency, and power level.



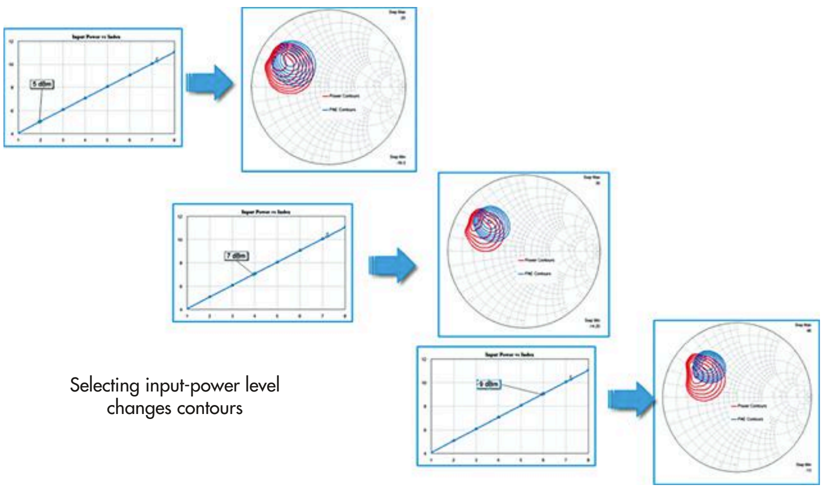
3. Shown are examples of data plotting and manipulation of device contours for fundamental and second harmonic impedances.



2. A traditional design flow includes the use of a nonlinear model of an active device and load pulling of that device model in circuit design software.



4. In the case of the NI AWR Design Environment software, denser data sets help to enhance post-processing of design data.



5. The rectangular graph on the left shows the input power versus index. A marker points to a specific input power and plots the contours in the Smith chart. When the marker is moved, it results in a new set of contours.

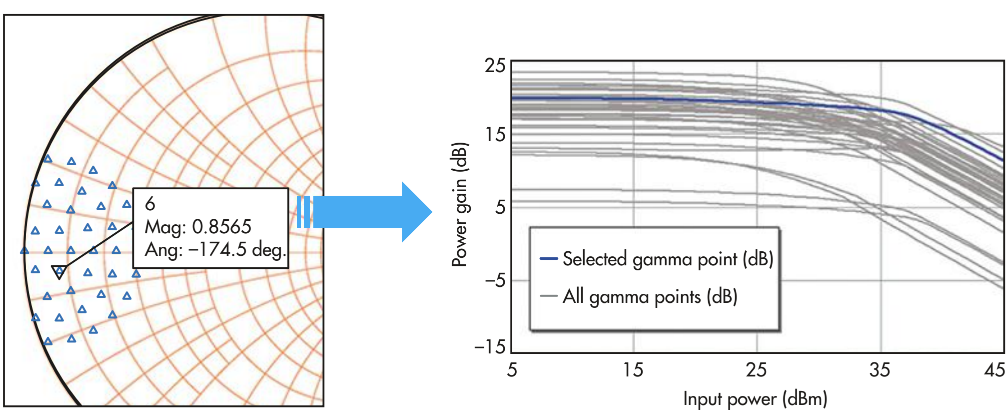
Designing for such a broad and dynamic set of operating conditions is a growing concern among designers faced with developing PAs used in modern communications systems. In addition, nonlinear-device-model development is a timely process, requiring multiple cycles of measurement and model extraction, curve fitting, and model optimization, further cutting into the short design cycle time typically associated with wireless devices and underlying PA components.

To circumvent the dependence on active-device nonlinear models, PA designers have begun designing impedance-matching networks and associated circuitry based directly on measured load-pull data for a device of interest. This offers several advantages compared to the traditional PA design flow. For instance, the entire design process is within the control of a design group—there is no reliance on a nonlinear device model developed from an outside source and outside measurements. Device data can be regenerated or redefined in-house if necessary, rather than relying on a third-party source for nonlinear active-device-model generation.

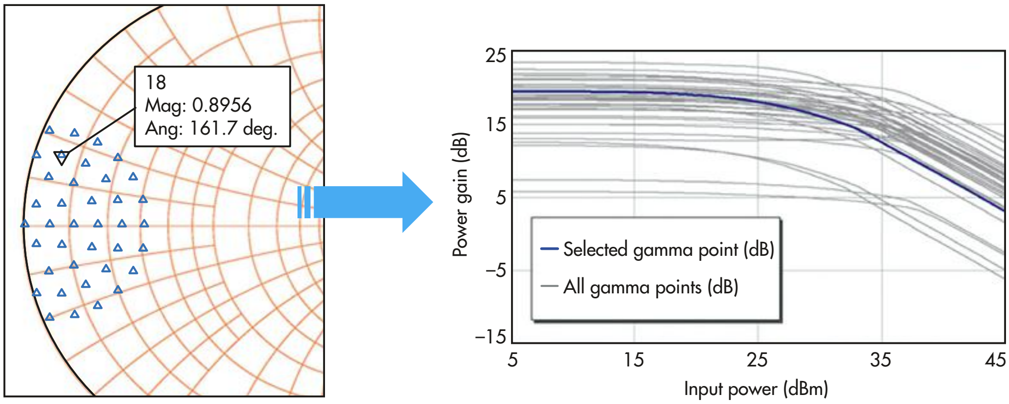
GRAPPLING WITH THE COMPLEXITY

The challenge for the majority of EDA software companies is to provide a manageable and intuitive way for dealing with complex, swept load-pull data sets. These data sets can include nested harmonic load-pull data, nested load- and source-pull data, and two-tone excitation data, in which intermodulation-distortion (IMD) levels can be studied as a function of load impedance. Furthermore, the data can include multiple fundamental frequencies.

6. By choosing a gamma point from a set of impedances in a local data file, gain-compression curves can be plotted for that point. The grayed-out curves show gain compression for all gamma points, while the dark blue trace corresponds to the gamma point swept with the marker.



Load-Pull Simulation



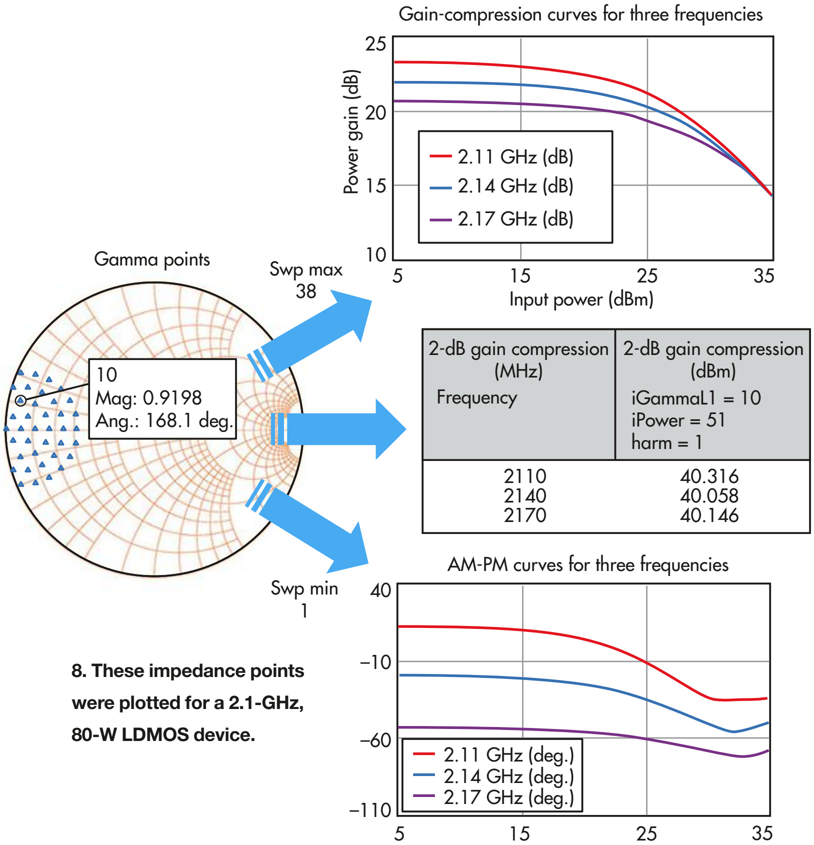
7. If the marker is moved to another gamma point, the gain-compression curve changes to update results for that impedance.

As such, an entire array of possibilities exists for manipulating the data, including plotting circuit performance as a function of frequency, power, bias, load impedance, or source impedance at a fundamental frequency of interest, and the results of changing load or source impedance at harmonic frequencies. *Figure 3* illustrates an example of data plotting and manipulation of contours for impedances at fundamental and second-harmonic frequencies. Managing all of this information for use by the PA designer ultimately requires support from software automation.

Measurements that can be plotted for an active device include output power, gain, efficiency, IMD levels, AM-to-PM-conversion performance or, essentially, any performance parameter that is able to be measured on a modern load-pull system. If an active device's internal matching elements and package parasitic elements are known, measurements can also be de-embedded to the current generator plane of the device.

Above and beyond viewing and plotting swept load-pull data, the capability to directly determine matching network source and load impedances to achieve optimal PA performance is of paramount importance.

Matching networks that are designed from measured load-pull data enable fast and accurate assembly of PA circuit prototypes. That's because the uncertainty of a nonlinear model is removed and replaced with verifiable data, which can be easily obtained through measurement for the specific operating conditions under consideration. In this way, once the load-pull data have been imported into a circuit design software simulator,



2-dB gain compression (MHz) Frequency	2-dB gain compression (dBm) iGammaL1 = 10 iPower = 51 harm = 1
2110	40.316
2140	40.058
2170	40.146

8. These impedance points were plotted for a 2.1-GHz, 80-W LDMOS device.

the matching networks can be designed directly using the EDA software and its built-in matching network utilities and harmonic balance analysis (for frequency-domain, nonlinear simulations).

Another requirement for the design software is the ability to produce data sets that are equivalent to the measurement-based data used to develop the nonlinear models. Fitting simulation results to empirical data is required for modeling teams to verify the accuracy of their nonlinear device models. Therefore, the circuit design software must be able to produce equivalent measurements within the software, including more complex measurements such as adjacent channel power and intermodulation distortion. In this way, the circuit simulator is used not only for data manipulation and circuit design, but also to improve the accuracy of nonlinear device models.

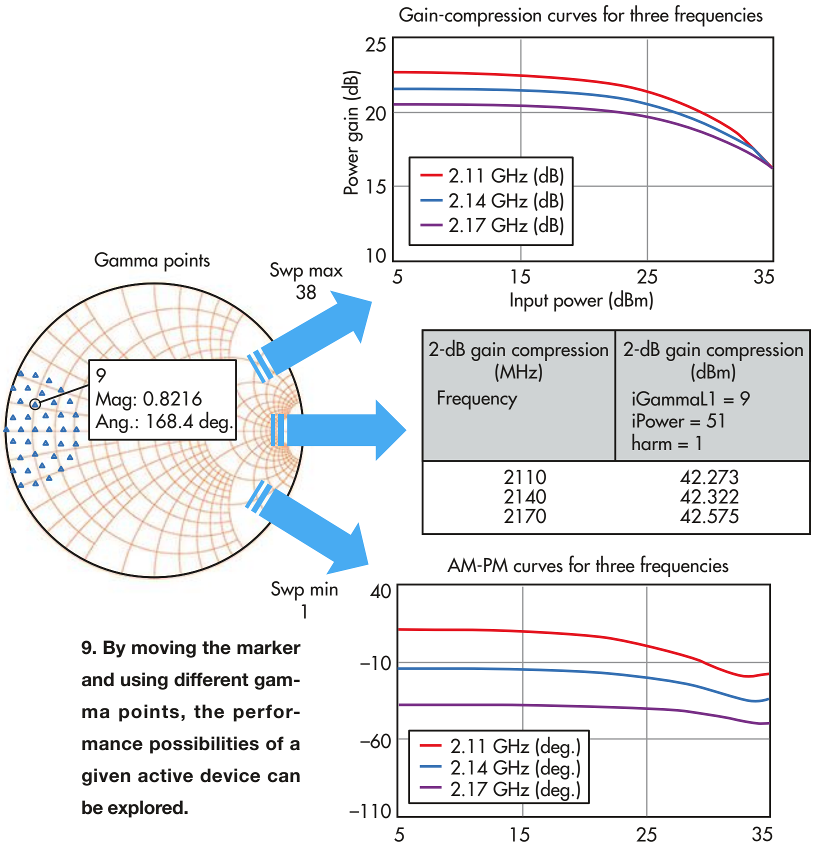
LOAD-PULL DESIGN ENVIRONMENT

Historically, single-sweep point files have been supported by commercial load-pull system suppliers (LP/SP files from Maury Microwave and LPD files from Focus Microwaves). NI AWR Design

Our new website was designed with the milimeterwave engineer in mind.

More than 750 full datasheets with measured data and comprehensive mechanical and electrical specifications. ***PRODUCTS FROM 18 TO 140 GHz.***

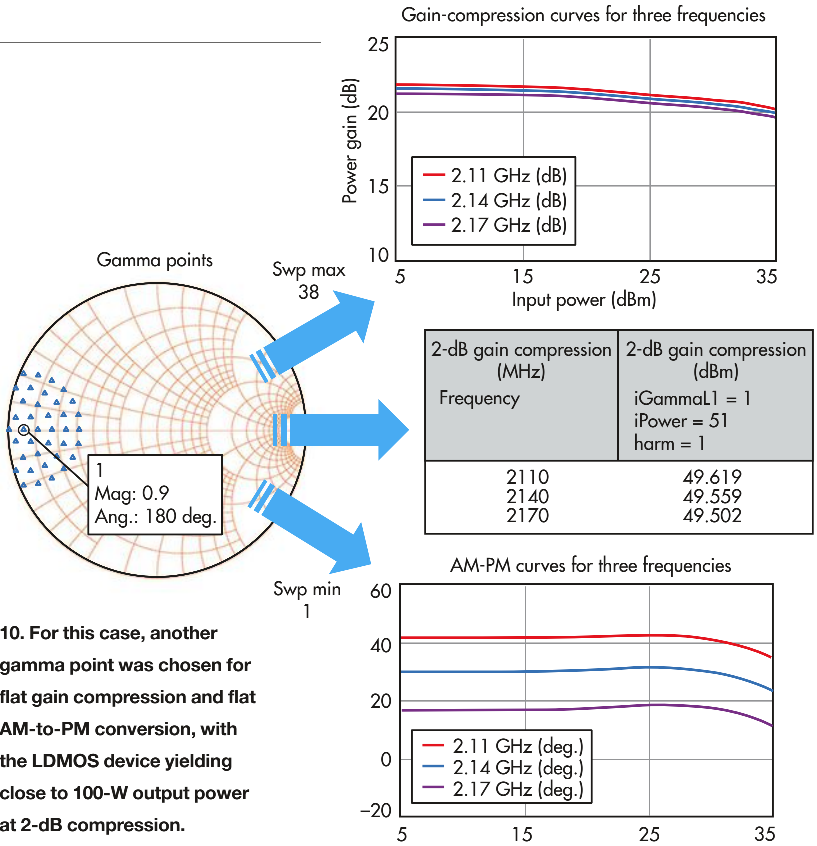
Load-Pull Simulation



9. By moving the marker and using different gamma points, the performance possibilities of a given active device can be explored.

Environment V12 software now supports multidimensional load-pull files such as Maury's SPL and CST files and Focus's LPD files, based on swept data. Files with more extended data sets, such as multiple gamma points, frequencies, and power steps, give NI AWR V12 software the opportunity to execute more seamless, intuitive post-processing of data with more comprehensive results in terms of PA design *(Fig. 4)*.

The new load-pull formats in the NI AWR Design Environment, specifically Microwave Office circuit-design software, offer circuit designers access to an extensive array of data-manipulation functions. *Figure 5* shows a rectangular graph of input power versus the index on the left. A marker points to a specific input-power level, with the contours for that power level plotted on the right. When the marker is moved, another set of contours will be shown corresponding to that power level. If the marker is moved again, a third set of contours is obtained, and so on, providing designers with multiple views of critical aspects of a PA circuit design's behavior—a much more comprehensive analysis tool than possible with older single-point local files.



2-dB gain compression (MHz) Frequency	2-dB gain compression (dBm) iGammaL1 = 1 iPower = 51 harm = 1
2110	49.619
2140	49.559
2170	49.502

10. For this case, another gamma point was chosen for flat gain compression and flat AM-to-PM conversion, with the LDMOS device yielding close to 100-W output power at 2-dB compression.

Conversely, instead of choosing an input-power level and plotting contours, users can select a gamma point or impedance value and plot swept data for that data point. *Figure 6* shows how gain-compression curves can be plotted by choosing a gamma point from the impedances in a data file. The plots in Fig. 6 show both gain-compression curves for all gamma points in the file, as well as the gain-compression behavior for a gamma point selected with the marker.

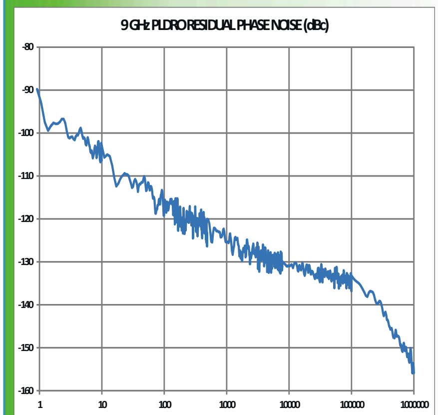
If the marker is moved to another gamma point, the gain-compression curve changes to reflect the performance at the new impedance *(Fig. 7)*. This feature highlights the tradeoffs in gain compression as a function of load for the entire swept input power range, enabling designers to quickly choose the load necessary for optimum gain-compression behavior given an expected input power.

NEW DESIGN FLOWS

The new load-pull analysis capabilities in this latest version of the NI AWR Design Environment (V12) make it possible to develop a new design flow for base-station PAs and other active circuits. As an example, *Figure 8* shows impedance points plotted for a 2.1-GHz active device, a silicon, laterally diffused, metal-oxide-semiconductor (Si LDMOS) transistor, capable of 80-W output power at 1-dB compression (P1dB). A gamma point was chosen and the AM-to-PM and gain-compression curves were plotted for three frequencies in the file (2.11, 2.14, and 2.17 GHz). The 2-dB gain-compression output power was also computed and plotted in tabular format.

Figure 9 shows how users can move a marker to select different gamma points and parse through the performance possibilities of a device, assessing tradeoffs at different points. If another impedance point is chosen, a new set of performance curves is automatically generated, corresponding to that new load impedance, as well as another set of AM-to-PM-conversion and gain-compression curves and another 2-dB gain-compression output-power value.

(continued on p. 150)



Design Feature

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Stripline Combline Filter Tunes 900 to 1300 MHz

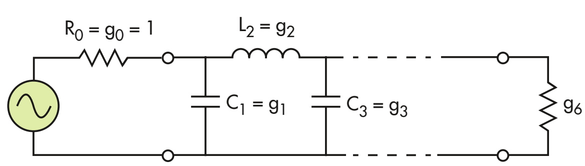
With the aid of 2.5D and 3D computer simulations, a novel compact stripline combline bandpass filter was designed and fabricated with a tunable passband across a wide frequency range.

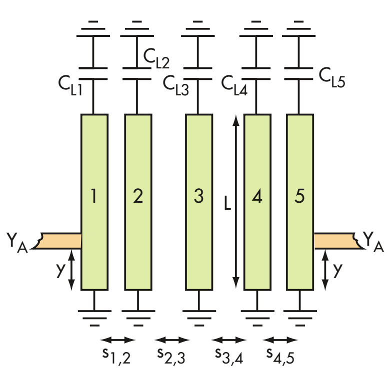
Filter designs are gaining in importance, along with the growing number of wireless applications and occupied bandwidths. Bandpass filters with low passband loss and high rejection are needed throughout the wide expanse of wireless communications bands. This prompted an attempt to design a five-pole Chebyshev stripline combline bandpass filter (BPF) with a tunable center frequency. The tuning capability adds to the filter's flexibility, while the stripline circuit technology supports high performance levels.

To demonstrate the feasibility of a stripline Chebyshev combline BPF, a circuit was fabricated on RO4003C substrate material from Rogers Corp. (www.rogerscorp.com) with dielectric constant of 3.38, using varactor diodes to achieve frequency tuning. The experimental filter covers a frequency range of 900 to 1,300 MHz while maintaining nearly constant fractional bandwidth.

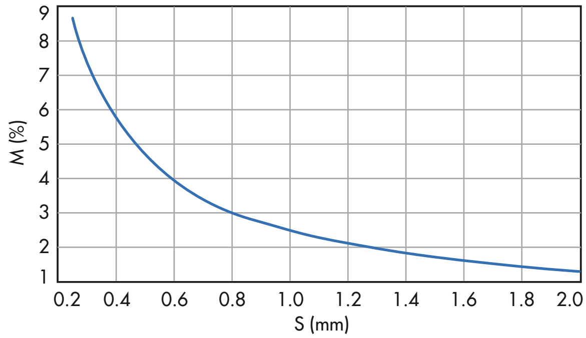
Many RF/microwave filters are designed for use for different bands from 0.1 to 20.0 GHz.[1] Tunable BPFs are of great interest for modern multiband communications systems with many efforts made to decrease the size of these components.[2] Such BPFs have been realized with a number of topologies—including combline filters, which are compact and offer ease of integration with other circuits due to their planar implementation.[3,4] A typical combline structure includes a series of transverse-electromagnetic (TEM) resonators with a circular or rectangular cross-section and a capacitor for resonance at the open-circuit end of the structure.

1. This block diagram represents a prototype Chebyshev lowpass filter circuit.

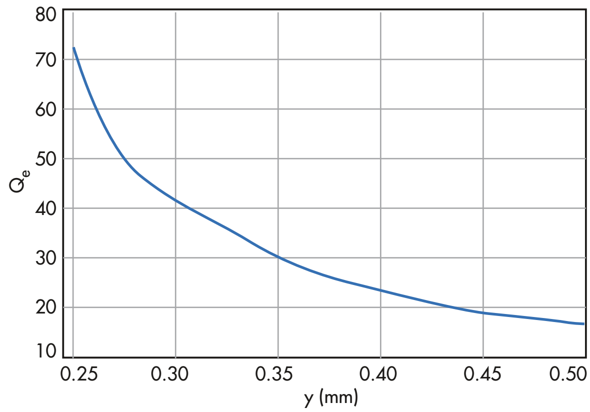




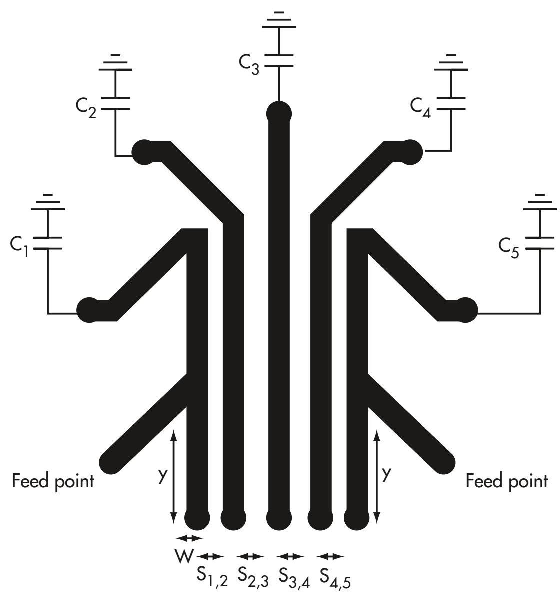
2. This diagram shows the general structure of a tapped combline filter.



3. The curve plots the coupling coefficient of two coupled stripline resonators as a function of spacing, s.



4. The curve plots the external Q of the combline filter as a function of y.



5. This diagram represents the proposed five-pole stripline combline filter.

The bandwidth and response of a combline filter is governed by the coupling of each resonator to its immediate neighbor. This is also a function of the resonator size, resonator spacing, and ground-plane separation.[1] Different components and circuit elements are added to a combline BPF structure to tune the passband frequency, including PIN diodes, [5] ferroelectric diodes,[6] RF microelectromechanical systems (RF MEMS) devices,[7] barium strontium titanate (BST) varactor diodes,[8] and silicon/GaAs varactor diodes.[9-13]

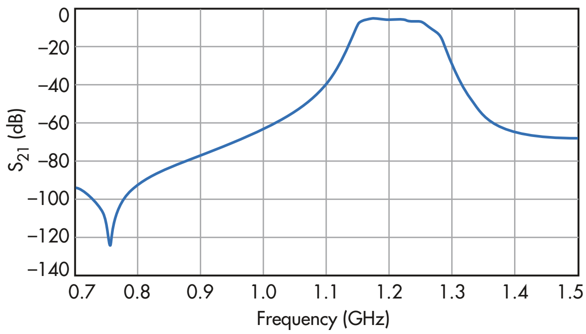
Microstrip has been the basis for many tunable combline filter designs.[14-21] In ref. 14, a tunable planar microstrip combline filter with multiresonator coupling is realized to achieve high selectivity. In ref. 15, a combline bandpass filter using step-impedance microstrip lines is investigated. Reference 16 detailed a 1.4- to 2.0-GHz miniature filter with high linearity. Reference 17 offers results on a tunable RF-MEMS microstrip filter with constant bandwidth by means of corrugated coupled resonators, while ref. 18 features a tunable combline bandpass filter loaded with series resonator.

Reference 19 details a compact dual-mode second-order filter with constant bandwidth, while ref. 20 presents a high-quality-factor (high-Q) fully reconfigurable tunable microstrip bandpass filter. Reference 21 details a tunable microstrip filter design with independent frequency and bandwidth control.

All of the above examples were based on microstrip. Few researchers have investigated stripline combline filters, although such filters can achieve much better bandwidth than their microstrip counterparts, with excellent isolation between adjacent traces.

To explore the performance capabilities of stripline combline filters, a five-pole stripline Chebyshev combline filter with tunable center frequency was designed and simulated. Tuning is performed by means of varactor diodes and capacitance that varies as a function of applied voltage. The filter provides tuning capability over a wide range of frequencies while maintaining a nearly constant fractional bandwidth and high stopband rejection.

Figure 1 depicts a simple schematic diagram of the prototype Chebyshev lowpass filter. For the required passband ripple, L_{ar}, in dB, and the minimum stopband attenuation, L_{as}, in dB, at a stopband characteristic impedance of Ω_s, in Ω, the degree of the prototype lowpass Chebyshev filter that will meet the required specifications can be found by Eq. 1:



6. This is a simulated response of the stripline combline filter with 100-MHz bandwidth centered at 1,200 MHz.

$$n \geq \cosh^{-1}\{[(10^{0.1L_{as}} - 1)/(10^{0.1L_{ar}} - 1)]^{0.5}\}/\cosh^{-1}(\Omega_s) \quad (1)$$

By assuming that the minimum stopband attenuation at $\Omega_s = 2\Omega_{cutoff} = 2$ and the passband ripple have been chosen as 50 dB and 3 dB, respectively, the degree of the Chebyshev lowpass prototype is calculated to be n = 5. The lowpass prototype parameters that were calculated from Eq. 1 can be found in the *table*.

Figure 2 shows the general structure of a tapped combline filter. To design a combline BPF, the following parameters are also required: center passband frequency (F_0) and passband bandwidth (BW). The filter is designed for a BW of 100 MHz and a F_0 of 1,200 MHz.

7. These simulated responses for the five-pole filter at 913 MHz show (a) S_{21} and (b) S_{11}.

To implement the proposed filter, quarter-wave transformers were employed as impedance inverters. Using parameters g_i calculated previously, it is possible to obtain the coupling coefficients of adjacent resonators $M_{i,\,i+1}$ and the external quality factors (Qs) of the resonators at the inputs and outputs as[1]:

$$M_{i,\,i+1} = BW/F_0(g_i g_{i+1})^{0.5},\quad i = 1, 2, 3, 4 \quad (2)$$

$$Q_{e1} = F_0 g_0 g_1/BW,\ Q_{e5} = F_0 g_5 g_6/BW \quad (3)$$

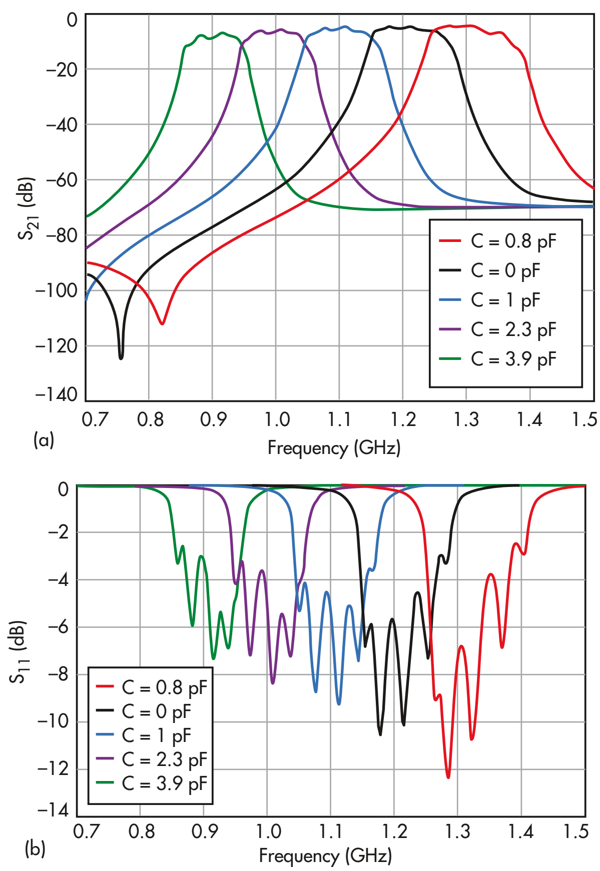
From the above equations, $M_{1,2} = M_{4,5} = 0.0511$; $M_{2,3} = M_{3,4} = 0.0448$; and $Q_{e1} = Q_{e5} = 41.7804$. The prototype stripline combline filter was designed on a circuit laminate with relative dielectric constant of 3.38 and thickness of 0.98 mm (Rogers Corp.'s RO4003C material). A line width was established at W = 0.55 mm with a line length of L = 20 mm and trace thickness t = μm for all of the filter line elements, except for the terminating lines. The terminating lines measured 0.93 mm wide, which matches a terminating impedance of 50 Ω.

The coupling coefficient of the two adjacent resonators can be calculated by Eq. 4[1]:

$$M = (F^2_H - F^2_L)/F^2_H + F^2_L \quad (4)$$

where F_H and F_L are representing the frequencies of the even- and odd-mode oscillations, respectively, in a system that incorporates two coupled resonators. These correspond to the clearly pronounced peaks in the attenuation characteristic for the dual resonator circuit.

By changing the spacing between the resonators and calculating the coupling coefficient using Eq. 4, the design curve of the coupling coefficient versus spacing, s, can be obtained. The dimensions of the spacing required to achieve the design requirements for the resonant circuit for the design parameters can then be found from a curve of coupling coefficient versus s *(Fig. 3)* as: $s_{1,2} = s_{4,5} = 0.45$ mm and $s_{2,3} = s_{3,4} = 0.53$ mm.



The external Q of the filter can also be extracted from Eq. 5[1]:

$$Q_e = \omega_0/(\Delta\omega_{\pm 90°}) \quad (5)$$

where ω_0 is the resonant frequency of the filter and $\Delta\omega_{\pm 90°}$ is the absolute bandwidth between ±90-deg. points in the phase of S_{11}. By changing the taping position y and calculating the external Q of the filter using Eq. 5, it is possible to generate a design curve of external filter Q versus y. With this curve (*Fig. 4*), the required taping position is obtained as y = 0.30 mm.

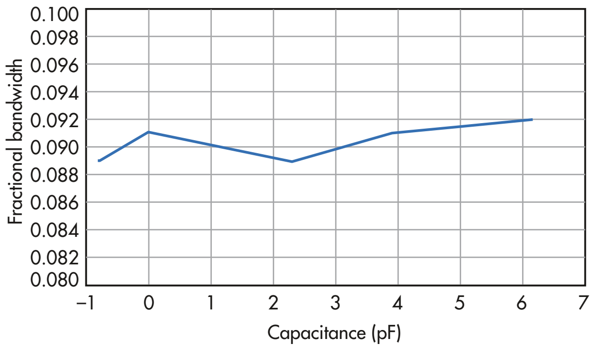
For tuning capability, varactor diodes were added to the proposed filter as variable capacitors, in place of the short-circuited end of the combline filter. Due to the small size of the proposed filter and fabrication issues involving small circuit dimensions, there is insufficient space to add varactor diodes in place of the short-circuited end of the coupling lines without interference. Therefore, the ends of the coupling lines are bent so that they do not interfere with each other after adding the varactor diodes. *Figure 5* shows the modified structure of the combline filter after the coupling lines have been bending the end of the couple lines. A bending angle of 45 deg. was chosen for minimum impact on the design.

SIZING UP SIMULATIONS

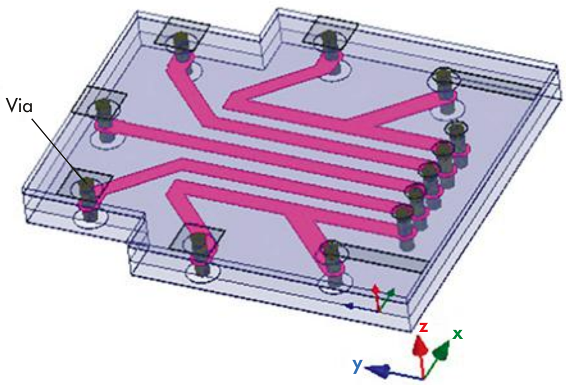
The filter circuit's performance possibilities were simulated with the Advanced Design System (ADS 2009) computer-aided-engineering (CAE) simulation software from Agilent Technologies (now Keysight Technologies; www.keysight.com). With the aid of the modeling software, the dimensions of the filter and the capacitance values were optimized with the following goals: The filter passband loss should be less than 2 dB and the filter stopband rejection should be more than 50 dB.

Figure 6 shows the simulated frequency response of the bandpass filter. As displayed in Fig. 6, the filter has a bandwidth of 100 MHz with center frequency (F_0) of 1,200 MHz. The stopband rejection level and passband ripple of the filter are about 50 dB and 3 dB, respectively, which are in keeping with the design goals.

To demonstrate filtering tuning, a constant capacitance value (C) was added to the capacitance of each varactor diode; *Fig. 7* shows the simulated filter frequency response for different values of C. As the plots show, by changing the capacitance of the varactor diodes, the center frequency of the filter can be tuned across a frequency range of 900 to 1,300 MHz with good impedance matching.



8. The plot presents filter fractional bandwidth as a function of capacitance, C.

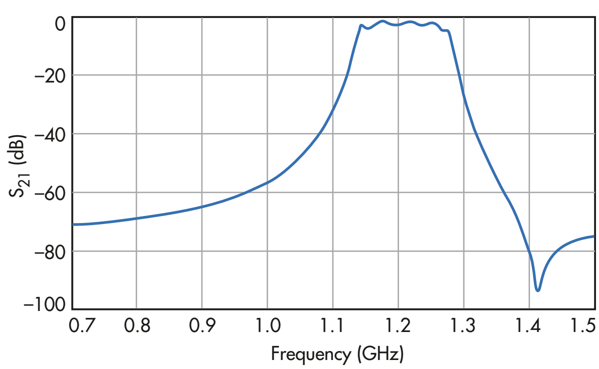


9. This schematic diagram was produced with the help of a 3D circuit simulator.

Figure 8 shows the filter's fractional bandwidth as a function of C. The fractional bandwidth of the filter (about 9%) is very stable when tuning the center frequency, due to the constant coupling coefficient of adjacent resonators during tuning.

The simulation results were achieved using two-and-one-half-dimension (2.5D) ADS simulation tools. Although more time-consuming, a three-dimensional (3D) software solver was needed for greater simulation accuracy. But even a 3D solver may not properly predict the effects of certain circuit structures, such as viaholes. For improved accuracy, the High-Frequency Structure Simulator (HFSS) full-wave electromagnetic (EM) simulator from Ansys (www.ansys.com) was used in the filter simulations. *Figure 9* shows a 3D HFSS schematic diagram of the stripline combine BPF, with each viahole modeled as a cylindrical structure.

As *Fig. 10* shows, the presence of viaholes will change the frequency response of the combline BPF. As an example, the 3D-modeled filter has a narrower transition band than simulations from the 2.5D ADS analysis. Still, the effects of



10. This simulated filter response was produced with a finite-element-method EM simulator (HFSS from Ansys).

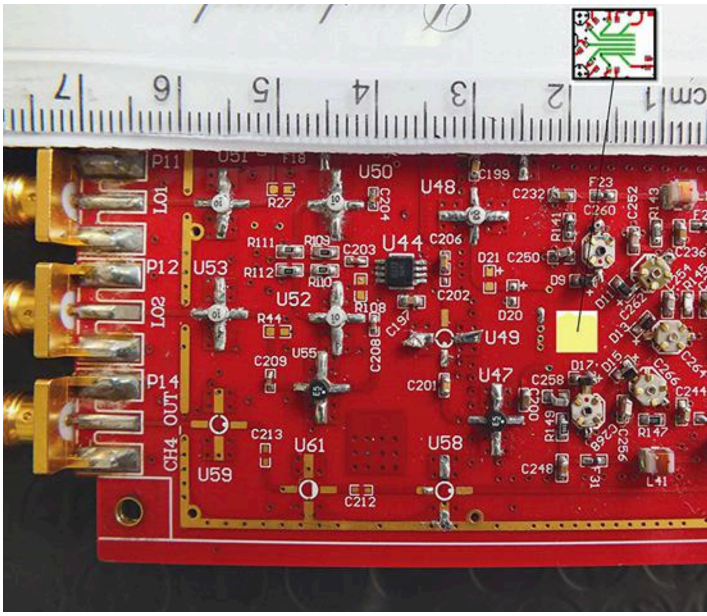
the viaholes on filter frequency response are negligible, meaning that the 2.5D simulations are still valid and accurate.

A hardware version of the filter was fabricated on RO4003C laminate using surface-mount-technology (SMT) packaged varactor diodes to provide the variable capacitances needed for filter passband tuning *(Fig. 11)*. Unfortunately, these diodes contribute to the losses of the filter and, for some applications, an additional amplifier may be needed to compensate for undesirable passband losses.

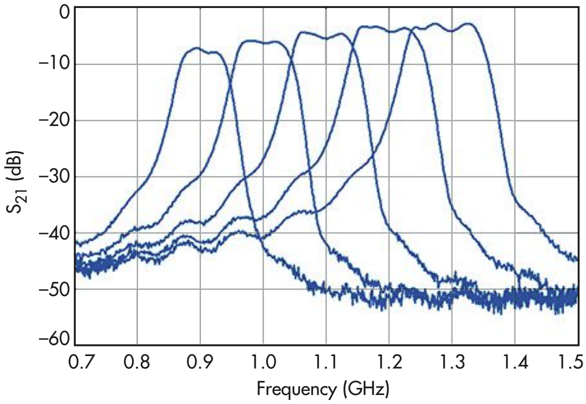
The filter was characterized *(Fig. 12)* with a model FSL6 spectrum analyzer from Rohde & Schwarz (www.rohde-schwarz.com). The filter tuning range from 0.9 to 1.3 GHz had a nearly constant fractional bandwidth (about 9%). The rejection level at both upper and lower stopbands was about 50 dB, and measured passband ripple was about 3 dB. The frequency range and response measured with the spectrum analyzer was found to be quite similar to the performance predicted by the computer simulations. mw

INITIAL DESIGN PARAMETERS FOR THE PROPOSED FILTER

n	0	1	2	3	4	5	6
g_n	1.0	3.4817	0.7618	4.5381	0.7618	3.4817	1.0



11. The photograph shows the fabricated tunable stripline BPF on RO4003C laminate.



12. The frequency responses of the stripline combline filter were measured with a commercial spectrum analyzer.

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5 - 500 WATTS PRODUCTS

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Model #	Frequency (MHz)	Insertion Loss (dB) [Typ./Max.] ◊	Amplitude Unbalance (dB) [Typ./Max.]	Phase Unbalance (Deg.) [Typ./Max.]	Isolation (dB) [Typ./Min.]	VSWR (Typ.)	Input Power (Watts) [Max.] ◦	Package
2-WAY								
CSBK260S	20 - 600	0.28 / 0.4	0.05 / 0.4	0.8 / 3.0	25 / 20	1.15:1	50	377
DSK-729S	800 - 2200	0.5 / 0.8	0.05 / 0.4	1 / 2	25 / 20	1.3:1	10	215
DSK-H3N	800 - 2400	0.5 / 0.8	0.25 / 0.5	1 / 4	23 / 18	1.5:1	30	220
P2D100800	1000 - 8000	0.6 / 1.1	0.05 / 0.2	1 / 2	28 / 22	1.2:1	2	329
DSK100800	1000 - 8000	0.6 / 1.1	0.05 / 0.2	1 / 2	28 / 22	1.2:1	20	330
DHK-H1N	1700 - 2200	0.3 / 0.4	0.1 / 0.3	1 / 3	20 / 18	1.3:1	100	220
P2D180900L	1800 - 9000	0.4 / 0.8	0.05 / 0.2	1 / 2	27 / 23	1.2:1	2	331
DSK180900	1800 - 9000	0.4 / 0.8	0.05 / 0.2	1 / 2	27 / 23	1.2:1	20	330
3-WAY								
S3D1723	1700 - 2300	0.2 / 0.35	0.3 / 0.6	2 / 3	22 / 16	1.3:1	5	316
4-WAY								
CSDK3100S	30 - 1000	0.7 / 1.1	0.05 / 0.2	0.3 / 2.0	28 / 20	1.15:1	5	169S

◦ With matched operating conditions

HYBRIDS RoHS

Model #	Frequency (MHz)	Insertion Loss (dB) [Typ./Max.] ◊	Amplitude Unbalance (dB) [Typ./Max.]	Phase Unbalance (Deg.) [Typ./Max.]	Isolation (dB) [Typ./Min.]	VSWR (Typ.)	Input Power (Watts) [Max.]	Package
90°								
DQS-30-90	30 - 90	0.3 / 0.6	0.8 / 1.2	1 / 3	23 / 18	1.35:1	25	102SLF
DQS-3-11-10	30 - 110	0.5 / 0.8	0.6 / 0.9	1 / 3	30 / 20	1.30:1	10	102SLF
DQS-30-450	30 - 450	1.2 / 1.7	1 / 1.5	4 / 6	23 / 18	1.40:1	5	102SLF
DQS-118-174	118 - 174	0.3 / 0.6	0.4 / 1	1 / 3	23 / 18	1.35:1	25	102SLF
DQK80300	800 - 3000	0.2 / 0.4	0.5 / 0.8	2 / 5	20 / 18	1.30:1	40	113LF
MSQ80300	800 - 3000	0.2 / 0.4	0.5 / 0.8	2 / 5	20 / 18	1.30:1	40	325
DQK100800	1000 - 8000	0.8 / 1.6	1 / 1.6	1 / 4	22 / 20	1.20:1	40	326
MSQ100800	1000 - 8000	0.8 / 1.6	1 / 1.6	1 / 4	22 / 20	1.20:1	40	346
MSQ-8012	800 - 1200	0.2 / 0.3	0.2 / 0.4	2 / 3	22 / 18	1.20:1	50	226
180° (4-PORTS)								
DJS-345	30 - 450	0.75 / 1.2	0.3 / 0.8	2.5 / 4	23 / 18	1.25:1	5	301LF-1

◊ In excess of theoretical coupling loss of 3.0 dB

COUPLERS RoHS

Model #	Frequency (MHz)	Coupling (dB) [Nom]	Coupling Flatness (dB)	Mainline Loss (dB) [Typ./Max.]	Directivity (dB) [Typ./Min.]	Input Power (Watts) [Max.] ◦	Package
KFK-10-1200	10 - 1200	40 ±1.0	±1.5	0.4 / 0.5	22 / 14	150	376
KDS-30-30	30 - 512	27.5 ±0.8	±0.75	0.2 / 0.28	23 / 15	50	255 *
KBS-10-225	225 - 400	10.5 ±1.0	±0.5	0.6 / 0.7	25 / 18	50	255 *
KDS-20-225	225 - 400	20 ±1.0	±0.5	0.2 / 0.4	25 / 18	50	255 *
KBK-10-225N	225 - 400	10.5 ±1.0	±0.5	0.6 / 0.7	25 / 18	50	110N *
KDK-20-225N	225 - 400	20 ±1.0	±0.5	0.2 / 0.4	25 / 18	50	110N *
KEK-704H	850 - 960	30 ±0.75	±0.25	0.08 / 0.2	38 / 30	500	207
SCS100800-10	1000 - 8000	10.5 ±1.5	±2.0	1.2 / 1.8	8 / 5	25	361
KBK100800-10	1000 - 8000	10.5 ±1.5	±2.0	1.2 / 1.8	8 / 5	25	322
SCS100800-16	1000 - 7800	16.8 ±1.5	±2.8	0.7 / 1.0	14 / 5	25	321
KDK100800-16	1000 - 7800	16.8 ±1.5	±2.8	0.7 / 1.0	14 / 5	25	322
SCS100800-20	1000 - 7800	20.5 ±2.0	±2.0	0.45 / 0.75	12 / 5	25	321
KDK100800-20	1000 - 7800	20.5 ±2.0	±2.0	0.45 / 0.75	14 / 5	25	322
KEK-1317	13000 - 17000	30 ±1.0	±0.5	0.4 / 0.6	30 / 15	30	387

* Add suffix - LF to the part number for RoHS compliant version.

◦ With matched operating conditions

Unless noted, products are RoHS compliant.

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CHRIS DEMARTINO | Technical Editor

The Differences Between Receiver Types, Part 2

As designers consider the performance tradeoffs between direct-conversion and superheterodyne implementations, a newer direct RF-sampling technique has entered the fray.

This two-part series examines various types of receiver implementations, focusing in on the roles played by receivers, as well as some of the characteristics that describe their performance. Part 1 analyzed both the direct-conversion and superheterodyne implementations. In Part 2, we'll take a deeper look into the dual-conversion superheterodyne receiver, as well as discuss the newer direct RF-sampling technique.

DUAL-CONVERSION SUPERHETERODYNE RECEIVERS

Part 1 discussed the single-conversion implementation of the venerable superheterodyne receiver. However, dual-conversion superheterodyne receivers are often utilized, too, thanks to several key advantages *(Fig. 1)*. This approach is particularly beneficial for higher-frequency applications, such as certain military radar receivers. In these instances, a high-frequency input signal is converted to an intermediate-frequency (IF) signal, which could be in the 1- to 3-GHz range. This signal is then converted again to an even lower frequency before being processed.

Given their name, dual-conversion receivers obviously have two frequency-conversion stages, meaning their configuration consists of two mixers as well as two local-oscillators (LOs). The first mixer converts the RF signal to a lower frequency, which can be called the first-IF frequency. The second mixer then converts this signal again to an even lower frequency, called the second-IF frequency. Although this configuration increases the complexity of a receiver, it also offers a number of advantages. On top of that, triple-conversion receivers are actually employed in some instances, as well.

The image frequency band is an obstacle that presents itself in every superheterodyne receiver. When an RF input signal and an LO input signal enter a mixer, it generates an IF output signal at the mixer's output. The frequency of this IF signal is equal to the difference of the RF input signal's frequency and the LO signal's frequency.

However, a different RF input signal along with the same LO signal can enter a mixer and generate the same IF output signal. This other input signal is known as an image frequency signal. It can be represented mathematically as follows:

$|F_{RF} - F_{LO}| = F_{IF}$

$|F_{image} - F_{LO}| = F_{IF}$

where:

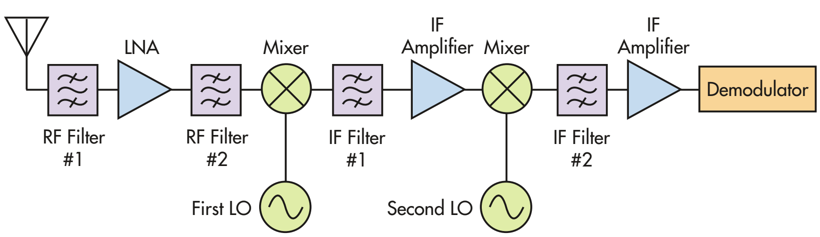
F_{RF} = frequency of the RF input signal

F_{LO} = frequency of the LO signal

F_{IF} = frequency of the IF output signal

F_{image} = frequency of the image signal

To suppress these unwanted image frequencies, a superheterodyne receiver requires filtering prior to the mixer. However, converting a high-frequency input signal to a very-low-frequency signal in just one conversion stage causes a problem: The image band will be very close in frequency to the actual RF input band. Thus, filtering these image frequencies



1. The dual-conversion superheterodyne receiver offers a number of performance advantages, especially with regard to higher-frequency applications.

> "It is obvious that receivers are critical to the performance of any communications system. Designers must take many factors into account during the development process."

becomes a challenge because of their close proximity to the actual RF input frequencies.

A dual-conversion configuration can remedy this situation. Employing two frequency-conversion stages makes it possible to space the image frequency band further away from the actual input frequency band.

The increased separation between the input frequency band and the image frequency band is due to the higher first-IF frequency. Converting the RF input frequency to this first-IF frequency allows the image frequency band to be further away when compared with the approach of converting the input frequency to the lower final output frequency directly. Consequently, the task of filtering the image frequencies becomes much easier.

As stated, dual-conversion superheterodyne receivers have the benefit of a higher first-IF frequency, which allows them to achieve good image rejection. Furthermore, such receivers can also achieve excellent selectivity thanks to their lower second-IF frequency—greater selectivity is generally easier to obtain at lower frequencies. Thus, dual-conversion superheterodyne receivers can simultaneously achieve superior image rejection and selectivity.

PERFORMANCE TRADEOFFS

Direct-conversion receivers do offer some advantages versus their superheterodyne counterparts. For example, they avoid the image-frequency problem. They also require fewer components, leading to simpler, lower-cost solutions. In fact, as mentioned in Part 1, direct-conversion receivers are available as integrated circuits (ICs).

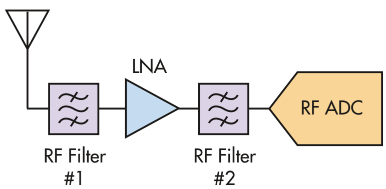
However, direct-conversion receivers are also plagued with several disadvantages. One of the biggest problems surrounds dc offset issues. For example, LO leakage mixing with the actual LO signal may inflict large dc offset errors on the output signal. LO leakage can be minimized by maintaining high isolation between a mixer's LO and RF ports. Another way to resolve dc offset problems is by converting the input signal to a frequency that is close to, but not exactly, dc. This implementation is known as a low-IF receiver. However, using such an approach reintroduces the image-frequency problem.

Superheterodyne receivers offer a number of benefits, such as the ability to achieve unmatched selectivity and sensitivity. They also are immune to the dc problems that occur in direct-conversion receivers. However, as mentioned, superheterodyne receivers have to cope with the image-frequency band. In addition, they are generally much larger in size because they require components like bulky filters. Therefore, these receivers typically are not suitable to be designed as ICs.

DIRECT RF SAMPLING

Performance advances in analog-to-digital converters (ADCs) over the past few years have enabled them to directly digitize signals at RF frequencies. While operating at high frequencies, they can maintain low noise and good linearity.

These advanced ADCs have enabled the direct RF-sampling receiver *(Fig. 2)*. They can directly sample signals at RF frequencies, thereby eliminating the need to convert an RF input signal to a lower frequency. This technique obviously represents a significant change from the traditional superheterodyne receiver. Now the promise of true software-defined radios (SDRs) can be fulfilled because of the capabilities of this new breed of ADCs.



2. Significantly fewer components are needed when building a receiver with the direct RF-sampling approach.

A direct RF-sampling receiver basically consists of a low-noise amplifier (LNA), the required filters, and the ADC. The ADC digitizes the RF signal directly and sends it to a processor. Because frequency conversion is not required, the overall design of a direct RF-sampling receiver is much simpler in comparison to a superheterodyne receiver. The ADC essentially replaces the mixer, oscillator, and entire IF signal chain found in superheterodyne configurations. Because they have fewer components, direct RF-sampling receivers can be built in smaller form factors.

CONCLUSION

It is obvious that receivers are critical to the performance of any communications system. Designers must take many factors into account during the development process. In particular, performance characteristics like noise figure, selectivity, and sensitivity must be examined closely.

The superheterodyne receiver is a traditional implementation found in many applications. However, direct-conversion receivers are good fits in certain situations, too. Lastly, the direct-RF sampling technique, the most recent receiver implementation, is a technology to keep an eye on. It holds a great amount of promise for future wireless systems. mw

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Investigate Wideband Frequency Converters

Wideband frequency converters can be designed using different architectures depending upon requirements for dynamic range, spurious rejection, size, and cost.

Wideband frequency conversion is essential in many high-frequency systems, and wideband frequency converters are the components that perform the required frequency translation over broad bandwidths. They come in different configurations and technologies, each with tradeoffs in cost, size, and performance.

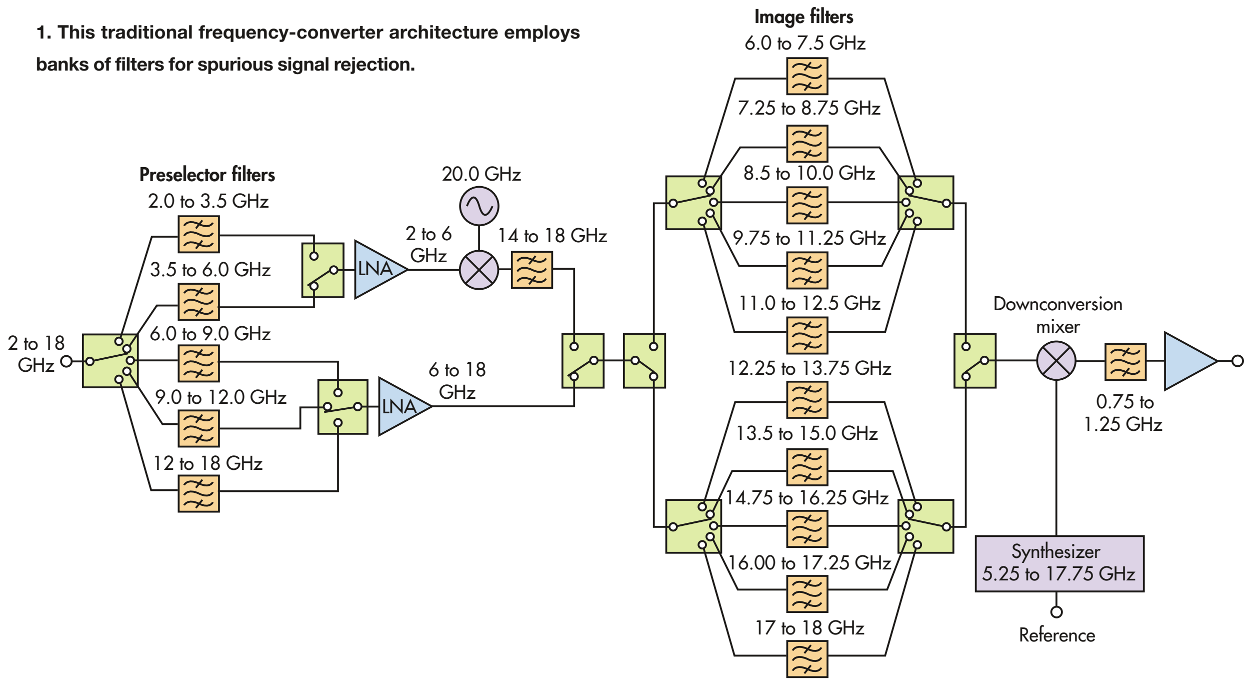
One frequency-conversion architecture that has been widely used in high-end signal intelligence receivers involves dual conversion of a received signal. In this architecture, a received signal is first upconverted to an intermediate-frequency (IF) signal at a low millimeter-wave frequency, then filtered, and finally downconverted to a lower-frequency second IF.

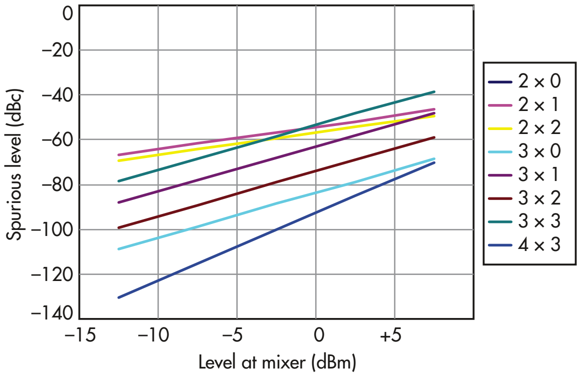
This technique greatly reduces the need for large, complex switched microwave filter banks, but it also demands the capabilities provided by broadband millimeter-wave frequency synthesizers. While such synthesizers were formerly very expensive, they have become more affordable with the advent of high-performance commercial-off-the-shelf (COTS) frequency converters fabricated with monolithic-microwave-integrated-circuit (MMIC) technology.

Wideband systems—especially for SIGINT and electronic-warfare (EW) applications—attempt to detect signals at the lowest possible signal levels, and with the fastest possible acquisition speeds. Such requirements dictate that a wideband frequency converter should have:

1. A careful frequency plan, so that the spurious responses do not fall within the down converted frequency band.
2. Low noise figure in support of the signal sensitivity levels that are required.

1. This traditional frequency-converter architecture employs banks of filters for spurious signal rejection.





2. This plot shows typical mixer spurious levels as a function of signal power to the mixer.

3. High linearity.
4. The capability to function effectively in the presence of interference, jammers, and blocking signals.
5. Mitigation of local oscillator and transmitter signal leakages;
6. Acceptable signal-to-noise ratio (SNR), phase-noise performance, and overall noise levels.

By using a wideband tunable receiver as an example, a traditional design will be evaluated through the use of different frequency upconversion and downconversion approaches. It will be shown that the traditional wideband receiver design can be improved via selection of different frequency converters, including through the use of a wideband converter design that employs readily available COTS MMICs.

The receiver example processes 2- to 18-GHz input signals in single 0.5-GHz-wide bandwidths at one time as it steps through the wide input bandwidth. Frequency downconversion is performed using frequency mixers. The incoming RF signal (f_{RF}) is converted to an IF signal (f_{IF}) by mixing with a local-oscillator (LO) signal (f_{LO}) signal, with this action expressed as:

$$f_{IF} = \pm mf_{RF} \pm nf_{LO}$$

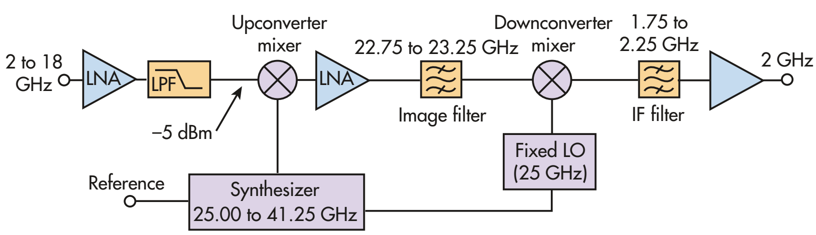
where m and n are integer harmonics of the RF and LO frequencies that add and subtract to create numerous combinations of spurious signal products, owing to the nonlinear properties of semiconductor devices (e.g., diodes and transistors used in frequency mixers). Filters are used to reject out-of-band RF signals that might cause in-band IF responses. IF filter sensitivity following the mixer is specified to pass only the desired frequencies, thereby filtering the spurious signals ahead of the final detector or signal processor.

Spurious responses that appear within the IF band will not be attenuated by the IF filter. Therefore, careful frequency planning is done in broadband converters so that the spurious signals do not fall within the IF band. This behavior and frequency plan is very well covered in the technical literature, with several examples presented in refs. 1 and 2.

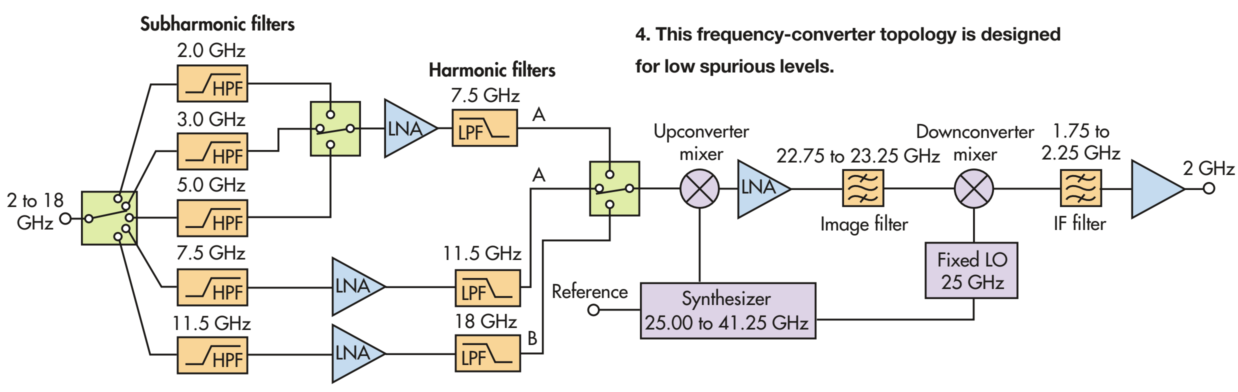
One approach to broadband frequency downconversion is to use mixers with several filters *(Fig. 1)*. In this case, a broadband signal search is performed from 2 to 18 GHz in five frequency bands: 2.0 to 3.5 GHz, 3.5 to 6.0 GHz, 6.0 to 9.0 GHz, 9.0 to 12.0 GHz, and 12.0 to 18.0 GHz. Bands covering 2 to 6 GHz are not converted and are passed through initially. They are then upconverted using a high-side LO of 20 GHz, so that all frequency bands now fall within the 6- to 18-GHz range.

The 6- to 18-GHz band in question is processed through 10 1.5-GHz-wide filters. This 1.5-GHz bandwidth is processed in 0.5-GHz bands through the second mixer using a wideband 5.25- to 17.25-GHz frequency synthesizer. Consequently, this configuration employs multiple filters and two frequency-conversion stages.

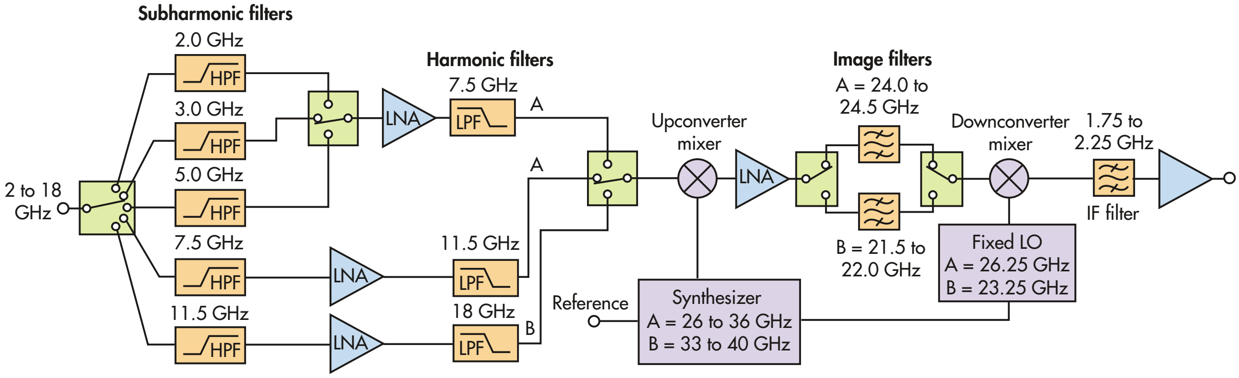
This frequency-conversion topology provides about 50-dB dynamic range and, with careful design, can achieve slightly higher dynamic range. The architecture requires many high-performance image filters, which are difficult to integrate. VSWR interactions associated with the filter banks also result in considerable amplitude and phase ripple. Since a broadband frequency synthesizer



3. This frequency-conversion architecture was designed for minimum filtering requirements.



4. This frequency-converter topology is designed for low spurious levels.



5. This frequency-conversion architecture includes additional filtering for outstanding spurious rejection and excellent SFDR performance.

is needed for the second LO, this frequency plan is difficult to establish and change. Fortunately, the problems with this frequency plan can be resolved by upconverting to higher frequencies and then downconverting.

Upconverting the 2- to 18-GHz input signals generates m × n products that are now at higher frequencies and are readily filtered, thereby eliminating signal products folding within the IF band. This approach enables the lowest possible spurious performance. Microprocessor control of signal gains can further optimize dynamic range by minimizing remaining spurious signal products.

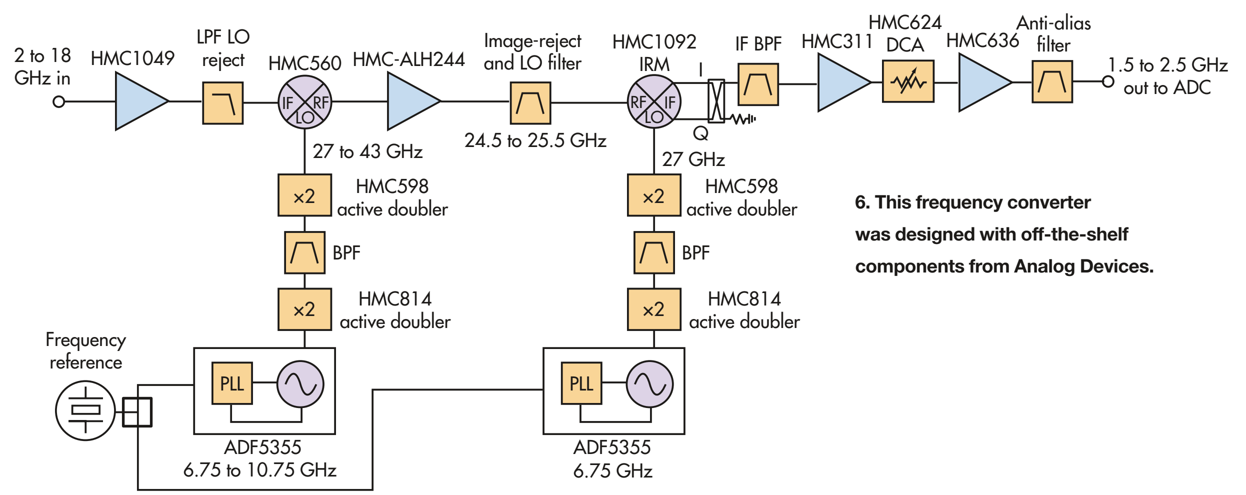
Many requirements can be met using only one bandpass filter for image rejection. This frequency plan is very flexible and has no difficulty with images. The low-noise-amplifier (LNA) harmonics generated in front of the frequency converter are the main spurious signals of concern.

This approach uses high-side LO signals generated by millimeter-wave frequency synthesizer. Several computer-simulation programs are available for calculating frequency mixer spurious power and spurious order[2] that, when combined with a spurious search program, allow tradeoffs to be made among frequency plans, power levels allowable at the mixer, and required filter rejection.

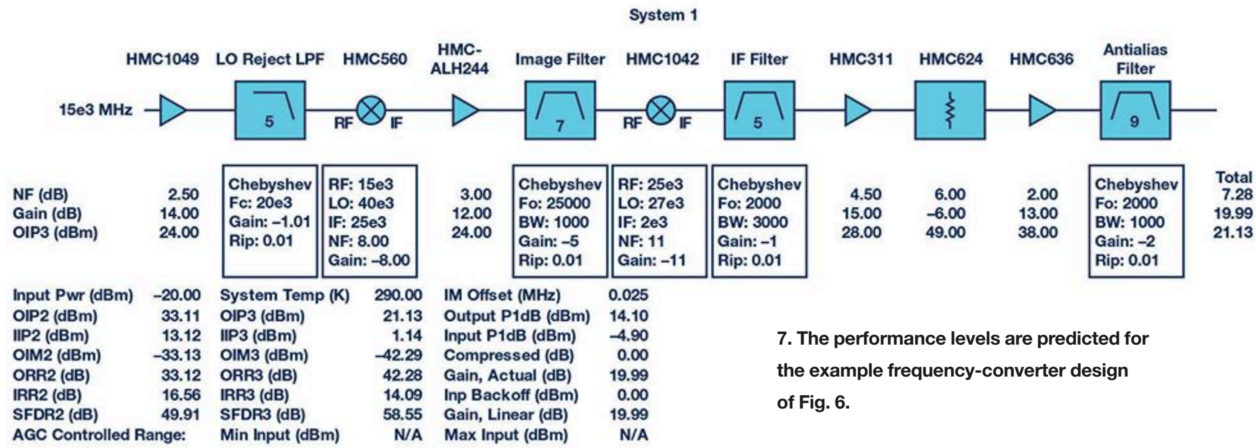
The equations that are employed in these computer-simulation programs were developed many years ago, and they have shown good agreement with actual test results when utilizing standard double-balanced mixers. These equations have shown

TABLE 1: PREDICTED SPURIOUS PERFORMANCE OF A SIMPLE WIDEBAND FREQUENCY CONVERTER

mxRF	nxLO	dBc	Ent-LO (GHz)	Ex-LO (GHz)	Ent-RF (GHz)	Ex-RF (GHz)	Ent-IF (GHz)	Ex-IF (GHz)
–1	1	0.02	25.00	41.25	22.0	24.00	2.00	18.00
2	0	–59.34	25.00	41.25	22.00	24.00	11.00	12.00
–2	1	–56.58	26.00	41.25	22.00	24.00	2.00	9.63
–2	2	–59.34	25.00	30.00	22.00	24.00	13.00	18.00
3	–1	–67.91	25.00	32.00	22.00	24.00	15.67	18.00
–3	1	–67.91	28.00	41.25	22.00	24.00	2.00	6.42
–3	2	–79.08	25.00	39.00	22.00	24.00	8.67	18.00
–3	3	–58.37	25.00	26.00	22.00	24.00	17.00	18.00



6. This frequency converter was designed with off-the-shelf components from Analog Devices.



7. The performance levels are predicted for the example frequency-converter design of Fig. 6.

TABLE 2: PREDICTED PERFORMANCE FOR A LOW-SPURIOUS FREQUENCY CONVERTER

Band	RF (GHz)	LO (GHz)	Spurs > –80 dBc with +5 dBm at mixer
1	2.0-3.0	24.75-28.35	–51 dBc 2 x 0 from 11.4-11.6 GHz –75 dBc 3 x 0 from 7.6-7.8 GHz
2	3.0-5.0	25.75-28.25	–51 dBc 2 x 0 from 11.4-11.6 GHz –75 dBc 3 x 0 from 7.6-7.8 GHz
3	5.0-7.5	27.75-30.75	–51 dBc 2 x 0 from 11.4-11.6 GHz –75 dBc 3 x 0 from 7.6-7.8 GHz
4	7.5-11.5	30.35-34.75	–51 dBc 2 x 0 from 11.4-11.6 GHz –75 dBc 3 x 0 from 7.6-7.8 GHz
5	11.5-18	34.25-41.25	–51 dBc 2 x 0 from 11.4-11.6 GHz –65 dBc 3 x 2 from 8.9-18 GHz

TABLE 3: PREDICTED PERFORMANCE FOR AN ULTRA-LOW-SPURIOUS FREQUENCY CONVERTER

Band	RF (GHz)	LO (GHz)	Spurs > –80 dBc with +5 dBm at mixer
1	2.0-3.0	26-27.5	None
2	3.0-5.0	27-29	None
3	5.0-7.5	29-32	None
4	7.5-11.5	31.5-36	–75 dBc 3 x 0 from 8.0 to 8.17 GHz
5	11.5-18	33-40	–65 dBc 3 x 2 from 14.67 to 18 GHz

good agreement with actual results in standard double balanced mixers.

The spurious performance of a typical double-balanced mixer is shown in *Fig. 2*. It can be seen that it is critical to control the gain in front of the mixer, and even modest levels of highpass filtering can greatly improve the performance.

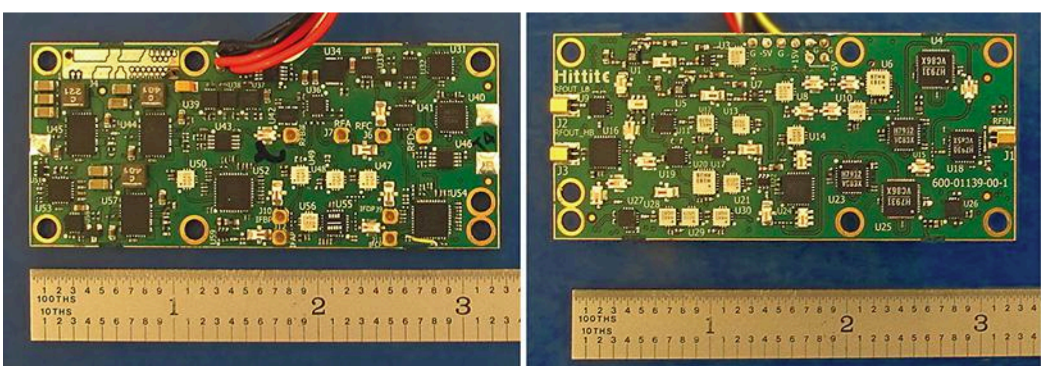
MINIMUM FILTERING CONVERTER ARCHITECTURE

The minimum filtering topology shown in *Fig. 3* uses a wideband tunable LO synthesizer. This allows the 2- to 18-GHz band to be upconverted in 500-MHz segments within a fixed 22.75- to 23.25-GHz frequency range. It is then downconverted using a fixed second LO to fall within the 1.75- to 2.25-GHz band that can then be readily processed.

This frequency-conversion scheme takes maximum advantage of a single bandpass filter for all image filtering. Along with the fact that all RF × nLO spurious products (where n is the harmonic number) are above band, this provides excellent performance with almost no filtering. *Table 1* shows predicted spurious performance at expected maximum input power levels.

For this example *(Fig. 3)*, assuming a noise figure of 8 dB, bandwidth of 20 MHz, and 10-dB SNR, the instantaneous spurious-free dynamic range (SFDR) is greater than 55 dB, the upper limit of the SFDR is about –20 dBm, and the compression level is about 15 dB above the upper limit of the SFDR. For this architecture, the use of signal processing to minimize spurious levels can

8. This multilayer PCB shows the RF/microwave components on the front (left) and back (right) sides of the board.



improve the total usable range of the system. In addition, all spurious signals not related to the input level are well out of band in this configuration. This architecture supports lightweight, miniature, and low-cost designs, but will be sensitive to high level interference and jamming as a result of the lack of preselection filtering.

The architecture in Fig. 3 can be further improved in terms of spurious reduction by simple filtering *(Fig. 4)*. This involves the addition of five highpass filters and three lowpass filters prior to upconversion. In this configuration, the 2- to 18-GHz band is upconverted in three bands: 2.0 to 7.5, 7.5 to 11.5, and 11.5 to 18.0 GHz.

This configuration offers ultimate spurious rejection of more than 20 to 30 dB by means of low-loss highpass and lowpass filters. The only exception is the image band, which is handled differently and only once. The only remaining significant spurious signals are harmonics of the RF input signal generated in components preceding the highpass filters.

The spurious levels for this architecture are summarized in *Table 2*. Ignoring the 2 × 0 and 3 × 0 spurious responses results in about 80-dB instantaneous SFDR. Using an image-reject mixer (IRM) for downconversion eases the millimeter-wave filter requirements and allow as much as 80-dB image rejection with standard microstrip construction methods.

Further performance improvements can be obtained if additional filtering is added between the upconverted signal and prior to the second downconversion. Adding additional switch-filter components allows virtually all single-tone spurious signals to be eliminated *(Fig. 5)*. The main result is to eliminate the 2RF direct harmonic feedthrough by using two selectable IF bands *(Table 3)*.

This frequency-conversion architecture is desirable for only the highest levels of system performance. It requires significantly more complex RF and LO circuitry compared with the earlier architectures.

Numerous components employed in these frequency-conversion architectures are available as integrated circuits (ICs) to shrink and simplify a frequency converter design. *Figure 6* offers an example of a frequency-converter design using components from Analog Devices.[4] In this example, input RF signals are upconverted in the first conversion stage and then downconverted in the second conversion stage; this shifts higher-order spurious products out of the passband. These components are available as packaged devices for surface-mount application on PCBs.

Between the two mixers, the only critical filter is the bandpass filter. The lowpass filter at the input serves to minimize

TABLE 4: COMPARING BROADBAND FREQUENCY CONVERSION APPROACHES

Parameter	Traditional (Fig. 1)	Up and down conversion (Fig. 3)	Low spurious (Fig. 4)	Ultralow spurious (Fig. 5)	Comments
Filtering	17	3	10	11	Filters are tougher to design per Fig. 1 and the filters in other configurations are relatively simple
Amplitude and phase control	Very difficult	Relatively easy	Moderate	Difficult	Amplitude and phase control is a direct function of the chain complexity
Resistance to jamming	High	Low	Moderate	High	This refers to resistance to external signals
Local oscillator	Multiple octave	Millimeter wave	Millimeter wave	Millimeter wave	
Frequency plan	Most complex	Simple	Complex	More complex	
Dynamic range (dB)	50	60	75	80	
Size	Largest	Compact	Medium	Large	
Weight	Highest	Low	Medium	High	

LO leakage through the input port. The bandpass filter after the second mixer minimizes in-band second harmonics caused by the IF amplifiers and falling within the band of the anti-alias filter, and provides additional LO rejection. There are many ways to create the LOs for this signal chain depending on system requirements. The example of Fig. 6 presents a simple, high-performance method for generating the LO with newly available PLL/VCO ICs from Analog Devices, with the performance shown in *Fig. 7*.

The predicted performance of downconversion with these PLL/VCO ICs includes a noise figure less than 8 dB and SFDR of greater than 55 dB. This simple configuration, which lends itself to compact, lightweight surface-mount-technology (SMT) assemblies, supports many applications.

Figure 8 shows an example of a wideband multichannel receiver designed with several catalog components surface-mounted on a multilayer circuit board. The board is populated with parts both on the front and back sides and is very compact, measuring 3.25 × 1.5 × 0.060 in. Passive components, ground connections, and signal interconnections are contained within various circuit-board layers.

Selection of any broadband frequency-converter topology depends on several performance metrics. *Table 4* offers a comparison of various types of frequency converters and their respective merits.

Digital approaches to wideband frequency conversion are described in ref. 3. Whether analog or digital techniques are considered, the selection criteria apply when it comes to frequency planning, spurious mitigation, and noise considerations. The main change for digital is to replace the second downconversion stage in an analog architecture with a high-speed analog-to-digital converter (ADC) and perform signal processing in the first and second Nyquist zones.

The development of broadband frequency converters is greatly simplified by the availability of many of the required components as standard ICs.[4] Their use makes possible affordable, high-performance wideband converters. mw

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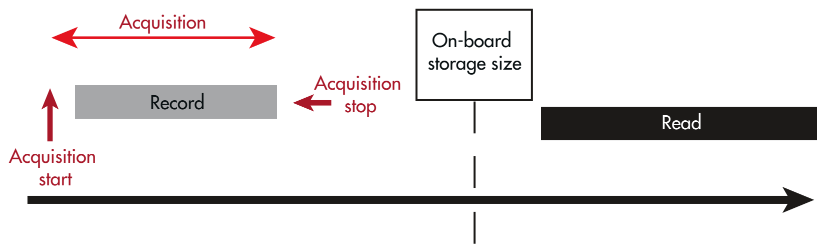
Managing Multichannel Signal-Acquisition Data

A modular digitizer/receiver can simplify the implementation of multichannel signal-acquisition systems with continuous data recording and display.

Signal acquisition in radar, signal intelligence (SIGINT), and electronic-warfare (EW) systems across megahertz and gigahertz instantaneous bandwidths can produce massive amounts of data that must be stored and processed. The data must be preserved in ways that ensure recovery of the best signal fidelity possible. To make the task even more formidable, signal acquisition and measurement usually occurs in these systems across multiple channels, turning even minutes of acquisition time into large amounts of data.

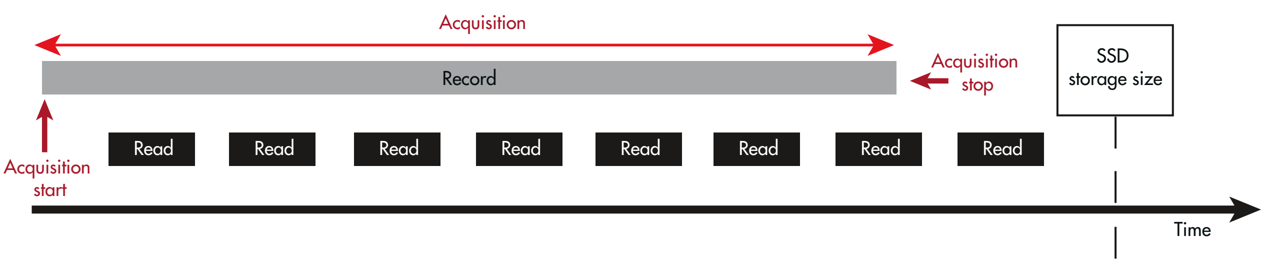


1. This is an example of a standard signal-acquisition and readout system configuration. It allows for data-recording times of as long as several minutes.

In particular, systems designed for signal acquisition require the acquisition, storage, and processing of an uninterrupted stream of samples at the highest possible data rate while guaranteeing no loss of data. A multichannel system composed of several subsystems—including analog frequency downconverters, high-speed digitizers, and data recorders—can be used for this purpose.

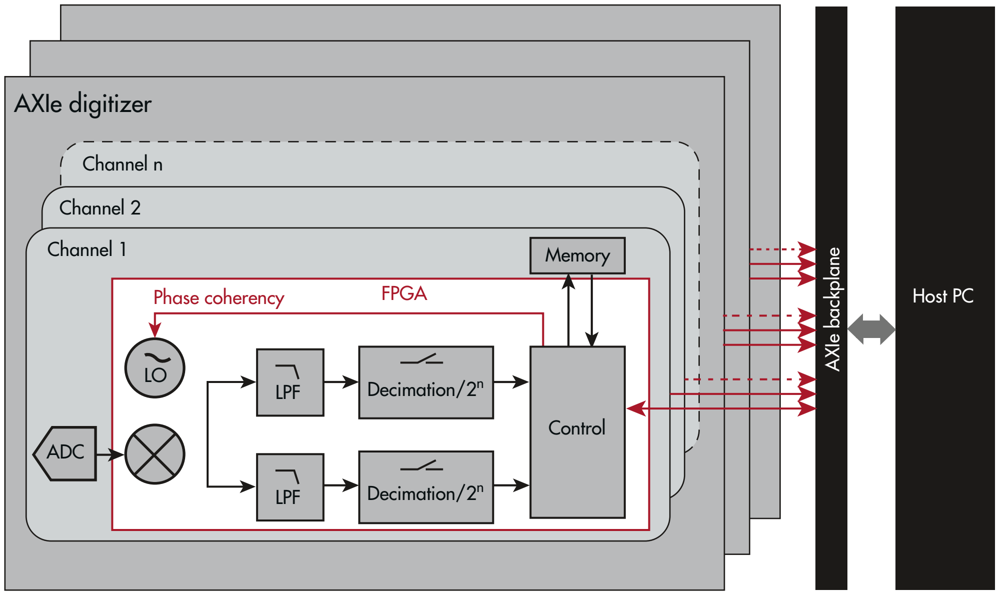
However, current fully integrated solutions can be very expensive; they are based on proprietary architectures with slow evolution of higher-performance generations. Therefore, solution providers are introducing new signal-acquisition systems based on commercial-off-the-shelf (COTS) components, including modular digitizers with smaller form factors at lower costs than previous generations of analog-to-digital converters (ADCs). These newer, integrated digitizers include all required data processing.

To enable viable data streaming and recording, continuous signal acquisition and readout across multiple channels is required. In standard acquisition and readout practices, the duration of the acquisition is limited by the internal buffer-memory size of the digitizer. The readout of the data is performed after signal acquisition has stopped, with the signal-acquisition data rate supported by the maximum speed allowed by the digitizer. This sequential approach to signal acquisition and readout operation is not suitable for aerospace and defense applications, however, where larger time windows are required for acquisition of signals related to potential threats *(Fig. 1)*.



2. This is an example of a continuous signal-acquisition and readout approach showing gapless acquisition (no data loss). This system records signal-acquisition data from several hours to as long as several days at a time.

3. This is a simplified block diagram of a DDC implementation within an FPGA, with phase coherency control across channels and modules.



For defense and aerospace applications, a continuous and simultaneous approach to signal acquisition and readout is more suitable, where data readout is performed simultaneously to the signal acquisition. Incoming data from the signal acquisitions are stored in a continuous manner within a suitable memory storage device, using the application provided with the digitizer *(Fig. 2)*.

In radar and other RF/microwave applications, the signal of interest is located at high frequencies that must be translated to a frequency range for signal processing and digitization in order to perform analysis and display of the captured signal. Frequency downconversion is performed to shift incoming signals to an intermediate frequency (IF) that is within the sampling rate of available ADCs for effective signal processing in the digital realm.

A frequency downconverter allows for conversion of a high-frequency signal around a center frequency (F_c) to a complex, lower-frequency baseband signal. Lowpass filters (LPFs) are utilized to remove any unwanted signal content, such as harmonics and spurious signals, produced in the process of frequency downconversion.

Threat signals, like those from a hostile radar system, are readily masked by a plethora of surrounding signals—including noise and harmonics from licensed broadcast systems—and extracting those signals for acquisition and analysis is a challenge for most signal-acquisition systems. To improve signal detection in noisy RF environments, it is common to use multiple-input, multiple-output (MIMO) types of algorithms to detect signals from a given source across multiple antennas, so as to gain as much detail about the incoming signals as possible.

A multichannel system that can successfully perform complex measurements must meet certain requirements. In particular, phase coherency of measured signals is critical. This requires that all local oscillators (LOs) used for frequency downconversion within the system operate at the same frequency and phase. Also, all input signal paths must be tightly balanced in gain and phase.

A typical means of achieving LO phase coherency is by performing distribution of a single LO's outputs to feed the multiple channels. This involves a complex calibration scheme to ensure that those divided signals remain tightly controlled in phase. Newer implementations of multichannel signal-acquisition systems employ multiple LOs locked in frequency and phase to a precision reference source.

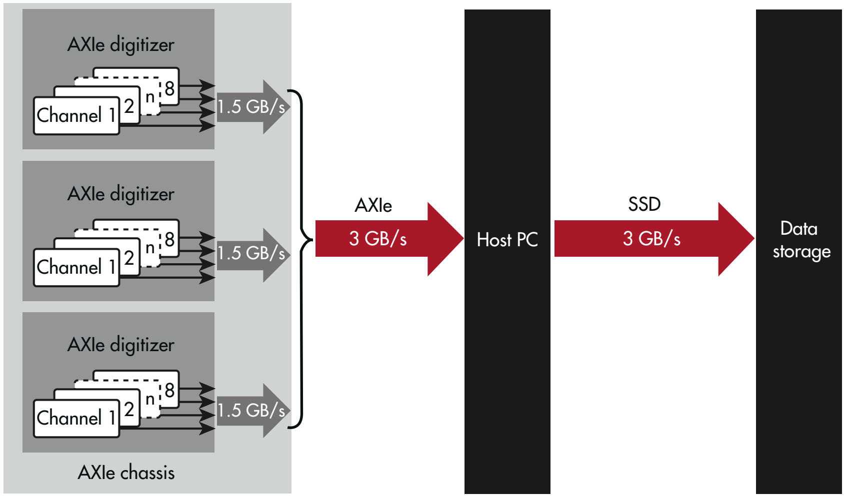
MODULAR SOLUTION

A complete signal-acquisition solution includes a modular digitizer and a standard host personal-computer (PC) workstation with solid-state-drive (SSD) memory-storage devices. Such a system approach is based on three key elements: a wideband digitizer, a digital downconversion process, and simultaneous data-acquisition and read-out processes. The digitizer must operate at high-speed sampling rates (typically in the gigasample-per-second range), with real-time processing capabilities and on-board field-programmable gate arrays (FPGAs) capable of implementing digital downconversion (DDC).

A multiple-circuit-board synchronization process is required to scale up the synchronization of the multiple signal-acquisition channels in such a system. It is enabled by two key factors: a common reference clock oscillator, with outputs distributed to each downconversion module to ensure synchronous clocking of each ADC channel; and a dedicated multiboard synchronization infrastructure that ensures phase coherency of each DDC LO. Phase coherency of the DDC LO is managed via a dedicated control FPGA. It allows for system synchronization of all channel FPGAs located on a single module and the control FPGAs of all adjacent modules *(Fig. 3)*.

An effective signal-acquisition system must permit selection of the decimated sampling rate, enabling reduction of the data volume to be streamed without losing any signal information. It should also provide the largest possible instantaneous bandwidth, free from unwanted spurious signal products, and continuous streaming without overflow.

To reduce data volume, the acquisition data rate can be adapted to the target application by several mechanisms: downsampling, which allows reduction of the signal-acquisition sample rate by means of binary decimation; truncation and compression, which



4. A data-streaming architecture was implemented using three AXIe digitizers with maximum data rate per connection, enabling high-performance configurations.

truncates signal samples on fewer digital bits and packs them continuously to reduce the total volume of data; and controlling the sampling frequency with an external clock source, which allows fine tuning of the incoming-signal sampling rate. To reduce data without impacting signal quality, a compact sample-size mode is implemented. When switching to this mode, output data are further packed, allowing faster streaming.

The M9703B high-speed digitizer/receiver from Keysight Technologies (www.keysight.com) is an example of a commercial solution for wideband signal acquisition and data streaming. The device, which is designed in the AXIe modular format, operates over a signal-acquisition range from dc to 2 GHz, with eight channels that sample at rates up to 3.2 Gsamples/s with 12-b resolution.

Given the compact size of the AXIe format (with each M9703B digitizer fitting into a single AXIe card slot) and the capability of synchronizing as many as three of these M9703B modules, up to 24 signal-acquisition channels can be achieved in a compact system architecture with full data-streaming and recording capabilities *(Fig. 4)*.

The digitizer/receiver features interleaving capability that allows two channels to be combined to achieve signal-acquisition rates at sampling rates of 3.2 Gsamples/s across four channels and at instantaneous bandwidths as wide as 1.4 GHz. The M9703B contains generous on-board signal-acquisition memory and powerful real-time data-processing capabilities by merit of four Virtex 6 FPGAs from Xilinx (www.xilinx.com).

The on-board FPGAs can be configured with an optional real-time wide-dynamic-range DDC that allows for tuning and zooming on a signal to be analyzed. (More information on the model M9703B AXIe 12-b digitizer/receiver and DDC options CB1 and CB2 can be found at www.keysight.com/find/m9703b.)

Depending on the requirements of an application, such as the instantaneous bandwidth and number of channels, the data-streaming configuration can be adjusted to optimize the data throughput and recording time to an SSD memory storage device. The maximum recording time depends on the following criteria: selected instantaneous bandwidth, standard mode or 12-b mode, digitizer sampling rate, number of channels, and data-storage capabilities.

To show the capabilities of this modular signal-acquisition architecture, three different signal-acquisition system configurations were assembled based on the model M9703B wideband digitizer, an HP Z440 PC workstation from Hewlett-Packard Co. (www.hewlettpackard.com), and multiple 8-TB SSD memory storage devices.

The first example was designed for the largest instantaneous bandwidth, 320 MHz. It achieves a signal-acquisition sampling rate of 1.6 Gsamples/s and a data rate of 1.2 Gsamples/s using 24-b mode. This performance was implemented with two AXIe card slots using two digitizers. The system achieves maximum data-recording time of around two hours in single-channel mode and about one hour operating with two signal-acquisition channels.

To achieve maximum instantaneous bandwidth with the largest number of channels, the AXIe digitizer/receiver was configured with two modules for eight channels operating across an instantaneous bandwidth of 100 MHz. It functions with a signal-acquisition sampling rate of 1 Gsamples/s and data rate of 350 MB/s. This configuration delivers maximum signal data-recording time of about six hours in single-channel mode.

For a setup with the largest number of channels and a long recording time, three AXIe digitizer/receiver modules were combined to achieve 24 channels operating across an instantaneous bandwidth of 10 MHz and a signal-acquisition sampling rate of 1.6 Gsamples/s. This compact three-module configuration runs at a data rate of 37.5 MB/s with maximum data-recording time of more than 59 hr in single-channel operation, and around 7.5 hr per channel with eight channels in use.

These examples provide some insight into the relationships of bandwidth, sampling rate, memory size, and data-recording time, as well as how continuous signal acquisition requires some "juggling" of system performance goals to achieve certain requirements, such as long data recording times. Fortunately, modern modular signal-acquisition instruments like the M9703B provides a great deal of flexibility in system planning, without adding a lot of size when adding capabilities. mw

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A Special Section to PENTON'S DESIGN ENGINEERING & SOURCING GROUP APRIL 2016

JACK BROWNE | Technical Contributor

SEEKING SECURE AND MOBILE COMMUNICATIONS

Military forces have long sought a universal communications network that is far-reaching, secure, and capable of handling the bandwidth requirements of the modern battlefield.

MILITARY COMMUNICATIONS equipment may lack the pocket-sized convenience of a modern smart cellular phone, but it must endure punishing operating conditions and deliver secure communications at all times. The need for ruggedness can add size and weight to mobile military radios, which is acceptable if the radio works as designed. Modern mobile military communications equipment come in many forms—from point-to-point terrestrial radios to satellite-based systems for greater range—with the goal always the same: get the message through.

Troops from different branches of the U.S. military have long suffered from incompatibilities in communications equipment. Whether in frequency, bandwidth, modulation scheme, or some other parameter, each branch typically specified gear in such a way that made networking among the different branches difficult (if not impossible). The Army,

(continued on p. 110)

1. Tactical communications equipment is taking after commercial cellular telephones, aiming for small size and weight and longer operating times on a single battery charge. Taking a lead from the JTRS program, some available tactical radios can even work with commercial battery packs and chargers. *(Courtesy of Harris Corp.)*

RAYTHEON TO ADD VIIRS SENSORS for NASA/NOAA

RAYTHEON CO. (www.raytheon.com) has received a $564-million contract modification award from NASA for two satellite sensors as part of the National Oceanic and Atmospheric Administration's (NOAA) Joint Polar Satellite System (JPSS) Polar Follow-On missions. These two sensors, Polar Follow-On JPSS-3 and JPSS-4, are the fourth and fifth visible infrared imaging radiometer suite (VIIRS) sensors that Raytheon has been contracted to build for NASA. The JPSS is a collaborative effort between NOAA and NASA.

The first VIIRS sensor from Raytheon, launched in 2011, is flying on the NOAA/NASA Suomi National Polar-orbiting Partnership satellite. The sensor collected imaging data across light spectra from visible through infrared (IR) bands so that scientists can study weather and climate patterns in great detail. According to Robert Curbeam, vice president and deputy of space systems for Raytheon's Space and Airborne Systems business, "This technology gives weather forecasters the data they need to make accurate predictions, and help individuals and communities better prepare for severe weather events." ■

(continued on p. 107)

Making Sure
the Message Gets Through

COMMUNICATIONS TECHNOLOGY may never receive the attention given to defense or weapons systems, but it is every bit as essential to any fighting force. After all, it is no exaggeration to say that a wrong message or instructions not properly received could prove to be fatal.

One challenge facing both commercial and military wireless communications systems designers is limited bandwidth, coupled with a growing need for bandwidth as the number of users and the amount of data, video, voice, and other information to be transferred increases. Modern in-field communications to a command station may include voice, digital photography, video, and telemetry data. Not only does this consume bandwidth, but it must be transferred securely in the midst of adversarial forces. Effective encryption is also essential.

Approximately two years ago, the U.S. Navy began construction on an impressive solution to the communications needs of modern military forces: the Mobile User Objective System (MUOS; *see p. 110*). On the ground, it borrows from the thinking of the previous Joint Tactical Radio Systems (JTRS) program to create a "universal" radio—equipment that would allow all branches of the military to communicate seamlessly but securely. In the air, it is based on connecting radios by means of four geosynchronous satellites.

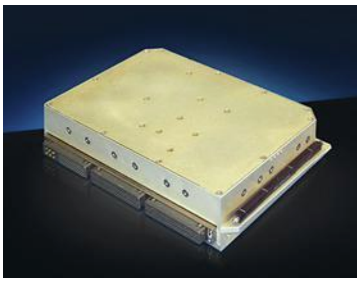
Of course, every branch of the Armed Forces has its own way of implementing a communications solution, and even its own communications waveforms. Among other things, the JTRS efforts helped foster software-defined-radio (SDR) technology, which makes it possible to redefine the essential characteristics of a radio via software.

Physically, military radios are borrowing more from their commercial counterparts. They must be rugged, so admittedly, they will never match the small sizes and light weights of commercial cellular telephones. But modern military radios are continuously evolving from the familiar "manpack" radios still widely in use. The new generation of military satellite-based radios will allow secure communications on the move and on the go, which could make a life-saving difference during critical times. ■

Jack Browne, Technical Contributor

MILPOWER SOURCE Energizes Northrop Grumman for SABR

MILPOWER SOURCE (www.milpower.com), a developer of custom power supplies and energy systems for defense and military systems, has signed a long-term agreement with Northrop Grumman (www.northropgrumman.com) to provide power supplies for the APG-83 Scalable Agile Beam Radar (SABR) system. The firm will deliver lightweight, low-noise power supplies for the program. According to the contract, Milpower Source will initially provide 288 power supplies that will be used for the first radars as part of the Taiwan Air Force F-16 upgrade program. The first production power-supply units will be delivered to Northrop Grumman in 2016.



"Milpower Source values the relationships we have built with Northrop Grumman, and we will continue to strive to meet the needs of every program," says Bruce Maroni, president of Milpower Source. "To achieve this goal, Milpower is constantly innovating new technology, and our engineers work to stay ahead of this ever-changing market." ■

USAF LOOKS TO LOCKHEED MARTIN for Enhanced Polish Aircraft

THE UNITED STATES AIR FORCE (USAF) recently awarded a $7.9-million Foreign Military Sales contract to Lockheed Martin (www.lockheedmartin.com) for additional integration of the Joint Air-to-Surface Standoff Missile (JASSM) onto Polish Air Force F-16C/D aircraft. Poland became the third international customer for the JASSM system in September 2015. This second JASSM order, issued in December 2015, will conclude in 2018.

The missile technology greatly strengthens Polish air defense, according to Bob Adams, long-range strike systems international program manager for Lockheed Martin Missiles and Fire Control: "Our airworthiness efforts expand and refine JASSM's employment flexibility on Polish jets, ensuring the Polish Air Force has this vital cruise missile capability."

Adams adds, "JASSM's high reliability and effectiveness allows the missile to defeat current and future threats in challenging environments." JASSM is a stealthy, precision-guided cruise missile that employs an infrared seeker and digital antijamming Global Positioning System (GPS) receiver. It is integrated on the USAF's B-1, B-2, B-52, F-16, and F-15E aircraft, and internationally on the F/A-18A/B and F-18C/D aircraft. ■

STRONG MARKETS EXPECTED for Manpack and Vehicular Radios

GLOBAL MARKETS for military manpack and vehicular radios are expected to remain robust during the period from 2016 through 2024, according to research firm Research and Markets (www.researchandmarkets.com). A compound annual growth rate (CAGR) of 4.59% is projected, with strong growth in sales of a universal battery pack (UBC) that is used to power many of these portable military radios. This latest-generation battery pack, developed by the U.S. Army's Communications Electronics Development and Engineering Command (CERDEC), provides advantages in weight and operating time compared to those of earlier power packs.

The Army achieves reliable terrestrial communications without need of satellite, using line-of-sight communications with various vehicle-mounted and manpack radios. Radio systems include the Mid-Tier Networking Vehicular Radios (MNVRs) supplied by Harris (www.harris.com), based on the firm's proven Falcon series of wideband tactical radios. The MNVR radios provide ground-level connectivity with rapid exchange of voice messages, images, and videos, enabling the creation of secure, mobile networks on the battlefield. ■

ROCKWELL, STAUDER Team for Joint Fires Defense Market

ROCKWELL COLLINS and Stauder Technologies have announced a strategic alliance agreement to better serve the worldwide joint fires defense market. Rockwell Collins (www.rockwellcollins.com) is prime contractor for a number of global joint fires programs, including for the U.S. Air Force Tactical Air Control Party, Close Air Support System (TACP CASS) and the United Kingdom Joint Fires program. Stauder Technologies (www.staudertech.com) brings a proven track record of developing integrated digital communications solutions to the warfighter, and is the prime contractor for the U.S. Marine Corps' Target Location, Designation, and Handoff System (TLDHS) program.

The combined strengths of the two major suppliers are expected to greatly benefit all customers and end users. According to Mike Jones, vice president and general manager, communications, navigation, and electronic warfare products at Rockwell Collins, "The agreement with Stauder Technologies enables Rockwell Collins to deliver a revolutionary joint fires digital interoperability capability from both a ground and airborne aspect that will provide tactical overmatch to our customers in a dynamic defense environment."

"We are excited about the opportunity to team with Rockwell Collins, a highly respected and experienced partner in the joint fires market," adds Jerry Stauder, president and CEO of Stauder Technologies. "This agreement enables our team to provide unparalleled and proven targeting and interoperability solutions to the worldwide joint fires defense market." ■

Romania Gains SITUATIONAL AWARENESS with Dual TPS-77s

THE ADDITION of two new TPS-77 radar systems from Lockheed Martin (www.lockheedmartin.com) has enhanced the situational-awareness capabilities of the Romanian fighting forces. Supplied under a contract agreement with Lockheed Martin, these next-generation radar systems feature Digital Array Row Transceiver (DART) technology for improved surveillance detection performance and energy efficiency compared to older radar systems.

Romania and Lockheed Martin have worked in partnership since 1995, including the delivery of more than two dozen ground-based radar systems from Lockheed Martin. "For over 20 years, Lockheed Martin and Romania have built a strong partnership to enhance Romania's air surveillance and weather radar network," says Mark Mekker, director of surveillance radar for Lockheed Martin. "The feedback we receive from our ongoing collaborations with countries like Romania leads to the development of system enhancements, like DART. Our teams thrive on developing leading-edge technologies to meet our customers' needs."

Part of the energy efficiency possible with the TPS-77 subsystems is due to the use of solid-state gallium-nitride (GaN) power amplification, a component in Lockheed Martin radar systems for more than six years. ■

Image Processing Critical for PHALANX SEARAM SYSTEM

THE PHALANX SeaRAM Close-In Weapon System (CIWS) developed by Raytheon Co. (www.raytheon.com) is an important component of the U.S. Navy's defense technology, and the VIEW 7000 image processor from RGB Spectrum (www.rgb.com) is a key component within that system. The Phalanx SeaRAM platform is a combination radar and infrared (IR) guided weapons system that provides defense against a variety of threats.

The system uses advanced radar and computer technology to acquire, identify, track, engage, and destroy enemy threats that have penetrated other ship defense systems. This latest version is onboard the Navy's newest fighting ships, including the Littoral Combat Ships U.S.S. Independence (LCS 2) and U.S.S. Coronado (LCS 4).

As part of the system's fire-control console in the latest upgrade to the Phalanx SeaRAM system, the VIEW 7000 processor combines high-resolution computer sources, radar inputs, and forward-looking-infrared (FLIR) thermal-imaging video inputs in real time. Doing so provides protection against the various types of threats mentioned above.

The Phalanx SeaRAM system's computer feeds the VIEW 7000 processor with graphical information comprised of a range table, target acquisition imagery, weapons control and ordnance data, and system status information.

The FLIR integrates multispectral thermal detection and target tracking capabilities into the system. The VIEW processor combines the many inputs and resizes the data to be compatible with the single console monitor. The processor also equips operators with the capability to superimpose critical data over thermal images. ■

for example, still relies on high-frequency (HF) terrestrial line-of-sight portable radios in the frequency range from 1.6 to 30.0 MHz and beyond.

The Joint Tactical Radio Systems (JTRS) program attempted to develop some form of universal tactical radio that could serve all branches of the military, using software-defined-radio (SDR) technology to change the nature of the radio as needed for different applications and operating conditions. If anything, the JTRS program has helped accelerate the adoption of SDR technology in tactical radios and added to their performance levels and flexibility, while pushing the development of smaller, more portable tactical communications equipment that could be used anywhere at any time *(Fig. 1)*.

Newer tactical radios are taking to the sky—for greater range via connections with orbiting satellites—and taking more after their commercial counterpart, the cellular telephone, than ever before. The Navy's Mobile User Objective System (MUOS) is a satellite-based communications network that is being developed to provide military personnel with ruggedized, secure versions of cellular telephones. The system is based on five geosynchronous orbiting satellites (four active and one serving as a spare), with the fifth satellite about to be launched in May 2016 *(Fig. 2)*.

2. The fifth satellite in the MUOS system is meant as a spare, with four active satellites in the tactical communications network. *(Courtesy of Lockheed Martin)*

The satellites, in orbit about 22,300 miles above the Earth, are managed by Lockheed Martin (www.lockheedmartin.com), while the MUOS ground communications equipment is being manufactured by General Dynamics Mission Systems (www.gdmissionsystems.com) and others. Satellite launches began in 2012. The satellite communications (satcom) network is expected to serve all branches of the military and compatriots in support of inter-branch networking.

An example of the system's mobile radio—the AN/PRC-155 from General Dynamics—was recently validated by the Army for use on the MUOS network during field trials, primarily in the Hawaiian Islands. The two-channel SDRs were used with the MUOS network to connect soldiers in that region *(Fig. 3)*, helping soldiers talk, share data, and maintain communications on board military vehicles.

3. The AN/PRC-155 tactical radio connects with satellites for mobility and is designed for mobility in the field. *(Courtesy of General Dynamics)*

In addition to the MUOS waveforms, the radios support a number of other tactical radio waveforms, including SINCGARS, SRW, WNW, high-frequency (HF), and single-sideband (SSB) communications.

While not quite as compact as a cellular smartphone, the AN/PRC-155 is small as far as traditional tactical radios go, measuring 3 × 10.1 × 7.8 in. without battery and 3.0 × 10.1 × 12.5 in. with battery bucket. It weighs 9 lb. without the battery pack and 14 lb. with the battery.

The AN/PRC-155 *(Fig. 3)* can operate from 2 MHz to 2.5 GHz in bands. It is capable of transmit power levels to 20 W on its own and as much as 5-W transmit power with the addition of external amplifiers. The MUOS network, which provides considerably more capability than the legacy tactical satcom system, employs a secure waveform developed by General Dynamics as an offshoot of wideband-code-division-multiple-access (WCDMA) technology used in third-generation (3G) cellular networks.

An AN/PRC-155 works with JTRS APIs and has full JTRS compliance for compatibility with other tactical radios in the field. It is also versatile mechanically, and can be used as a man-pack radio or (with hardware) as a vehicular radio.

It is compatible, for example, with the AN/PRC-154 Rifleman Radio *(Fig. 4)* produced by General Dynamics C4 Systems (Phoenix, Ariz.), an SDR capable of transmitting SRW signals. This terrestrial line-of-sight radio operates across frequency ranges of 225 to 400 MHz, 1,250 to 1,390 MHz, and 1,755 to 1,850 MHz. It was designed to create mobile, self-forming networks with similar radios and includes a Global Positioning System (GPS) receiver for precise position location.

4. A Rifleman Radio operates to 1,850 MHz and includes a GPS receiver for position location. *(Courtesy of General Dynamics)*

As with the AN/PRC-155 (with which it seamlessly communicates), the AN/PRC-154 is software programmable and upgradable and

5. Operating at these lower frequencies (1.6 to 60 MHz), an AN/PRC-150(C) tactical radio provides reliable operation whether carried or mounted in a vehicle. *(Courtesy of Harris Corp.)*

functions very much like a cellular telephone. It can also be used as a carried, armor-worn, or vehicular radio. With the aid of a satellite, however, it has a communication range limited to about 2 km when operating with about 5-W transmit power.

The AN/PRC-154 Rifleman Radio communicates with classified and non-classified networks. It operates over temperatures of –40 to +55°C and features JTRS-compliant APIs. For flexibility, it operates with USB and RS-232 ports for displays and radio control. It will run about 9 h on a battery charge, and can even work with a commercial battery and its associated charger.

In terms of enhancing satcom technology for tactical use, Hughes Network Systems LLC (www.hughes.com) has devoted a great deal of work to the refinement of its advanced time-division-multiple-access (TDMA) waveform technology. The company, recently tested its satcom waveforms under a variety of conditions during the biannual Talisman Sabre event with Australian and U.S. military forces.

While satellites provide convenience and long-distance communications, short-distance communications is often all that is needed in tactical situations. Conventional manpack radios, often considered as glorified walkie-talkies, generally provide reliable point-to-point communications in these situations. The Falcon II line of tactical manpack portable tactical radios from Harris Corp. (www.harris.com) is an example of how SDR technology is providing flexibility and adaptability to battlefield communications—for example, in the AN/PRC-150(C) tactical radios *(Fig. 5)*.

The multiband radio operates SSB at HF and with frequency modulation (FM) at VHF, with a frequency range that runs to 60 MHz for secure frequency-shift-keying (FSK) voice and data rate of 16 kb/s at VHF. The portable radios transmit with as much as 20-W peak envelope power (PEP) and as much as 10-W FM output power.

The radios are certified by the National Security Agency (NSA) for U.S. Type 1 voice and data encryption compatible with ANDVT/KY-99, ANDVT/KY-100, VINSON/KY-57, and KG-84C cryptographic devices, eliminating the need for external encryption. They also include a Citadel encryption mode for secure communications with coalition forces.

Operating at these lower frequencies (1.6 to 60 MHz), an AN/PRC-150(C) tactical radio is considerably larger and heavier than a MUOS satellite radio modeled after a cell phone. The Falcon II radios operate across temperatures from −40 to +70°C and have been long trusted for their durability and reliability. However, they are also built to last, measuring 10.5 × 3.5 × 13.2 in. with battery case and weighing 10 lb. (4.7 kg) without batteries.

6. Mid-Tier Networking Vehicular Radios (MNVRs). MNVRs are vehicle-mounted modular radios designed for secure, short-range mobile communications on the battlefield. *(Courtesy of Harris Corp.)*

In addition to the Army's manpack radio needs, Harris has contributed to the advancement of vehicular radios for secure, mobile communications—in particular, the Mid-Tier Networking Vehicular Radios (MNVRs). MNVRs are vehicle-mounted modular radios capable of running SDR waveforms to create a secure wireless network on the battlefield for effective ground communications. They can form a dynamic, scalable on-the-move (OTM) network architecture to connect soldiers to mission command.

MNVRs from Harris Corp. *(Fig. 6)* are based on the Falcon line of manpack radios. They provide ground-level connectivity with rapid exchange of voice messages, images, and videos, enabling the creation of secure, mobile networks on the battlefield.

Silvus Technologies (www.silvustechnologies.com) has helped to demonstrate multiple-input, multiple-output (MIMO) radio technology for potential military users with its StreamCaster MIMO radio for tactical applications. The approach is another example of commercial technology, as used in fourth-generation (4G) cellular communications systems, "leaking" over to the military side to the benefit of the warfighter. The technology is designed into the firm's mission-critical radio. de

JIM TABER | Director of Sales and Marketing, X-COM Systems

Instruments Team Up for EW and Radar Signal Analysis

A high-performance record-and-playback system combines with a series of high-speed signal analyzers to form an effective signal-analysis tool.

SIGNAL CAPTURE and analysis over broad instantaneous bandwidths is vital for military forces knowing "what's out there" in terms of potential threats. Detecting signals from missile guidance, radar, and other military electronic systems can provide much-needed warnings about their presence, and even their locations.

The model IQC5255B RF record and playback system from X-Com Systems (www.xcomsystems.com) and the N9040B UXA Series signal analyzer from Keysight Technologies (www.keysight.com) combine to form a powerful measurement system—one that can capture, analyze, and characterize signals within a 255-MHz instantaneous bandwidth with 16-b resolution at frequencies to 50 GHz.

Since the dissolution of the Soviet Union, the United States has faced few challenges to its stated "spectrum dominance." Consequently, the military could operate more or less with impunity on the ground, in the air, and at sea thanks in large measure to advanced electronic-warfare (EW) capabilities. This level of confidence came to an abrupt end—at least for ground-based operations—when Russia revealed its well-orchestrated, advanced arsenal of EW assets in Crimea, Ukraine, and (most recently) Syria, which the Pentagon called an "eye-watering" revelation.

A crucial need for advancing the performance of current EW systems is the capability to detect, analyze, and counter threats. This is a far more difficult challenge today: The frequency spectrum is densely packed with signals over a wide range of frequencies, and threats are far more complex and more easily obscured in such environments.

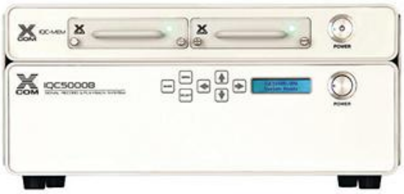
For effective signal intelligence (SIGINT) to take place, a number of things must happen. It is necessary to capture signals within wide instantaneous bandwidths of interest over long periods; digitize those signals without errors; separate signals of interest from clutter and known signals; analyze potential threat signal waveforms in detail; create electronic countermeasures (ECM) to defuse them; incorporate them in an EW system; and, finally, test their viability against the original threats.

The aforementioned system recently introduced by X-COM Systems and Keysight Technologies is designed to perform many of these required tasks, using commercial-off-the-shelf (COTS) instruments for conducting as much signal capture, simulation, analysis, and testing as early in the design process as possible. The system can additionally subject a candidate EW system to a broad array of signal types with constantly changing waveforms over a wide bandwidth.

The entire system consists of the new model IQC5255B *(see figure)* from X-COM Systems, the latest entrant in the company's IQC5000 Series of RF record and playback systems, combined with the new model N9040B UXA Series signal analyzer from Keysight Technologies. The instruments together expand the instantaneous signal-capture system bandwidth to 255 MHz. The compact, lightweight IQC5255B record-and-playback system

THE IQC5255B RECORD-AND-PLAYBACK SYSTEM SPECIFICATIONS, AT A GLANCE

Recording interface	
Signal-analyzer compatibility	Keysight X-Series (N9040B, N9030B/A, N9020B/A, N9010B/A)
Maximum record bandwidth	255 MHz (300 Msamples/s, 16-b I/Q)
Number of I/Q channels	Two, running concurrently
Maximum data rate	400 MB/s at each connector
Playback interface	
Maximum playback 1-dB bandwidth	255 MHz centered at 0 Hz (single channel) or 160 MHz (dual channel)
RF output	
Frequency	2,400 MHz
1-dB bandwidth	255 MHz
Markers	
Inputs	Two
Number per recording	100,000
Content	Date, time of day, latitude, longitude, altitude, ground speed, sample number
Latency	<1 μs
Triggers	
Inputs	2
Latency	400 ns
Instrument control	Windows-based software resident in either signal analyzer or PC with full control of record, playback data offload, and upload
SSD data storage	
Internal	2 or 4 TB in RAID 0, removable
External	To 15 TB in RAID 0
PCIe 2.0 offload	8 lanes, >800 MB/s
Power supply	100 to 240 V ac at 5 A
Physical	12 × 5.25 × 10.5 in., 14 lb.



The IQC5255B RF system can be used as a standalone instrument or as a turnkey signal-analysis system in combination with the UXA Series signal analyzers.

measures a mere 12 × 5.25 ×10.5 in. and weighs less than 15 lb.

Files of captured signal data can be examined using signal analysis and characterization tools from both X-COM Systems and Keysight Technologies. As a standalone instrument, typical applications for the IQC5255B are recording, storing, and playing back RF signals for threat analysis and building libraries.

When combined with a UXA Series signal analyzer, the instruments collectively become a comprehensive, COTS-type solution for capturing, analyzing, and characterizing signals over periods from seconds to days, with very high resolution of 16 b at carrier frequencies to 50 GHz with 100% probability of intercept.

When combined with the N9040B UXA series signal analyzer, the IQC5255B has spurious-free dynamic range (SFDR) of 78 dB over its 255-MHz bandwidth, making it possible to detect very weak signals in the presence of multiple stronger signals; this is an increasingly critical metric when used in congested signal environments *(see table)*.

When recording a single channel at this bandwidth, the system is able to continuously record and play back more than 50 minutes of uninterrupted in-phase/quadrature (I/Q) signal data in a single channel, or more than 40 minutes of two time-synchronous channels at 160-MHz bandwidth.

By adding external data packs to a maximum of 15 TB, the IQC5255B will continuously record or play back a single channel for more than three hours at full bandwidth. The instrument's dual-channel record-and-playback capability makes it possible for users to note differences in timing between the two data streams.

Finally, the powerful computer in the UXA Series instruments can incorporate and run X-COM's comprehensive and recently updated Spectro-X signal-analysis software, as well as its RF Editor drag-and-drop graphical editing tool, Keysight's 89600B vector signal-analysis software, and Mathworks' MATLAB. de

X-COM SYSTEMS LLC, 12345-B Sunrise Valley Dr., Reston, VA 20191; (571) 612-5490, *www.xcomsystems.com*

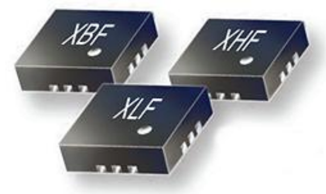
VNA Test Cables Reach 67 GHz

FLEXIBLE TEST cables for use with microwave vector network analyzers (VNAs) are available for use at frequencies from dc through 50 and 67 GHz. These durable cables provide repeatable frequency response in support of accurate measurements in test laboratories and on production lines. The cables exhibit VSWR of 1.30:1 at 50 GHz and 1.40:1 at 67 GHz with ±6° phase stability at 50 GHz and ±8° phase stability at 67 GHz. The cables are protected with braided stainless-steel armor and rated for more than 100,000 flexures, as well as more than 5,000 mating cycles, for 2.4- and 1.85-mm coaxial connectors.

PASTERNACK,

17802 Fitch, Irvine, CA 92614; (949) 261-1920, www.pasternack.com

Reflectionless Filters Operate to 35 GHz



THE X-SERIES reflectionless monolithic-microwave-integrated-circuit (MMIC) RF/microwave filters absorb and terminate stopband signals rather than reflecting them back to the source. Available in lowpass, highpass, and bandpass configurations, these compact filters can be specified with passbands from dc to 17 GHz and stopbands to 35 GHz. Measuring just 3 × 3 mm, an example of the lowpass filters, model XLF-173+ passes signals from dc to 17 GHz with typical passband insertion loss of 2.3 dB. Rejection is typically 17 dB from 23.9 to 26.0 GHz and typically 21 dB from 26 to 33 GHz. The filter has an operating temperature range of –55 to +105°C and handles as much as 2 W passband signal power.

MINI-CIRCUITS,

P.O. Box 350166, Brooklyn, NY 11235-003; (718) 934-4500, www.minicircuits.com

Miniature Filters Pass 1 to 60 GHz

MINIATURE THIN-FILM bandpass filters are available in octave and custom bandwidths from 1 to 60 GHz, miniaturized via fabrication on high-dielectric-constant ceramic substrate materials. These commercial-off-the-shelf (COTS) filters can be supplied in surface-mount formats and with integrated shielding. They feature outstanding stability with temperature for operating temperatures from –55 to +125°C. Typical units offer center frequencies from C- through K-band frequencies.

KNOWLES CAPACITORS, DIELECTRIC LABORATORIES INC.,

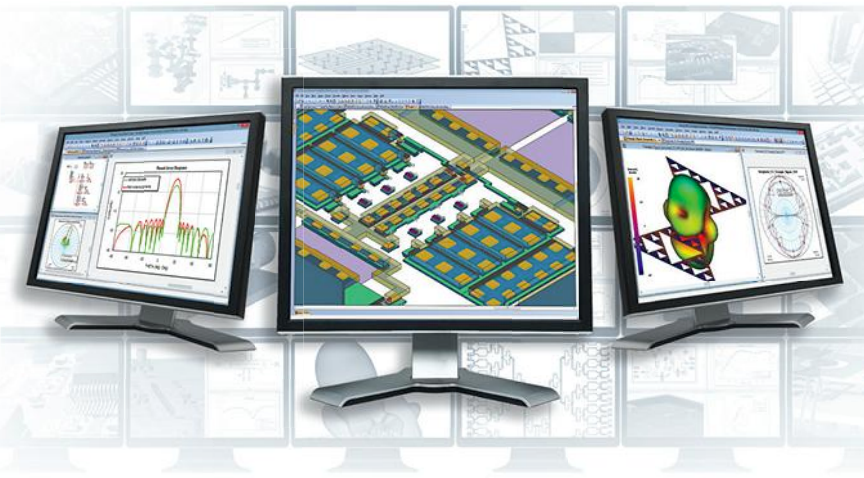
2777 Rte. 20 E., Cazenovia, NY 13035; (315) 655-8710, www.knowlescapacitors.com

Converters Supply 400-Hz AC Power

MODELS FC5003-C1-115-400 and BLX3X500C-8-5362 are commercial-off-the-shelf (COTS) frequency converters that serve industrial, commercial, and military 400-Hz system power requirements. Model FC5003-C12-115-40 converts 120/208-V ac, three-phase 47- to 63-Hz power into regulated 115/200-V ac three-phase, 400-Hz power for avionics and defense applications. It supplies 6,000 VA, 16 A per phase, and incorporates protective circuitry for long-tem reliability. Model BL3X500C-8-5632 converts 115- or 230-V ac, single-phase 47- to 63-Hz power into regulated, 115/200-V ac, three-phase, 400-Hz power at 1,500 VA, 4.3 A per phase.

BEHLMAN ELECTRONICS INC.,

80 Cabot Ct., Hauppauge, NY 11788; (631) 435-0410, www.behlman.com



Digital Phase Shifter Commands 15.0 to 18.5 GHz

MODEL HMC644ALC5 is a 5-b digital phase shifter designed for use from 15.0 to 18.5 GHz. Suitable for military and weather radar, electronic-warfare (EW) systems, and electronic beamforming applications, the phase shifter provides 360-deg. phase coverage with least-significant bit (LSB) of 11.25 deg. The root-mean-square (RMS) phase error is only 3.5 deg. with low insertion loss of typically 7.5 dB and insertion-loss variation of only ±0.5 dB. The phase shifter is controlled with complementary logic of 0/-3 V and does not require a fixed bias voltage. It is supplied in a 5- × 5-mm ceramic leadless surface-mount-technology (SMT) package and is internally matched to 50 Ω.

ANALOG DEVICES INC.,
One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106; (781) 329-4700, www.analog.com

RF-Over-Fiber Systems Link Antennas to Radios

FORAX-RM (FOR rack-mount) modular systems are RF-over-fiber links that can connect antennas to distances as great as 10 km from a radio location. These systems can combine any number of FORAX RF-over-fiber links. A link consists of a radio-interface module (RIM) and an antenna interface module. RIMs are mounted in a 19-in. rack chassis and connected by short coaxial cables to each radio's antenna port. At the antenna site, AIMs are installed in a 19-in. rack-mount chassis and connected to each antenna with coaxial cables. Radio signals are carried over flexible optical cables and the modules can handle frequencies from 30 to 512 MHz. The systems are immune to electromagnetic pulse (EMP) and electromagnetic interference (EMI).

SYNTONICS,
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New	CMA-82+	DC-7	15	20	42	6.8	5	6.45
New	CMA-84+	DC-7	24	21	38	5.5	5	6.45
	CMA-62+	0.01-6	15	19	33	5	5	4.95
	CMA-63+	0.01-6	20	18	32	4	5	4.95
	CMA-545+	0.05-6	15	20	37	1	3	4.95
	CMA-5043+	0.05-4	18	20	33	0.8	5	4.95
	CMA-545G1+	0.4-2.2	32	23	36	0.9	5	5.45
	CMA-162LN+	0.7-1.6	23	19	30	0.5	4	4.95
	CMA-252LN+	1.5-2.5	17	18	30	1	4	4.95

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FAIRVIEW MICROWAVE,
1130 Junction Dr., Ste. 100,
Allen, TX 75013; (972) 649-6678,
www.fairviewmicrowave.com

Power Splitter/Combiner Spans 2.0 to 26.5 GHz

DESIGNED FOR broadband systems and measurement applications from 2.0 to 26.5 GHz, model EP2K1+ is a two-way, 0-deg. power splitter/combiner in a miniature surface-mount-technology (SMT) package measuring just 4 × 4 × 1 mm. It features a usable bandwidth of 1.8 to 28.0 GHz and can handle as much as 2.5 W power as a splitter. The model EP2K1+ power splitter/combiner is suitable for commercial-off-the-shelf (COTS) use in satellite-communications (satcom) systems, with amplitude balance within 0.1 dB and typical phase balance within 1 to 5 deg.

MINI-CIRCUITS,
P.O. Box 350166, Brooklyn, NY
11235-003; (718) 934-4500,
www.minicircuits.com

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Digital Attenuator Covers 1 to 20 GHz

MODEL LDA-203 is the latest addition to the Lab Brick family of digital attenuators, boasting a frequency range of 1 to 20 GHz. Featuring Universal Serial Bus (USB) connectivity to personal computers, the digital attenuator is ideal for engineering and production testing. It provides attenuation from 0 to 63 dB in 0.5-dB steps. It is programmable for fixed attenuation or swept-attenuation ramps by means of the graphical-user-interface (GUI) software provided with the unit. P&A: $1,199; stock.

VAUNIX TECHNOLOGY CORP.,
7 New Pasture Ct., Newburyport, MA 01950; (978) 662-7839, www.vaunix.com

Kits Assist on RF/MW Field-Strength Tests

THE RFP Smart Fieldmeter Kits provide everything needed for calibrated RF field-strength measurements from 0.2 MHz to 18 GHz. The kits, which are manufactured by EMC Test Design (www.emctd.com), contain a calibrated field-strength meter, a calibrated omnidirectional Omnifield Antenna, and a 6-in. table tripod. The cost-effective measurement kit enables electromagnetic (EM) field measurements from cellular basestations, radio broadcast stations, and other RF/microwave signal sources. Three versions of the kit are available: one for field-strength measurements of 0.2 to 600.0 V/m from 0.2 MHz to 3 GHz, and two providing a field-strength range of 0.8 to 800 V/m from 3 MHz to 18 GHz.

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71 Perinton Pkwy., Fairport, NY 14450; (888) 7SAELIG, (585) 385-1768, www.saelig.com

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AN ASSORTMENT of standard and custom shielding vents help reduce electromagnetic interference (EMI) in critical electronic applications. Many of the vents are available with RoHS-compliant finishes. Nine different aluminum vent styles are offered, and additional shielding gaskets can be added to increase attenuation. The vents, which are suitable for cooling higher-power electronic systems, employ lightweight aluminum frames and Twinseal gaskets between the frame and mounting surface for excellent shielding.

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IEEE MTT-S

OCXO Keeps Time from 5 to 20 MHz

MODEL OX-208 is a compact oven-controlled crystal oscillator (OCXO) available for frequencies over a factory-set range of 5 to 20 MHz and at standard frequencies of 5, 10, and 20 MHz. It is based on a stress-compensated-cut (SC-cut) crystal resonator and is well-suited for use in frequency synthesizers, military systems, and test equipment. The OCXO features initial stability tolerance of ±25 ppb and is capable of an aging rate of 0.15 ppb/day. It requires a 5-minute warmup time to reach within ±10 ppb of the final frequency.

The source provides a sine-wave output and is available for use with a supply voltage of typically +3.3 to +5.0 V dc. It generally delivers as much as +8-dBm output power with a +5-V dc supply. The phase noise is no worse than −95 dBc/Hz offset 1 Hz from a 10-MHz carrier, −140 dBc/Hz offset 100 Hz from the same carrier, and −155 dBc/Hz offset 10 kHz from the same carrier. The high-stability ovenized oscillator is supplied in a 25- × 25-mm package.

VECTRON INTERNATIONAL,

267 Lowell Rd., Unit 102, Hudson, NH 03051; 88-VECTRON-1, www.vectron.com

Test Receiver Checks for EMI

FOR PRECISION electromagnetic-interference (EMI) measurements, the R&S ESW EMI test receiver can perform standards-compliant certification testing on high-frequency components and devices per the most demanding standards. Versions are available for use from 2 Hz to 8, 26, and 44 GHz. Test modes include sweep, scan, and real-time spectrum analysis. A spectrogram function displays spectrum versus time with a real-time analysis bandwidth of 80 MHz.

The instrument includes a fast-Fourier-transform-based time-domain scan that reduces the time of testing. Persistence mode and a frequency-mask trigger help reveal hidden signals. The R&S ESW offers additional highpass filters at 150 kHz and 2 MHz as well as notch filters for testing at license-free Industrial-Scientific-Medical (ISM) bands around 2.4 and 5.8 GHz. The EMI test receiver features a touchscreen display with intuitive graphical user interface (GUI).

ROHDE & SCHWARZ USA INC.,

6821 Benjamin Franklin Dr., Columbia, MD 71046; (410) 910-7800, www.rohde-schwarz.com

Amplifier Boosts 57 to 66 GHz

WELL-SUITED FOR point-to-point radios, radar transmitters, and test equipment, model HHPAV-548 is a power amplifier (PA) with 30-dB small-signal gain from 57 to 66 GHz. The monolithic-microwave-integrated-circuit (MMIC) PA is supplied in a WR-15 waveguide package with standard UG-385/U flange, complete with voltage regulator and bias-sequencing circuit for use with a single bias supply of typically 850 mA at +6 V dc. The amplifier delivers +21-dBm typical output power at 1-dB compression with typical noise figure of 5.5 dB. It measures 1.31 × 1.34 × 0.97 in.

HXI LTD.,

12 Lancaster County Rd., Harvard, MA 01451; (978) 772-7774, www.hxi.com

Amplifier Module Drives X-Band Radar

MODEL BPM928109-1000 is a compact power amplifier module capable of 1,000-W pulsed output power from 9.2 to 10.0 GHz for X-band radar systems. It exhibits 60-dB nominal gain with ±2-dB gain variation when operating with pulse widths from 0.25 to 100 μs at 10% maximum duty cycle. Second harmonics are held to less than −40 dBc while third harmonics are less than −50 dBc. The module draws 25.5 A from a +28-V dc (±1 V dc) supply. It has output load of less than 2.0:1 and includes integral output VSWR load protection. The amplifier module weighs 5 lb. and measures 9.6 × 6.8 × 2.15 in.

COMTECH PST,

105 Baylis Rd., Melville, NY 11747; (631) 777-8900, www.comtechpst.com

MULTI-TONE TESTING MULTIPLIES TEST SOLUTIONS

BY PERFORMING MULTI-TONE testing, a large number of benefits can be achieved. For instance, equipment efficiency can be improved and equipment-under-test (EUT) can be tested under real-world threat conditions. Faster time-to-market for both new and enhanced products is another benefit of this approach. In the application note, "Multi-Tone: Testing, Theory and Practice," AR RF/Microwave Instrumentation discusses the multi-tone test methodology. The document explains how this approach can be implemented, as well as the advantages of using this method.

The application note begins with a basic definition of a multi-tone signal. An explanation of how these signals are represented in both the frequency- and time-domains is presented. Modern audio measurements are one example of an application that utilizes multi-tone signals. Intermodulation distortion (IMD) measurements are mentioned, as multi-tone signals are used to test the nonlinear distortion of amplifiers and receivers.

Various methods of generating multi-tone signals are explained. The traditional approach is to generate multiple signals by using multiple independent continuous-wave (CW) generators that are added together with a combiner. Alternately, multiple signals can be generated by using one vector signal generator (VSG) in place of multiple CW generators. A VSG can generate fixed or random initial phase sets, deliver accurate repeatable multi-tone signals, and is easily configurable by independently setting each tone. The third approach is to use multiple signal generators, multiple amplifiers, and multiple antennas. When using this technique, the signals are actually combined in free space. Furthermore, a comparison between analog signal generators and VSGs is provided.

AR RF/Microwave Instrumentation, 160 School House Rd., Souderton, PA 18964-9990; (215) 723-8181; www.arworldwide.com

Electromagnetic-compatibility (EMC) testing with multi-tone signals is analyzed. By using a VSG with a frequency selective power measurement device like a vector signal analyzer (VSA), multiple tones can be generated, measured, and controlled. An explanation of how test times can be reduced by using a multi-tone test method is provided. Real-world threats can also be simulated by using this test approach, as EUTs can be exposed to more than one tone at a time in real-world applications.

LOAD-PULL ANALYSIS WITH SOFTWARE ENABLES WAVE OF DESIGNS

LOAD-PULL ANALYSIS IS an important aspect of the design process of an amplifier, as this technique is often used to determine an appropriate load. Thus, by utilizing load-pull techniques, amplifiers can be designed more efficiently. In the application note, "Load-Pull Analysis Using NI AWR Software," National Instruments presents three design examples that take advantage of the load-pull technique. These designs are aided with the NI AWR Design Environment.

The first example demonstrates a simple load-pull analysis. The impedances that were obtained are presented on the Smith Chart. Additional graphs display saved data sets of measured output power versus gain compression, output power versus power-added efficiency (PAE), and input power versus output power. By taking advantage of the capabilities of the NI AWR software, designers can quickly learn the impact of load/source terminations on an amplifier's performance over swept input power. Power amplifier (PA) designers can therefore gain a better understanding of the tradeoffs between load impedance and gain compression behavior.

National Instruments Corp., 11500 N Mopac Expwy., Austin, TX 78759-3504; (877) 388-1952; www.ni.com

In the next example, a device was terminated in a matching network based on a microstrip transmission line transformer. The impedances that were obtained are once again displayed on the Smith Chart. Contour lines on the Smith Chart indicate where +45 dBm of output power and 70% PAE can be attained, respectively. The layout of the matching circuit is presented, as well as the performance characteristics of the device with the matching network.

The third example investigates circuit optimization by means of electromagnetic (EM) field analysis. By leveraging EM analysis, a more accurate representation of the matching network impedance can be achieved. Although EM analysis is often used in design verifications after the final design has been achieved, this example illustrates the accuracy of EM analysis when used earlier in the design process. The schematic and layout of the final project is presented. The output matching circuit for the transistor model was also created based on the measured load-pull file to investigate the current distribution through the matching structure.

JACK BROWNE | Technical Contributor

Analyzers Squeeze Real-Time

These real-time spectrum analyzers improve upon the frequency ranges and performance levels of earlier USB-based analyzers, all while shaving cost and size.

PORTABLE SPECTRUM ANALYSIS once required hoisting an instrument with more mass than a car battery. Fortunately, with the introduction of the RSA500A and RSA600A series of real-time spectrum analyzers from Tektronix (www.tek.com), portable real-time spectrum analysis no longer requires a weightlifter's physique.

These "little boxes" bring all of the measurement power of those traditionally larger spectrum analyzers and then some, with total frequency coverage of 9 kHz to 7.5 GHz and capture bandwidths as wide as 40 MHz. The secret is in moving all command, control, and display capabilities to a personal computer (PC) via a Universal Serial Bus (USB) 3.0 connection, significantly cutting the size and cost of the test instruments.

With a tablet or laptop PC in control, these real-time spectrum analyzers deliver all of the measurement power of bench-top instruments, but in form factors that make it easy to test in the lab or in the field. They are ideal for spectrum management, Internet of Things (IoT) design, and network maintenance.

The new instruments include the battery-powered RSA500A Series analyzers, featuring the 9-kHz-to-3-GHz model RSA503A and 9-kHz-to-7.5-GHz model RSA507A *(Fig. 1)*. Also included are the slightly larger ac-powered RSA600A series analyzers, which include the 9-kHz-to-3-GHz model RSA603A and 9-kHz-to-7.5-GHz model RSA607A *(Fig. 2)*. Anyone accustomed to a traditional portable spectrum analyzer—with a built-in screen, control panel, and carrying handle—may not even recognize these compact units as spectrum analyzers.

Part of their portability lies within the operating system itself, contained within the versatile SignalVu-PC measurement software that is provided free of charge with each spectrum analyzer. The software can transform any compatible computer into the control panel and display screen, using a USB 3.0 connection to one of the portable analyzers to create a powerful (albeit compact) measurement solution *(Fig. 3)* at a fraction of the cost of a conventional all-in-one spectrum analyzer.

1. The battery-powered model RSA507A USB spectrum analyzer covers 9 kHz to 7.5 GHz.

The battery-powered RSA500A Series real-time spectrum analyzers parlay a superheterodyne receiver architecture with a 14-b, 112-Msample/s analog-to-digital converter (ADC) into full-sized spectrum-analysis capabilities. They are lightweight with a rugged enclosure, and designed for field use when combined with a Windows-compatible (Windows 7 or newer) tablet or laptop and SignalVu-PC software. At least 20 GB of available hard-disk memory is required for the SignalVu-PC software. For those in need of a controller for any of the portable real-time spectrum analyzers, Tektronix offers an accessory PC as an option: a Panasonic FZ-G1 tablet computer with USB 3.0 port.

The FZ-G1 tablet is equipped with an Intel Core i5 microprocessor, 8 GB of random access memory (RAM), and a 256-GB solid-state drive for data storage. The tablet features an integrated microphone and speaker, and shows captured signals on a 10.1-in. (25.6-cm) daylight-readable screen. The tablet has integrated battery backup for ease of swapping battery packs when making extended measurements in the field.

The RSA500A spectrum analyzers, in 3.0- and 7.5-GHz models, operate continuously for about four hours on a single +14.4-V dc lithium-ion rechargeable battery. They can also be powered by an external dc source (from about +12 to +20 V dc) and via ac power (using an ac adapter). They measure a mere 11.78 × 10.68 × 2.65 in. (299.1 × 271.3 × 67.3 mm) and weigh only 6.6 lb. (2.99 kg) with battery.

These small instruments provide big measurement power, however, with a reference level range that can be set from −170 to +40 dBm and input attenuation that is adjustable from 0 to 51 dB in 1-dB steps. The analyzers can safely handle as much as 2 W (+33 dBm) input power from 10 MHz to 7.5 GHz with RF attenuation of 20 dB or more.

Built-in preamplifier gain is 30 dB at 2 GHz and 24 dB at 6 GHz for boosting and capturing low-level signals. The RSA500A real-time spectrum analyzers also feature amplitude accuracy of typically ±0.8 dB from 9 kHz to 3 GHz, and ±1.5 dB from 3.0 to 7.5 GHz without the preamplifier.

Third-order intercept with the preamplifier off is typically +10 dBm from 9 kHz to 25 MHz, +15 dBm from 25 MHz to 3 GHz, +8 dBm from 3 to 6 GHz, and +10 dBm from 6.0 to 7.5 GHz. Third-order intermodulation distortion is typically −74 dBc measured at 2.120 GHz.

The second-harmonic distortion with the preamplifier off is typically −75 dBc or better across the full frequency range. Residual spurious levels are ≤−75 dBm from 500 kHz to 60 MHz, ≤85 dBm from 60 to 80 MHz, and ≤−100 dBm from >80 MHz to 7.5 GHz.

The battery-powered RSA500A Series portable analyzers are stable with frequency even in the small package. They exhibit $\pm 1 \times 10^{-6}$ initial frequency accuracy following calibration after a 30-minute warmup time and $\pm 1 \times 10^{-6}$ typical aging after the first year of operation. They show cumulative frequency error of $\pm 3 \times 10^{-6}$ with temperature and aging after one year, and frequency drift with temperature of $\pm 0.9 \times 10^{-6}$ from −10 to +60°C.

As with the RSA600A analyzers, the RSA500A instruments allow users to connect an external reference oscillator (with BNC connector) for enhanced frequency accuracy, working with reference oscillators from 1 to 20 MHz in 1-MHz increments and at power levels from −10 to +10 dBm.

2. The ac/dc-line-powered model RSA607A USB real-time spectrum analyzer operates from 9 kHz to 7.5 GHz.

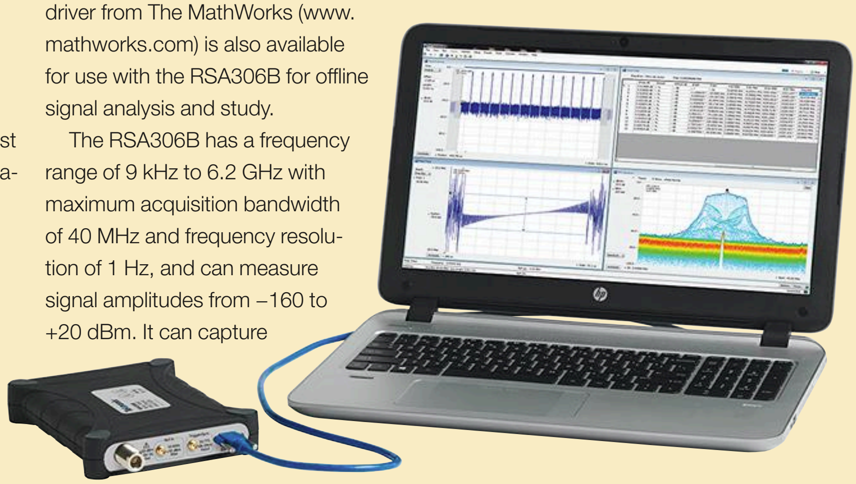
FOR GENERAL-PURPOSE TESTING

THE NEW RSA500A and RSA600A Series analyzers each provide a great deal of test capability to on-site measurements and laboratories, respectively. But what about users who desire the small size of those USB spectrum analyzers but prefer an instrument with more general-purpose RF measurement capabilities?

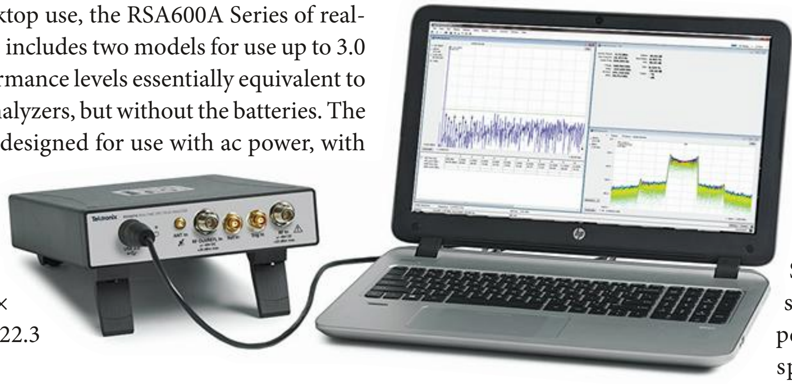
The model RSA306B real-time spectrum analyzer from Tektronix is the latest version of a compact USB spectrum analyzer (model RSA306A) introduced last year that can also leverage the many measurement functions of SignalVu-PC software. This includes enhancements such as spurious-free dynamic range (SFDR) that is improved by 10 dB and a three-year warranty compared to the previous version with a one-year warranty.

As with the RSA500A and RSA600A Series analyzers, the RSA306B real-time spectrum analyzer *(see photo)* connects to a MS Windows-compatible PC via USB 3.0 port. It takes on the measurement "character" of the SignalVu-PC software, performing its many basic measurements as well as any specialized test function modules added to the test program. A MATLAB software driver from The MathWorks (www.mathworks.com) is also available for use with the RSA306B for offline signal analysis and study.

The RSA306B has a frequency range of 9 kHz to 6.2 GHz with maximum acquisition bandwidth of 40 MHz and frequency resolution of 1 Hz, and can measure signal amplitudes from −160 to +20 dBm. It can capture pulsed and intermittent signals as brief as 100 μs. This is the smallest of the firm's portable spectrum analyzers, measuring just 7.5 × 5.5 × 1.25 in. and weighing 1.65 lb. (0.75 kg), although it runs on dc or ac line power and lacks the battery-powered mobility of the RSA500A.



For laboratory or desktop use, the RSA600A Series of real-time spectrum analyzers includes two models for use up to 3.0 and 7.5 GHz, with performance levels essentially equivalent to those of the RSA500A analyzers, but without the batteries. The RSA600A analyzers are designed for use with ac power, with maximum power dissipation of 45 W when the analyzer is fully loaded. They are compact, measuring 14.12 × 8.75 × 2.95 in. (358.6 × 222.3 × 75.0 mm) without the reinforced housing of the RSA500A Series analyzers, and weighing 6.15 lb. (2.79 kg).



3. When teamed with a PC with measurement software via a USB 3.0 connection, an RSA600 Series portable real-time spectrum analyzer represents a versatile, advanced RF/microwave laboratory test solution.

Both series of portable analyzers are available with an optional (Option 04) tracking generator covering 10 MHz to 3.0 GHz for the model RSA603A/503A analyzers and 10 MHz to 7.5 GHz for the model RSA607A/507A spectrum analyzers. Both versions of the tracking generator offer 100-Hz frequency resolution with −3-dBm maximum output power and sweep speeds of 6,700 MHz/s for 101 points and 50-kHz resolution bandwidth. The tracking generators connect to the analyzers by means of a Type-N coaxial connector.

DEFINING APPLICATIONS

While the portable RSA500A and RSA600A Series real-time spectrum analyzers provide the raw measurement power, the versatile SpectrumVu-PC test software provides the means to tailor the instruments for specific measurement applications—from audio through microwave frequencies.

The software has been enhanced with an updated, easy-to-use user interface and a number of new options and capabilities. These include support for mapping detected signals (with Global Positioning System, or GPS, receivers built into the RSA500A and RSA600A analyzers), channel navigation, and signal classification.

The basic SpectrumVu-PC software package contains a large number of program functions for essential measurements, such as basic spectrum analysis; analog modulation analysis including amplitude modulation (AM), frequency modulation (FM), and phase modulation; spurious signal analysis; DPX spectrum measurements; signal recording; pulse measurements (to a minimum pulse width for detection of 150 ns); and vector signal analysis. The latter includes measurements of amplitude versus time, frequency versus time, phase versus time, and in-phase (I) and quadrature (Q) signal components versus time.

The software also includes functions for measuring complementary cumulative distribution function (CCDR), multiple channel power measurements (MCPM), and occupied bandwidth (OBW) measurements, among others. In addition, a large number of application-specific function modules are available for the SpectrumVu-PC software, such as for performing standards-specific WLAN measurements, Bluetooth measurements, LTE downlink RF measurements, and signal survey and classification functions.

For example, using SpectrumVu-PC software with one of the analyzers and the DPX spectrum display enables analysis of 10,000 spectra per second. For pulsed or intermittent signals, the analyzers provide 100% probability of detection of signals as brief as 100 μs across a 40-MHz span. Captured signals and modulation are shown with vivid clarity using 201 × 801 dpi DPX bitmap resolution.

This measurement and display capability with SignalVu-PC signal-analysis software is ideal for analyzing signals with a wide range of digital modulation formats, including binary phase-shift keying (BPSK), frequency-shift keying (FSK), minimum-shift keying, quadrature amplitude modulation (QAM), and quadrature phase-shift keying (QPSK). The software permits signals to be displayed in multiple domains.

Whether selecting a battery-powered RSA500A spectrum analyzer or an ac/dc-line-powered RSA600A Series instrument *(see "For General-Purpose Testing," p. 129)*, each includes a GPS/GLONASS receiver for position marking and tracking. In addition to the tracking generator, a number of options are available for each of the portable analyzers, including the DFA-0047 Smart Antenna from Alaris Antennas (www.alarisantennas.com).

The antenna has a frequency range of 20 MHz to 8.5 GHz and available extension from 9 kHz to 20 MHz (in the form of a 0.3-m loop antenna). Its built-in USB compass simplifies locating interference and tracking the direction of signals of interest. A trigger control allows one-hand operation when switching an analyzer's preamplifier on and off for gauging signal levels across a wide dynamic range. P&A: (RSA500A Series): $5,900 and up (3-GHz models) and $9,900 and up (7.5-GHz models); (RSA600A Series): $6,900 and up (3-GHz models) and $9,900 and up (7.5-GHz models); stock. mw

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CHRIS DeMARTINO | Technology Editor

GaN Breaks Through Performance Barriers

Gallium nitride is exerting its strength in myriad communications applications, and suppliers are trying to keep pace by developing solutions for next-generation systems.

GALLIUM-NITRIDE (GaN) TECHNOLOGY has officially arrived, as applications ranging from defense to commercial cellular exploit its performance benefits—benefits that are simply unavailable with older semiconductor technology like gallium-arsenide (GaAs).

Today, a number of different suppliers offer an array of GaN devices. And GaN shows no signs of slowing down, as it will likely find its way into more future applications. So expect the GaN train to keep rolling along, with suppliers continuing to develop and deliver new cutting-edge GaN products.

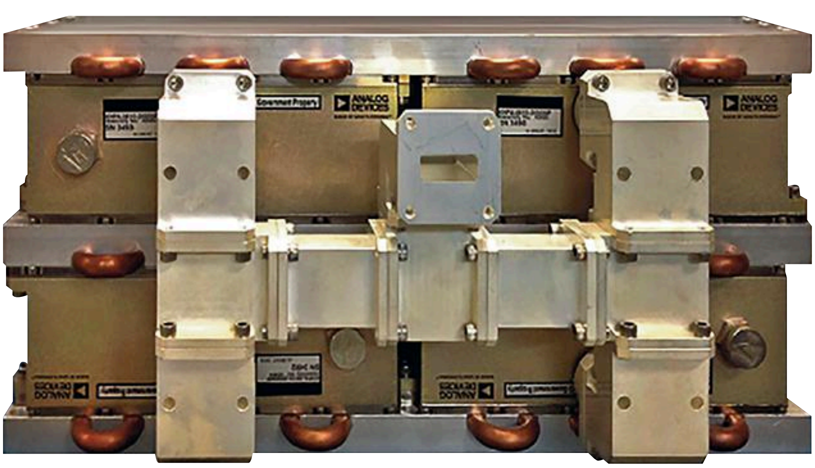
AEROSPACE AND DEFENSE

Aerospace and defense applications undoubtedly reap the benefits of GaN technology. "GaN is changing the RF and microwave landscape for aerospace and defense systems, with almost all future radar, military communications, and electronic-warfare (EW) systems investigating the benefits," says Mike Scott, senior business development manager for modules and subsystems at Analog Devices (www.analog.com). "By reducing device parasitic elements and using shorter gate lengths and higher operating voltages, GaN transistors have achieved higher output-power densities, wider bandwidths, and improved dc-to-RF efficiencies."

Phased-array radar is just one example of an application that benefits from GaN technology. "In modern phased-array radar systems with thousands of active elements, our GaN technology is providing comprehensive solutions for transmit/receive (T/R) modules," continues Scott. "Both power density and integration are increased, with the power amplifier (PA), low-noise amplifier (LNA), and T/R switch all developed in GaN. The high breakdown voltage also potentially mitigates the need for the limiter, which is traditionally used to protect the LNA. Thus, component count and area are reduced, which is critical at higher frequencies with minimal antenna aperture spacing."

Utilizing GaN technology can help designers satisfy the goal of delivering superior performance in a small package size. "The size of modern-day systems is becoming an ever more important issue," says Scott. "The improved power density of GaN is as much as six times greater than GaAs. Therefore, GaN can enable reduced system footprints with higher reliability."

Wider bandwidth capability, as mentioned, is another of the key performance



1. This solid-state power amplifier can provide 8 kW of output power at X-band frequencies. *(Courtesy of Analog Devices)*

> "GaN is changing the RF and microwave landscape for aerospace and defense systems, with almost all future radar, military communications, and electronic-warfare (EW) systems investigating the benefits."

enhancements offered by GaN. Scott notes, "Higher operating impedances also provide optimized solutions for electronic surveillance and countermeasures, as a single broadband PA can now cover multi-octave bandwidths. For example, our HMC7149 PA, which is based on a 0.25-µm process, can provide amplification across a frequency range of 6 to 18 GHz with minimal variation of output power and gain."

Power-combining solutions are incorporated with GaN in Analog Devices' new high-power amplifier modules, which the firm says offer a reliable alternative to traditional traveling-wave tubes (TWTs) *(Fig. 1)*. "Using proprietary power-combining methods and advanced bias-control/monitoring circuits in core power-combined modules, our solid-state high-power amplifiers (SSHPAs) range from 100-W broadband amplifiers to 8-kW X-band amplifiers, combining as many as 256 monolithic microwave integrated circuits (MMICs)," adds Scott.

WIRELESS INFRASTRUCTURE

The impact of GaN extends well beyond aerospace and defense applications. Commercial cellular networks are also capitalizing, with many wireless base stations now turning to GaN. Laterally diffused metal-oxide semiconductor (LDMOS) technology has dominated the wireless infrastructure arena for some time. However, GaN has clearly made inroads into this market, and seems destined to make a greater impact in this arena.

One of the players in the GaN space is Qorvo (www.qorvo.com), which offers a large number of devices that cover frequencies ranging from dc to Ka-band. The company is at the forefront of GaN-on-silicon-carbide (GaN-on-SiC) technology, which it sees as a solution for wireless base stations.

"The two leading GaN process technologies today are GaN-on-SiC and GaN-on-silicon (GaN-on-Si)," says Sumit Tomar, general manager of wireless infrastructure at Qorvo. "GaN-on-Si has the advantage of a lower-cost substrate. But that advantage is outweighed by GaN-on-SiC's support of much greater power density and better thermal management. As a result, GaN-on-SiC has become the natural choice for base stations that require high-power outputs."

Tomar adds, "The advantages of GaN-on-SiC will become even clearer as operators increase network capacity by using techniques that will require higher power, such as carrier aggregation (CA) and multiple-input, multiple-output (MIMO). Operators are demanding higher power output each year. Last year's base-station power requirements were at 30 to 40 W, but that number has increased to today's requirement of 60 W. We can expect as much as 100 W or more in next-generation base stations.

"As GaN PAs become more widely used in LTE networks, careful evaluation of solutions is essential to ensure they can meet the tough requirements placed on network infrastructure. Thus, a significant factor will be the choice between GaN-on-SiC and GaN-on-Si. Product reliability is also essential. It is critical that we keep our eyes on the power demands of our evolving technology—both now and in the future."

Qorvo currently offers a wide array of GaN devices, such as the recently introduced TGA2218-SM and QPA2237 PAs. The TGA2218-SM PA, which covers 13.4 to 16.5 GHz, provides 12 W of output power. The QPA2237 is a 10-W PA that spans 0.03 to 2.5 GHz. Additional new products include the TGF2977-SM, TGF2978-SM, and TGF2979-SM RF transistors, each of

which cover dc to 12 GHz, and provide 5, 20, and 25 W of output power, respectively.

Another company focused on delivering GaN-based solutions to the wireless infrastructure market is MACOM (www.macom.com), which recently announced its new MAGb series of GaN power transistors for wireless base stations *(Fig. 2)*. With these new series of transistors, MACOM is proving that GaN-on-Si is a viable technology solution for today's applications.

2. A new series of GaN power transistors is intended for next-generation wireless base stations. *(Courtesy of MACOM)*

"The wireless base-station market is fueling tremendous innovation in GaN technology," says Preet Virk, senior VP and general manager of the carrier networks group at MACOM. "Base-station original equipment manufacturers (OEMs) are now taking a much closer look at the relative merits of GaN-on-Si and GaN-on-SiC transistors for base-station PAs. These OEMs are assessing the advantages and tradeoffs that range from performance attributes to supply-chain ecosystems. In order to displace LDMOS in the commercial base-station domain, a favorable price/performance balance must also be established."

Virk adds, "We have addressed this requirement with our new MAGb series of power transistors, which provide GaN-caliber performance at LDMOS-like cost structures. We have also formed a path to better-than-LDMOS cost at scaled volume production levels. Leveraging our fourth-generation (Gen4 GaN) technology, these GaN-on-Si-based transistors have demonstrated efficiency in excess of 70% along with linear gain of 19 dB at 2.6 GHz. Furthermore, they can achieve greater than 80% peak efficiency when the devices are presented with proper harmonic terminations. This power-efficiency profile rivals that of GaN-on-SiC devices, and represents as much as 10% improvement in efficiency in comparison to LDMOS offerings."

In addition, the company believes these products lend themselves well to digital predistortion (DPD) techniques. "Another key challenge that GaN needs to overcome in the base-station domain is the nonlinearity that's common to Doherty amplifier implementations," says Virk. "This is typically corrected with DPD. However, DPD has proven to be difficult to implement with GaN-on-SiC devices. The charge-trapping effects in SiC, believed to be caused by crystalline defects in its silicon structure, ultimately yield PAs that are more difficult to linearize. MACOM GaN does not exhibit the same levels of the aforementioned artifacts, and is therefore easy to linearize and correct with DPD schemes."

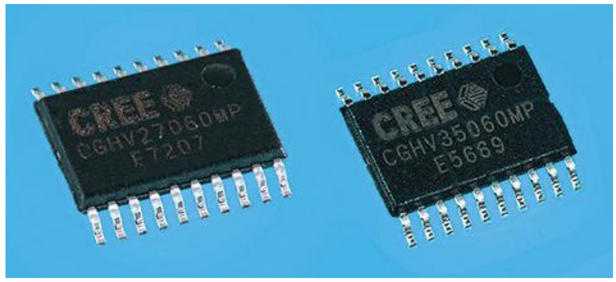
Among other suppliers introducing GaN devices for the wireless infrastructure market is Mitsubishi Electric (www.mitsubishielectric.com). The firm recently expanded its lineup of GaN high-electron-mobility transistors (HEMTs) for 4G base transceiver stations (BTSs). The four new transistors are intended for 3.5-GHz applications, with output-power levels that range from 5 to 180 W. According to Mitsubishi, using these new products can reduce BTS power consumption. The company also boasts that PA modules can be built in smaller sizes when designed with these transistors.

Infineon Technologies (www.infineon.com) entered the fray with its new family of GaN RF power transistors. Cellular amplifiers implementing these new devices can achieve high efficiency and broadband performance, says the company. The 70-W GTVA220701FA transistor covers 1805 to 2170 MHz, while the 170-W GTVA261701FA transistor spans 2620 to 2690 MHz.

MORE GaN SUPPLIERS

The aforementioned companies are certainly not alone as providers of GaN products. For instance, Wolfspeed's (www.wolfspeed.com) GaN devices find homes in applications that include satellite-communications (satcom), radar, and telecommunications. In fact, it was recently announced that the total output power of the GaN-on-SiC RF power transistors shipped by the company exceeds 1.3 GW.

Last year, Wolfspeed released the 60-W CGHV27060MP and CGHV35060MP GaN HEMTs *(Fig. 3)*. The CGHV27060MP covers a frequency range of dc to 2.7 GHz, while the CGHV35060MP spans 2.7 to 3.5 GHz. Both transistors are well-suited for radar and LTE applications.



3. These 60-W transistors are housed in a plastic package. *(Courtesy of Wolfspeed)*

Also sparking interest is Ampleon (www.ampleon.com), as the company recently extended its portfolio of GaN RF power transistors based on a 0.5-μm HEMT process technology. The CLF1G transistors are currently available in output-power levels ranging from 10 to 100 W. These products, housed in compact and thermally stable ceramic packages, will make their way into applications such as radar and wireless infrastructure, among others.

In addition, Sumitomo Electric Device Innovations (www.sei-device.com) offers numerous GaN devices targeting a range of applications. For example, the company recently expanded its offering of satcom products by unveiling both 30- and 60-W Ku-band devices. Additional products are available for other satcom bands, such as C- and X-band. One of the newer arrivals, the SGK5872-20A, is a C-band device that provides 20 W of output power over a frequency range of 5.85 to 7.2 GHz.

Sumitomo Electric Device Innovations also offers GaN devices for applications like radar. One such product is the SGC8598-200A-R GaN HEMT, which will find homes in X-band radar applications. The transistor, which spans 8.5 to 9.8 GHz, provides 200 W of output power in pulsed operation.

In the last several years, we have clearly witnessed a shift toward GaN technology. However, despite all of the activity surrounding GaN, the technology is still relatively new. We can expect to see GaN's capabilities grow, e.g. higher-frequency performance, in the near future as researchers further explore its capabilities. Although older semiconductor technologies are not likely to disappear anytime soon, it does seem apparent that next-generation applications will increasingly turn to GaN as the go-to solution. mw

TUAN NGUYEN | Product Line Director of Wireless Infrastructure, Qorvo Inc.

Small Cells Help Keep 5G Connected

Key to the success of small cells, which boost quality of service in wireless networks, is their high-frequency components that draw upon a number of different technologies.

AS MORE USERS tap into wireless-communications services, the demand on wireless-network capacity intensifies in both indoor and outdoor locations. Such network density or densification further pressures wireless carriers to keep pace with the increased consumption of frequency bandwidth via voice, video, and data. It also drives those carriers to expand their cellular/wireless infrastructure with minimum increases in cost or disruption of service to wireless customers. Thus, many are turning to small cells as a solution.

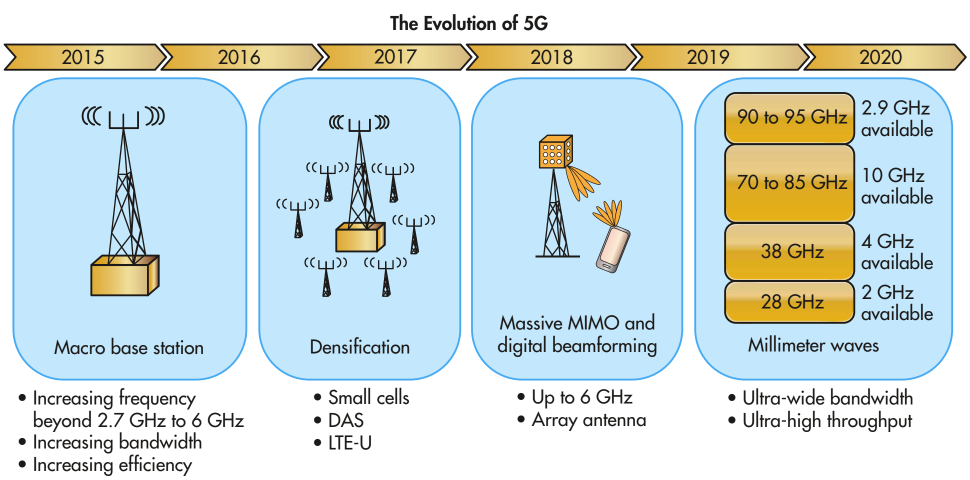
The rollout of Fifth-Generation (5G) wireless networks will address demands for increased capacity and data, but these networks are still some years away. So, a more practical answer that's in keeping with today's Fourth-Generation (4G) wireless networks is to use small cells, which function as miniature base stations that are added to an existing wireless network. They operate at relatively low power levels to fill any "holes" that exist in wireless coverage, both in indoor and outdoor locations.

As an example of the magnitude of growing wireless user demands, fans attending the National Football League's (NFL) 2016 Super Bowl championship game in Santa Clara, Calif., used more than 7 TB of data on the Verizon Wireless network alone—nearly three times as much data used at the 2015 Super Bowl game. Fans connected to the network via smartphones and many other unique wireless devices. They benefited from the capacity provided by 4G Long Term Evolution (LTE) bolstered by the use of small cells, macrocells, and mobile cell sites (as reported by Verizon Wireless in a press release dated February 8, 2016).

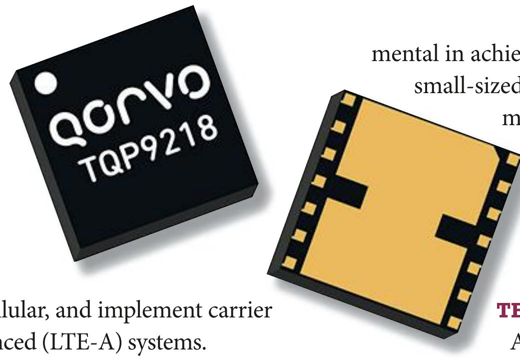
SMALL CELLS + DAS SOLUTIONS

Small cells and distributed antenna systems (DAS) are being employed *(Fig. 1)* to achieve increased data capacity in 5G wireless networks while enhancing quality of service (QoS) in those networks. But with densification comes interference and mobility handover challenges between small cells and the macro network, requiring careful network design and management.

As mobile communications devices move from a macrocell environment to a small-cell coverage area, the network will instantaneously switch profiles. The relatively low power levels of small cells allow mobile devices to be in close proximity to those small cells. They are able to gain network access while conserving battery life, and they needn't establish radio communications links with more distant larger cell sites at transmission levels diminished by distance. Mobile-device users will also benefit from increased data speeds, mobility, and flexibility, since small cells and DAS solutions support multiple standards, such as Third-



1. A number of technologies will be required to optimize performance in 5G wireless networks, including distributed antenna systems (DAS), millimeter-wave technology, and small-cell base stations.



2. The highly integrated model TQP9218 is an example of a PA for small-cell base stations. The space-saving device comes in a low-cost 7- × 7-mm SMT housing.

Generation (3G) and 4G cellular, and implement carrier aggregation with LTE Advanced (LTE-A) systems.

Antenna technologies such as multiple-user multiple-input, multiple-output (MIMO) approaches, beam steering, and phased-array techniques help provide additional wireless coverage and interoperability of multiple-band 3G and 4G systems. With massive MIMO methods, operators can increase data rates and network capacity by transmitting multiple, spatially separated data streams over the same frequency band, using multiple antennas on the base station and the user's device.

Massive-MIMO base stations seek to provide from 16 to 256 channels, challenging base-station designers to target smaller component sizes with high energy efficiency and effective thermal management. Therefore, highly power-efficient semiconductor technologies become attractive for such base stations.

High levels of semiconductor integration are also instrumental in achieving the high channel counts in these relatively small-sized base stations. Squeezing as many as 256 transmit channels into a single base station requires subsystems that package power amplifiers (PAs), low-noise amplifiers (LNAs), and switches into compact modules, and employing small-form-factor filter solutions.

TABLE 1: SIZING UP SMALL CELLS

Cell type	Output power (W)	Cell radius (km)	Users	Locations
Femtocell	0.001 to 0.25	0.010 to 0.1	1 to 30	Indoor
Picocell	0.25 to 1	0.1 to 0.2	30 to 100	Indoor/ outdoor
Microcell	1 to 10	0.2 to 2.0	100 to 2,000	Indoor/ outdoor
Macrocell	10 to >50	8 to 30	>2,000	Outdoor

TABLE 2: PAs FOR SMALL-CELL BASE STATIONS

PA model	Frequency range (MHz)	Average output power (dBm)
TQP9218	1,805 to 1,880	+24
TQP9418	1,805 to 1,880	+27
QPA9219	1,930 to 2,000	+24
QPA9419	1,930 to 2,000	+27
TQP9221	2,010 to 2,170	+24
TQP9421	2,010 to 2,170	+27
TQP9224	2,300 to 2,400	+24
TQP9424	2,300 to 2,400	+27

TECHNOLOGY POTPOURRI

As *Table 1* shows, small cells differ in output power levels, coverage areas, and number of users served. For the best performance and power efficiency, the subsystems used in small-cell base stations must combine components based on different process technologies. For example, PAs may provide suitable output power and power efficiency.

Filters could require yet a third technology, especially for operating conditions that may experience extremes of temperature and humidity. Temperature-stable bulk-acoustic-wave (BAW) LowDrift filters from Qorvo provide a solution for filtering high-power signals, while also avoiding interference from adjacent frequency bands.

In addition to the various components required for wireless infrastructure designs, including filters, switches, and LNAs, Qorvo developed a line of highly integrated PAs for small-cell base stations. The PAs do not require linearization, and feature on-chip bias control and temperature-compensation circuitry to further simplify the design of a small-cell base station. They are available with +24- or +27-dBm average linear output power when driving a 20-MHz-wide LTE signal *(Table 2)*. The PAs also incorporate two stages of amplifier gain in low-cost surface-mount-technology (SMT) packages.

For example, model TQP9218 is a 0.25-W (+24-dBm) PA designed for small-cell base stations operating from 1,805 to 1,880 MHz. It offers 31-dB small-signal gain across its frequency range with internal impedance matching, on-chip bias control circuitry, and temperature-compensation circuitry—all packed into a 7- × 7-mm RoHS-compliant SMT housing *(Fig. 2)*. The PA achieves 16% power-added efficiency (PAE) and draws just 240-mA quiescent current from a +4.5-V dc supply.

Simply put, better wireless network coverage is needed to support the demand for more voice, video, and data. Solutions for enhanced coverage include DAS and the addition of small-cell base stations to larger macro-cells. With millions of Internet of Things (IoT) devices to flood wireless operating bands, the need for small-cell base stations will rise in the years to come. mw

QORVO INC. (TriQuint), 2300 NE Brookwood Pkwy., Hillsboro, OR 97124; (844) 890-8163, *www.qorvo.com*

Ceramic Resonator Diplexer Splits 1,176 MHz and 1,590 MHz Channels for Differential GPS

Mini-Circuits' CDPL-1710A+ is a ceramic coaxial resonator based diplexer with channel 1 at 1,176 MHz and channel 2 at 1,590 MHz, ideal for differential GPS applications. This model provides 0.8 dB passband insertion loss, 10.9 dB passband return loss, and co-channel rejection of 47 dB, eliminating unwanted spurious signals in-band. The filter can handle RF input power up to +30 dBm and has an operating temperature range from -40 to +85°C. It comes housed in a nickel-silver alloy case mounted on a 16-lead printed wiring laminate (0.75 × 0.75 × 0.21 in.) with wraparound terminations for excellent solderability.

Rugged Coaxial Bias Tee Provides 40W Power Handling from 700 to 6,000 MHz

Mini-Circuits' ZX85-40W-63+ is a coaxial bias tee providing 40W power handling for a wide range of applications from 700 to 6,000 MHz including biasing of high power amplifiers, repeaters, transmit antennas and more. This model provides low insertion loss of 0.5 dB insertion loss, 1.4:1 VSWR, and 33 dB DC-RF isolation. It can handle up to 1A DC current and 30V at the DC input port. It comes housed in a rugged, compact unibody case (0.74 × 0.75 × 0.46 in.) which integrates SMA RF connectors into the case body, providing excellent survivability in touch conditions including military and industrial systems.

High Directivity Couplers, 50 to 6,000 MHz

Mini-Circuits' ZHDC-10-63-NS+ directional coupler provides 10 dB coupling with ±0.3 dB coupling flatness from 50 to 6,000 MHz. This model achieves outstanding directivity up to 33 dB, making it an ideal, low-cost solution for a variety of test applications including S-parameters and intermodulation measurements. It provides 4.0 dB mainline loss, 1.2:1 VSWR, and input power handling up to 1.0W. It comes housed in an aluminum alloy case (0.625 × 0.880 × 0.215) with Type-N input connector and SMA coupling and output connectors.

High-Directivity MMIC Amplifier Covers Applications from 0.5 to 2.5 GHz

Mini-Circuits' MNA-2A+ is a wideband PHEMT based MMIC amplifier supporting applications from 0.5 to 2.5 GHz including cellular infrastructure, defense, satcom, and more. This model provides high active directivity from of 21 to 36 dB, making it ideal for use as a buffer amplifier. It delivers 14.5 dB gain, +17.9 dBm P1dB, +31 dBm IP3, and 5.5 dB noise figure. The amplifier operates on a single +2.8 to +5V supply and integrates the entire matching network, DC blocks and RF choke all in a tiny 3 × 3mm MCLP package, making it very simple to use.

Surface Mount High Pass Filter, 5 to 400 MHz

Mini-Circuits' SXHP-5+ surface mount band pass filter provides a pass band from 5 to 400 MHz, supporting applications including electromagnetic sensors, defense communications, test and measurement, and more. Built using high-Q capacitors and wirewound inductors for superior performance, this model provides 0.5 dB passband insertion loss, 1.2:1 passband VSWR, and 29 dB stopband rejection. It can handle up to 2.0W RF input power and has an operating temperature range from -40 to +85°C. The filter comes housed in a miniature, 8-lead shielded package (0.445 × 0.745 × 0.27 in.) with wraparound terminations for excellent solderability.

Surface Mount VCOs with Linear Tuning, 1,000 to 1,100 MHz

Mini-Circuits' ROS-1100V+ surface mount voltage controlled oscillator supports applications from 1,000 to 1,100 MHz. This model provides linear tuning characteristics with tuning voltage from 0.5 to 12V, tuning sensitivity from 12 to 16 MHz/V, and 3 dB modulation bandwidth of 8.0 MHz. It also provides 0 dBm power output, low pushing (1.5 MHz/V), low pulling (1.5 MHz) and low phase noise (-103 dBc/Hz at 10 kHz offset). The VCO comes housed in a miniature, shielded package (0.5 × 0.5 × 0.18 in.), making it an excellent candidate for dense PCB designs.

Coaxial Bandpass Cavity Filter Covers X-Band Applications from 11,200 to 11,400 MHz

Mini-Circuits' ZVBP-4900+ is a connectorized bandpass filter with a narrow passband from 4,840 to 4,960 MHz, supporting Wi-Fi, telecommunications, broadband applications, and more. Utilizing cavity filter technology, this model provides 1.2 dB passband insertion loss, 1.22:1 passband VSWR, very high upper/lower stopband rejection of >95 dB at 2,000 and 7,000 MHz, and 10 W power handling. It has excellent selectivity with 28 dB rejection only 140 MHz away from the passband cut-off. The filter comes housed in a rugged, aluminum alloy case (4.4 × 1.1 × 0.9 in.) with SMA-F connectors.

New Hand Flex™ Interconnect Cable Features Right-Angle SMP Snap-On Connectors

Mini-Circuits' 086-8SMPR+ Hand-Flex™ interconnect cable features right-angle SMP-F blind-mate snap-on connectors, ideal for interconnections in tight layouts without loss of performance. The hand-formable cable has a minimum bend radius of 6 mm to create almost any shape without bending tools, adapters, or brackets. The connector interface meets MIL-STD-348 requirements, and an insulated outer jacket provides protection for the cable. An 8-in. cable exhibits 24-dB return loss, 0.8-dB insertion loss, excellent power handling (87 W at 0.5 GHz, 15 W at 18 GHz), and operating temperatures from -55 to +105°C.

BRIAN McCUTCHEON | Vice President, Fairview Microwave

Programmable Attenuators Step 30 MHz to 40 GHz

This family of programmable step attenuators tunes in fine steps with up to 10-b tuning resolution and as much as 60-dB attenuation to 18 GHz and 30 dB to 40 GHz.

AMPLITUDE CONTROL OVER wide bandwidths is essential for many commercial and military applications, and system architects often rely on digitally controlled PIN-diode attenuators to do the job. Typical applications include benchtop and automated test equipment, fading simulators for multiple-input, multiple-output (MIMO) communications systems, radar, and electronic-warfare (EW) systems.

To serve these requirements, Fairview Microwave (www.fairviewmicrowave.com) recently launched a line of digitally programmable step attenuators that cover wide frequency ranges well into the millimeter-wave region with attenuation steps as small as 0.03 dB.

The SDUA-400-030-0100-K USB-controlled programmable step attenuator covers 100 MHz to 40 GHz with 0- to 30-dB attenuation and 5-b tuning resolution.

Collectively, the seven attenuator models cover frequencies from 30 MHz to 40 GHz with either 0- to 30- or 0- to 60-dB maximum attenuation range; TTL-controlled tuning resolution of 5, 8, or 10 b; and switching speeds between attenuation states of typically 1-µs on time and 0.5-µs off

GETTING A GRIP ON VARIABLE ATTENUATORS

JACK BROWNE | Technical Contributor

VARIABLE ATTENUATORS COME in many forms, from mechanical, hand-adjusted components to digitally programmable units like those from Fairview Microwave. Such attenuators can be adjusted in level, discrete steps or by continuously variable changes.

With continuously variable mechanical attenuators, it's possible to achieve an almost exact attenuation setting by tuning a control back and forth until a precise amplitude is reached. A step attenuator, on the other hand, will provide whatever precision is possible by the size of the attenuation steps. In addition, there is some degree of variation in those tuning steps, measured as the repeatability of the tuning steps.

Modern programmable step attenuators such as Fairview Microwave's components provide one performance parameter that no mechanical variable attenuator can match: attenuation tuning speed. A mechanically tuned variable attenuator may be better suited for experimental applications, in which a desired attenuation setting may be unknown. But the fast attenuation setting speeds of programmable PIN diode attenuators makes them better candidates for automated testing and any functions that must use many known attenuation values.

A mechanically tuned variable attenuator may be larger than most programmable diode attenuators, but it can also handle more power. Thus, it might be better suited for applications requiring healthy amounts of signal power, such as when performing passive intermodulation (PIM) testing. While the two types of variable attenuators are distinctly different in form and function, they also have value in different applications, which means a test bench often makes room for both.

time for most models. With such performance parameters, these attenuators become particularly useful for the RF and intermediate-frequency (IF) sections of communications transceivers, as well as for level control in signal generators and other test equipment. The devices come with stainless-steel female SMA or 2.92-mm coaxial connectors, depending on frequency range.

An increasing trend in recent years, especially in automated and benchtop test environments, is use of the Universal Serial Bus (USB) as a source of power and control for variable attenuators. A USB connection to a personal computer (PC) can reduce the number of connections required in a system while eliminating the need for an external power supply. Two of the new attenuators, models FMAT3900 and SDUA-400-030-0100-K *(see figure)*, use this approach with an integrated USB 2.0 interface and driverless installation, along with downloadable Windows-based control software. All other models are controllable and powered by a 15-pin Micro-D interface.

The USB-controlled model FMAT3900 covers 100 MHz to 18 GHz with attenuation range of 0 to 30 dB in 1-dB steps. Models SDUA-400-030-0100-K (USB) and SDA-400-030-0100-K (Micro-D), which have the broadest frequency range among the family members, cover 100 MHz to 40 GHz with 0- -to 30-dB attenuation range, 5-b resolution, and 1-dB step size. These attenuators are excellent choices for measurement applications, as they can serve almost any likely test scenario thanks to their broad frequency-range coverage.

Other features common to all of the attenuators include an operating temperature range of –50 to +85°C, small size of usually 2.25 × 1 × 0.33 in., typical VSWR of 2.50:1 or less, maximum input power-handling capability to +20 dBm, insertion loss of 4.5 to 8.0 dB, attenuation accuracy of ±1.3 to ±2.5 dB, and attenuation flatness of ±1.5 to ±3.0 dB. The *table* shows key specifications of all models for comparison.

PROGRAMMABLE ATTENUATOR FAMILY AT A GLANCE

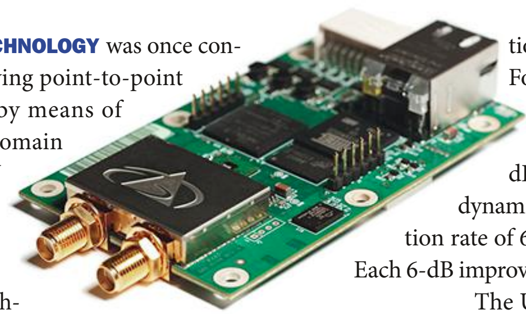
Model number	Frequency range	Control bits	Attenuation range (dB)	Step size (dB)	Maximum input power (dBm)
SDA-060-060-0025-SMA	30 MHz to 6 GHz	8	0 to 60	0.25	+20
SDA-180-030-0100-SMA	300 MHz to 18 GHz	5	0 to 30	1	+24
SDA-180-060-0006-SMA	500 MHz to 18 GHz	10	0 to 60	0.06	+30
SDA-400-030-0100-K	100 MHz to 40 GHz	5	0 to 30	1	+24
FMAT6001	18 to 40 GHz	10	0 to 30	0.03	+24
FMAT3900	100 MHz to 18 GHz	5	0 to 30	1	—
SDUA-400-030-0100-K	100 MHz to 40 GHz	5	0 to 30	1	—

FAIRVIEW MICROWAVE INC., 1130 Junction Dr., No. 100, Allen, TX 75013; (800) 715-4396, *www.fairviewmicrowave.com*

JACK BROWNE | Technical Contributor

Transceiver Tackles UWB Technology

This compact transceiver module employs ultrawideband radio technology by means of very low-level pulses spread across a wide bandwidth.



The PulsON P440 radio transceiver radio module transmits ultrawideband (UWB) pulses across the 3.1- to 4.8-GHz band to perform range determination, data transfer, and monostatic/bistatic radar analysis.

ULTRAWIDEBAND (UWB) RADIO TECHNOLOGY was once considered a global solution for achieving point-to-point high-data-rate communications by means of low-energy pulses. But, as Time Domain has shown with its versatile PulsON P440 radio transceiver module, there are a number of other uses for this technology.

With the right software, UWB technology can be used to perform precise wireless ranging between two P440 radio transceivers, boasting impressive accuracy over great distances. The radio employs packet communications techniques from 3.1 to 4.8 GHz. Its flexible systems can also perform monostatic, bistatic, or multistatic radar analysis, even conducting communications at rates from 19.2 to 612 kb/s. In fact, a PulsON P440 can simultaneously perform range determination, data transfer, monostatic radar analysis, and multistatic radar analysis.

The PulsON P440 packet radio module *(see figure)* employs pulsed signals much like a radar, although it operates with at least one additional radar to form a network. The maximum operating range of this network is a function of a number of variables, including transmit power (typically about 50 μW), pulse repetition rate, and the type of antenna used, but distance measurement resolution of 2 cm is typically achieved at distances to 600 m or more.

Each UWB module uses coherent radio techniques to boost the signal-to-noise ratio (SNR) and dynamic range by increasing the energy summed per number of pulses in a given amount of time. The power per pulse is not increased to boost reception, though the average amount of power transmitted over a pulse interval does climb upward.

The PulsON P440 operates with a nominal pulse repetition frequency of 10 MHz and at different pulse integration rates to achieve the required dynamic range. A variety of different pulse integration rates are available, with higher integration rates yielding wider dynamic range. For example, a pulse integration rate of 1 (which equates to instantaneous operation) provides a dynamic range of 30 dB. A pulse integration rate of 16 yields a dynamic range of 42 dB, while a pulse integration rate of 64 produces a dynamic range of 48 dB. Each 6-dB improvement will double the operating range.

The UWB radio module is based on a proprietary, fully integrated front-end (FIFE) silicon integrated circuit (IC). It is designed for compliance with the frequency masks established by compliance organizations such as the Federal Communications Commission (FCC; www.fcc.gov) in the United States and the European Telecommunications Standards Institute (ETSI; www.etsi.org) in Europe.

The PulsON P440 UWB radio module incorporates standard SMA coaxial connectors on its antenna ports. The radio is compatible with Time Domain's Broadspec Toroidal Dipole Antenna, as well as many third-party antennas. An antenna control transfer switch makes it possible to configure the antennas as transmit/receive on both antenna ports or, alternately, transmit on one port and receive on the other port.

The UWB radio employs an Application Programming Interface (API) over Universal Serial Bus (USB) for control with a personal computer (PC). USB driver support is provided for Microsoft Windows Vista (32/64 b), Windows 7 (32.64 b), Windows 8 (32/64 b), and Windows 10 operating systems (OSs), as well as Unix and OS X OSs.

The PulsON P440 radio module measures just 3.5 × 2.2 × 0.79 in. (89 × 56 mm) and weighs 1.6 oz. (45 g). It is designed for operating temperatures from –40 to +85°C. mw

TDC ACQUISITION HOLDINGS INC., DBA TIME DOMAIN, Cummings Research Park, 4955 Corporate Dr., Ste. 101, Huntsville, AL 35805; (256) 922-9229, (888) 826-8378, *www.timedomain.com*

JACK BROWNE | Technical Contributor

MEMS Oscillators Cut Size and Power

These MEMS-based Super-TCXOs provide standard and custom LVCMOS output frequencies as high as 1 MHz, drawing microcurrents of energy and in miniature CSP housings.

Model SiT1566 is a Super-TCXO based on MEMS technology with 32.768-kHz LVCMOS output and ±5 ppm total frequency stability. It is supplied in a miniature chip-scale-package (CSP) housing.

POWER CONSUMPTION IS a concern for any electronic device with a battery. For consumer and commercial mobile/portable products in the near future, the majority will require energy-efficient circuits and components to extend battery life. Time-keeping is essential to saving power in many circuits—for example, starting and ending "sleep modes" to conserve energy when a circuit is not in use.

Fortunately, microelectromechanical-systems (MEMS) and analog technology from SiTime enabled the development of low-power timing components: temperature-compensated crystal oscillators (TCXOs) with a wide range of uses, from sleep clocks to timing devices for Internet-of-Things (IoT) sensors. The firm recently unveiled three products from its Super-TCXO family, with ±5 ppm stability at 32.768 kHz and at factory-programmable frequencies from 1 Hz to 1 MHz, all contained within tiny chip-scale packages (CSPs).

For applications where even microamperes of current per active component can make a difference in the power consumption of a systems design, MEMS is an effective means for generating frequencies and saving power. By leveraging the low-power operation of silicon CMOS circuitry, the new Super-TCXOs provide LVCMOS outputs with excellent stability over wide operating temperature ranges. They achieve clock frequencies as high as 1 MHz, and at a fixed frequency (32.768 kHz) which has become popular for numerous timing applications both in consumer and industrial electronic products.

SiTime has built a strong reputation for its MEMS oscillators, developing miniature, cost-effective alternatives to crystal resonators and oscillators and other oscillator technologies for audio through microwave frequencies (see *Microwaves & RF*, June 2015, p. 72). In addition to combining electrical and mechanical devices in its MEMS technology, the firm has also developed sophisticated analog circuitry to maintain frequency stability over time and temperature. This circuitry also pairs with the Super-TCXOs to manage power consumption.

Although each Super-TCXO is supplied in a miniature CSP, it is actually a MEMS resonator with programmable analog circuitry within that package. Analog circuitry includes temperature sensing and regulation, a programmable divider, a low-

> For applications where even microampres of current per active component can make a difference in the power consumption of a systems design, MEMS is an effective means for generating frequencies and saving power.

power fractional-N phase-lock loop (PLL), voltage regulators, sustaining amplifier, and a programmable driver. In effect, SiTime has succeeded in bringing a technology once considered exotic to the masses.

The MEMS oscillators are fabricated with the firm's unique MEMS First process, which includes forming a protective seal around the MEMS resonator. This is achieved by the firm's EpiSeal process, during which the MEMS resonator is annealed at temperatures exceeding +1,000°C. This creates a strong vacuum chamber around the resonator for protection, ease of packaging, improved performance, and long-term reliability.

The EpiSeal process grows a polysilicon cap on top of the resonator cavity, eliminating the need for additional cap wafers or custom packaging. As a result, the Super-TCXOs can be treated like any other packaged CMOS device, not as some "exotic" MEMS device. In addition, it allows the integration of additional components and circuitry within the MEMS oscillator package for improved performance and ease of use, plus the elimination of such discrete circuits as temperature compensation outside of the oscillator package.

As an example, model SiT1566 is a low-jitter Super-TCXO with 32.768-kHz output and ±5 ppm total frequency stability under all conditions, all inclusive, without overmolding. Its current draw is a mere 4.5 μA for a supply voltage of 1.8 V ± 10%. The integrated peak-to-peak phase jitter is typically 1.8 ns RMS and maximum of 2.5 ns RMS, while the RMS period jitter is typically 2.5 ns and worst-case performance of 4.0 ms for 10,000 measurement samples. The peak-to-peak period jitter is typically 20 ns, also for 10,000 samples.

The SiT1566's temperature coefficient is calibrated and corrected over temperature by a portion of the programmable analog circuitry included within each package: an active temperature correction circuit. The miniature MEMS TCXO achieves dynamic temperature frequency response of ±0.5 ppm/s for a temperature ramp of as much as 1.5°C/s. SiT1566 models are available for operating temperature ranges of −20 to +70°C and −40 to +85°C.

Amazingly, the MEMS resonator and the analog circuitry are housed in a CSP measuring 1.5 × 0.8 × 0.6 mm and consuming just 1.2 mm^2 of circuit-board area. These MEMS Super-TCXOs are designed to provide significant power savings in electronic products—and in communication networks that rely on precision timing devices such as this—to send different parts of the network into "sleep" modes to conserve power. The SiT1566 becomes active quickly to conserve power, with a power-on start-up time of 300 ms to reach 90% of the final rated output voltage.

Model SiT1568 is a 32.768-kHz Super-TCXO with in-system auto-calibration. It can compensate for assembly-related frequency errors by connection to a 10-MHz external reference oscillator and running the auto-calibration routine during final system test.

The frequency stability of a model SiT1568 can be up to ±25 ppm stability following overmolding and prior to auto-calibration, and then reduced to less than ±5 ppm all-inclusive stability after auto-calibration. It has current draw of just 4.5 μA from a supply at 1.8 V ± 10%. The model SiT1568 is also supplied in the same miniature CSP housing as the SiT1566, with temperature-related specifications similar to those of the SiT1566.

The third member of the Super-TCXO family is model SiT1576, with factory-programmable LVCMOS output frequency from 1 Hz to 1 MHz. It is also specified for ±5 ppm total frequency stability under all conditions. Its current draw is a function of frequency for a supply voltage of 1.8 V ± 10%, only 2 μA for a 1-Hz output, 4.5 μA for a 33-kHz output, 8 μA for a 100-kHz output, and 20 μA for a 1-MHz output.

As with the 32.768-kHz oscillators, the integrated peak-to-peak phase jitter is typically 1.8 ns RMS and maximum of 2.5 ns RMS, while the RMS period jitter is typically 2.5 ns and worst-case performance of 4.0 ms. The peak-to-peak period jitter is typically 20 ns.

These LVCMOS clocks are a fraction of the size of traditional quartz crystal oscillators, with extremely low power requirements for wearable and portable electronic products including for home, industrial, and medical Internet of Things (IoT) sensors. The short turn-on times and high frequency accuracy can result in accurate setting of network sleep times and reliable saving of power at system levels.

In addition, the small size of the package simplifies placement in most circuit and system designs. The MEMS oscillators are capable of driving multiple loads, such as the wakeup clock for Bluetooth circuitry and the timing device for a microprocessor in a battery powered design. In doing so, it can save design time, components, cost, and design size. All three Super-TCXOs products are lead-free and both RoHS- and REACH-compliant. Versions available for use over the two operating temperature ranges: −20 to +70°C and −40 to +85°C. mw

Oven Control Silences SAW Oscillators

A TRIO OF OVEN-CONTROLLED SURFACE-ACOUSTIC-WAVE (SAW) oscillators (OCSOs) features extremely low noise at C- and S-band frequencies. Models LNO3200B3, LNO4800B3, and LNO5000B3 operate at fixed frequencies of 3.2, 4.8, and 5.0 GHz, respectively, with a low phase-noise floor of typically –157 dBc/Hz and better than –121 dBc/Hz offset 1 kHz from the carrier. The sources also exhibit low broadband jitter of better than 10 fs offset 10 kHz to 40 MHz, suiting them for use with high-speed analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). The OCSOs are also available with an internal phase-locked loop for phase locking to an external 10-MHz reference oscillator for enhanced stability. The sources are supplied in a compact housing measuring 120 × 76 × 23 mm.

RAKON LTD., 8 Sylvia Park Rd., Mount Wellington, Auckland 1060, New Zealand; +64 (9) 573-5554, e-mail: sales@rakon.com, *www.rakon.com*

Test Cables are Phase-Stable with Flexure

A LINE OF COAXIAL CABLES developed for test applications remains phase-stable with continuous flexure. These test cable assemblies are based on the firm's 195 coaxial cable, which is designed and tested to maintain phase stability with 50,000 flexure cycles. The cable assemblies feature stainless-steel connectors designed for secure mechanical retention and high stability even after 5,000 mating cycles. The operating lifetimes of these test cables is extended through the use of durable booting. The cables come with BNC, Type-N, TNC, and SMA connectors for applications to 18 GHz, and higher-frequency SMA connectors for use through 26.5 GHz; other connectors are available upon request.

P1DB INC., 117 Bernal Rd., Ste. 70-179, San Jose, CA 95119; (888) 512-7132, e-mail: sales@p1dB.com, *www.p1dB.com*

Amplifier Powers 20 to 500 MHz

MODEL BHED2758-750 is a broadband power amplifier capable of 600 W CW output power from 20 to 500 MHz. The LDMOS amplifier offers 59-dB nominal gain with typical input/output VSWR of 2.0:1. Harmonics are typically better than –20 dBc while spurious levels reach a maximum of –60 dBc. The Class-AB linear amplifier weighs 120 lb. and fits a standard 19-in. rack. It is equipped with an Ethernet/RS-422 control interface, Type-N female input connectors, and an SC female output connector.

COMTECH PST, 105 Baylis Rd., Melville, NY 11747; (631) 777-8900, *www.comtechpst.com*

Digital Step Attenuator Ranges from 1 MHz to 2.5 GHz

DEVELOPED TO PROVIDE GLITCH-FREE ATTENUATION for 75-Ω applications, model PE4314 is a digital step attenuator that operates from 1 MHz to 2.5 GHz. Based on the firm's HaRP technology, the 6-b digital attenuator provides as much as 31.5-dB attenuation in 0.5-dB steps. Maximum insertion loss is 1.5 dB. The input third-order-intercept (IIP3) point is +58 dBm. The component supports parallel and serial control and control voltage of 1.8 V, and is supplied in a 20-lead QFN package measuring 4 × 4 × 0.85 mm.

PEREGRINE SEMICONDUCTOR, 9380 Carroll Park Dr., San Diego, CA 92121; (858) 731-9400, *www.psemi.com*

Epoxy Bonds at Room Temperature

SETWORX UV-35G is a two-part epoxy that gels instantaneously upon exposure to ultraviolet (UV) light. It cures overnight at room temperature or with heat even when not exposed to UV light. Ideal for sealing and bonding, it features low shrinkage and high bond strength with metals, glass, ceramics, and most plastics. The clear bonding system employs a 2:1 mix ratio and is applicable to aerospace, automotive, electronic, and medical applications.

EPOXYSET, 1 Industrial Circle, Lincoln, RI 02865; (401) 726-4500, e-mail: info@epoxyset.com, *www.epoxyset.com*

Compact Filters Trim Harmonic Distortion

THE D68 SERIES of active filters is available in lowpass and highpass configurations at frequencies to 1 GHz with Butterworth, Bessel, elliptic, and constant-delay transfer functions. Filters can be specified with four, six, and eight poles and corner frequencies from 1 Hz to 100 kHz. The filters, which feature total harmonic distortion (THD) levels as low as –100 dB, operate on supplies from ±5 to ±18 V dc. They are supplied in a compact housing measuring 1.8 × 0.8 × 0.3 in.

FREQUENCY DEVICES, 1784 Chessie Ln., Ottawa, IL 61350; (815) 434-7800, e-mail: sales@freqdev.com, *www.freqdev.com*

Waveguide Amp Spans 33 to 50 GHz

MODEL N15-5206 is a millimeter-wave amplifier with in-line WR-22 waveguide transitions on input and output ports for use from 33 to 50 GHz. The amplifier delivers 35-dB gain across the frequency range with gain flatness of ±2.5 dB. It holds noise figure to less than 6 dB while the output power at 1-dB compression is +10 dBm. The VSWR is 1.50:1.

NORDEN MILLIMETER INC., 5441 Merchant Circle, Placerville, CA 95667; (530) 642-9123, e-mail: Sales@Nordengroup.com, *www.Nordengroup.com*

SPDT Switch Channels 700 MHz to 3 GHz

MODEL SKY13522-644LF is a single-pole, double-throw switch with single-bit control for applications from 700 MHz to 3 GHz. It achieves 47-dB typical isolation at 2.2 GHz. The switch features typical insertion loss of 0.7 dB and maximum insertion loss of 0.9 dB at the highest frequencies. Typical turn-on time is 400 ns. The switch is supplied in an eight-pin QFN package measuring 1.1 × 1.1 × 0.45 mm.

SKYWORKS SOLUTIONS INC., 20 Sylvan St., Woburn, MA 01801; (781) 376-3000, e-mail: sales@skyworksinc.com, *www.skyworksinc.com*

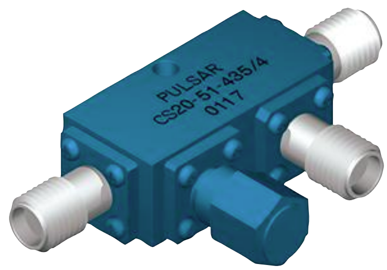
Hybrid Coupler Runs 698 to 2,700 MHz

A 4 × 4 HYBRID COUPLER has been developed for high-power applications from 698 to 2,700 MHz. Designed to handle power levels to 150 W with 6.1-dB maximum insertion loss, the hybrid coupler holds passive intermodulation (PIM) to –153 dBc when tested with two +43-dBm tones. The RoHS-compliant component achieves at least 20-dB isolation between ports and at least 20-dB return loss.

RENAISSANCE ELECTRONICS & COMMUNICATIONS LLC, 12 Lancaster County Rd., Harvard, MA 01451; (978) 772-7774, e-mail: sales@rec-usa.com, *www.rec-usa.com*

Coupler Directs 6 to 40 GHz

BROADBAND DIRECTIONAL COUPLER model CS20-51-435/4 maintains 20-dB coupling with ±1-dB coupling flatness from 6 to 40 GHz. The VSWR is 1.70:1, while insertion loss is 1.2 dB. The coupler, which is supplied with 2.92-mm coaxial connectors, handles input power levels to 20 W with 10-dB directivity. It



measures 1.06 × 0.625 × 0.40 in.

PULSAR MICROWAVE CORP., 48 Industrial West, Clifton, NJ 07012; (973) 779-6262, e-mail: sales@pulsarmicrowave.com, *www.pulsarmicrowave.com*

Low-PIM Attenuators Reach 2.7 GHz

A LINE OF ATTENUATORS is designed to maintain low levels of passive intermodulation (PIM) from 698 to 2,700 MHz. They are specified for PIM of typically –160 dBc when tested with two 20-W tones at +25°C. The attenuators, available with a wide range of fixed attenuation values, are available with 7/16 DIN, 4.3/10.0 DIN, and Type-N connectors.

MECA ELECTRONICS, INC., Denville, NJ 07834; (866) 444-6322, e-mail: sales@e-MECA.com, *www.e-MECA.com*

(continued from p. 79)

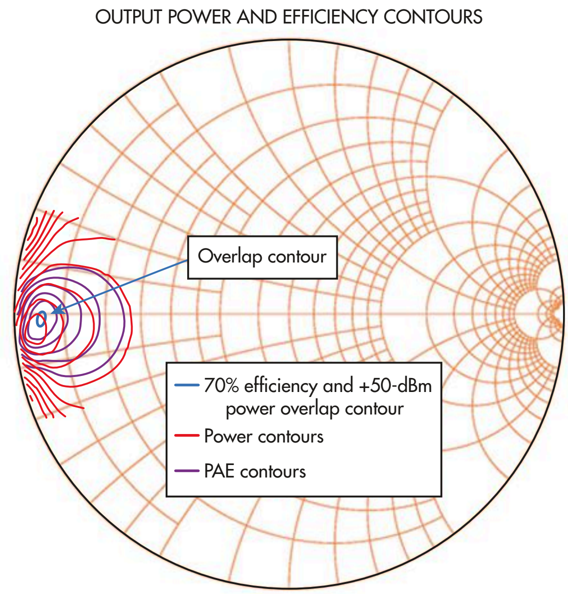
The marker can be moved throughout the operating area of interest for an active device until a designer reaches what might be considered the optimum impedance for a given set of design goals. As an example of working with a different design target, *Figure 10* shows another gamma point chosen for its flat gain compression, flat AM-to-PM conversion, and 2-dB gain-compression output power close to 100 W.

The latest version of the circuit-design software also includes a new capability called an overlap contour function. *Figure 11* illustrates an example of this capability, showing general contours for a PA circuit for output power and power-added efficiency (PAE), along with the overlap contour indicating specific output-power and PAE levels for comparison. An output-power level of +50 dBm and 70% PAE were chosen as reference points, and the overlap contour makes it possible to identify the small number of impedances that meet both design criteria.

Circuit designers rarely home in on a single target as a design goal. With this functionality, it becomes possible to quickly find matching impedances for a multitude of design goals simultaneously.

While the performance of a base-station PA as a function of swept input power is of considerable interest, a designer cannot be constrained to making all measurements based on input power. The multiple-parameter optimization capabilities of the latest version of the NI AWR Design Environment make it possible to perform input-power sweeps while, for instance, plotting contours based on output power, gain compression, or any other PA performance parameters.

As an example, *Figure 12* shows three curves for gain compression increasing to about 6 dB at three different frequencies. A center band at 2.14 GHz and 3-dB compression point were chosen for analysis. With this software simulation functionality, the contours can be plotted for any desired performance parameters. In the case of *Fig. 12*, contours are plotted for output power and PAE, two likely parameters of interest for designers of cellular base-station PAs.

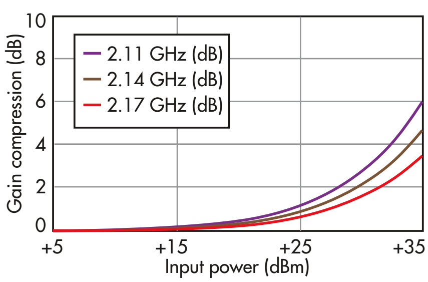


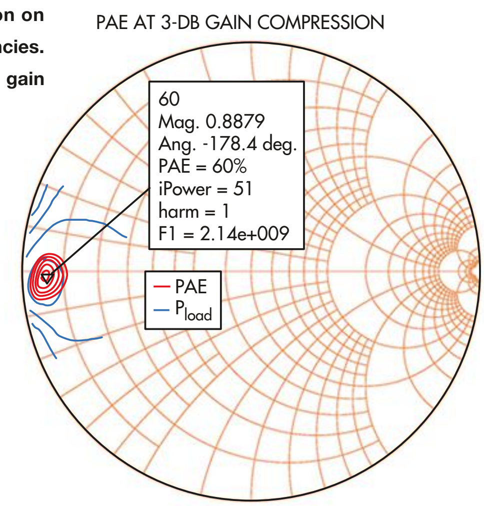
11. These overlap contours were set for +50-dBm output power and 70% PAE.

IMPEDANCE-MATCHING NETWORKS

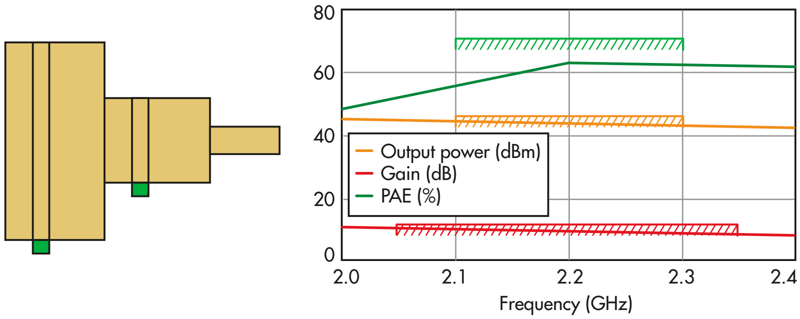
With the new EDA software package, impedance-matching networks can be optimized directly from the load-pull data. In *Figure 13*, output power, gain, and PAE are plotted, this time as functions of frequency. The impedance-matching networks can now be tuned or optimized based directly on achieving the best possible results for all three of those performance parameters. Obviously, the highest value for each parameter may not occur at the same impedance points. But having the ability to show simulations of performance parameters as functions of impedance values helps avoid the endless loop of trying to find the highest possible performance levels for one parameter, while not degrading the performance level of another parameter below an acceptable value.

Furthermore, the enhanced load-pull capabilities enable users to tune directly, or optimize using a wide variety of included optimization algorithms. The bars in *Fig. 12* establish goals for a designer seeking to optimize a circuit. Once goals are set, the optimization runs on the matching network to meet the desired performance, which in turn updates the physical parameters for the matching network.

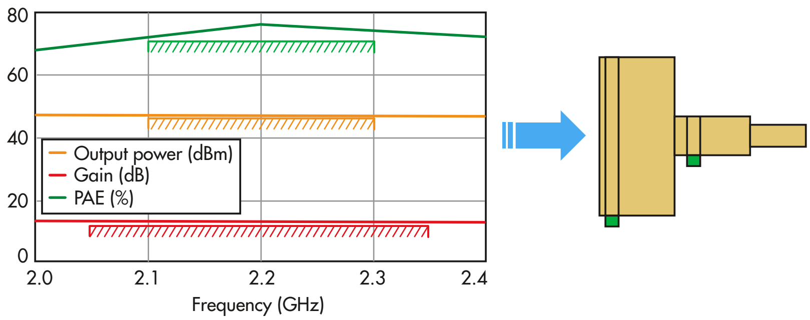




12. The three curves of gain compression on the left rise to about 6 dB at three frequencies. The chart on the right shows PAE at 3-dB gain compression.



13. Several performance criteria were plotted, which makes it possible to optimize matching networks based directly on those performance criteria.



14. Performing the optimization based on empirical load-pull data updates the matching network's physical parameters.

Figure 14 shows the result of the optimization and the updated matching network. The goals can easily be modified to further optimize the design, and the matching network parameters will be updated based on the optimization result. This capability to optimize directly from the local performance data file itself represents a very powerful concept.

Load-pull characterization will continue to be an integral part of the design process for RF/microwave power devices for the foreseeable future. The utilization of load-pull methods is becoming less "black magic" and more a practical design tool as swept-format device files and improved capabilities in EDA software tools emerge onto the market.

For an empirical-based design, load-pull functionality has lowered dependency on third-party nonlinear models and provided increased control of the design process for an engineering team. Designers can perform additional load-pull measurements on an active device as needed to "feed" the EDA software, rather than waiting for the creation of a new nonlinear device model. With a software tool such as the NI AWR Design Environment and its design flexibility, load-pull data can yield not only improved performance of power amplifiers for base stations, but shorter times to market that are often critical in competitive marketplaces. mw

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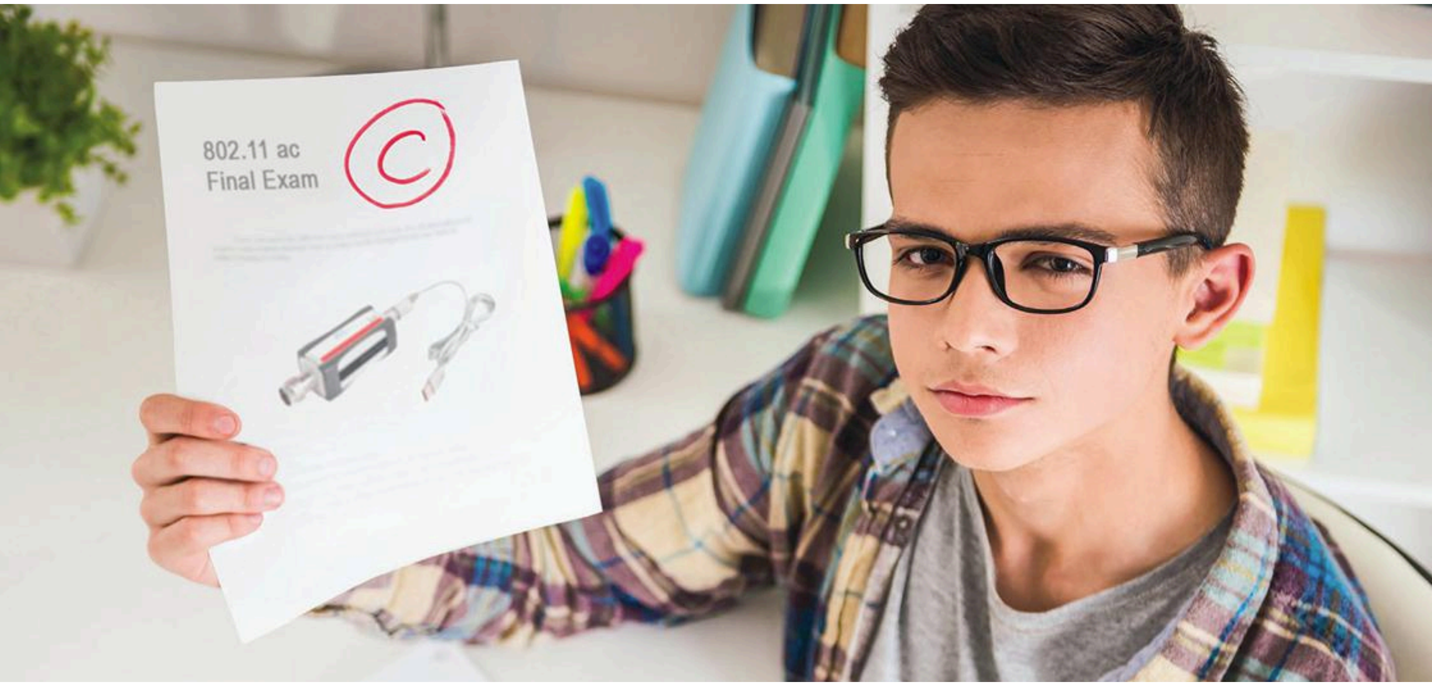
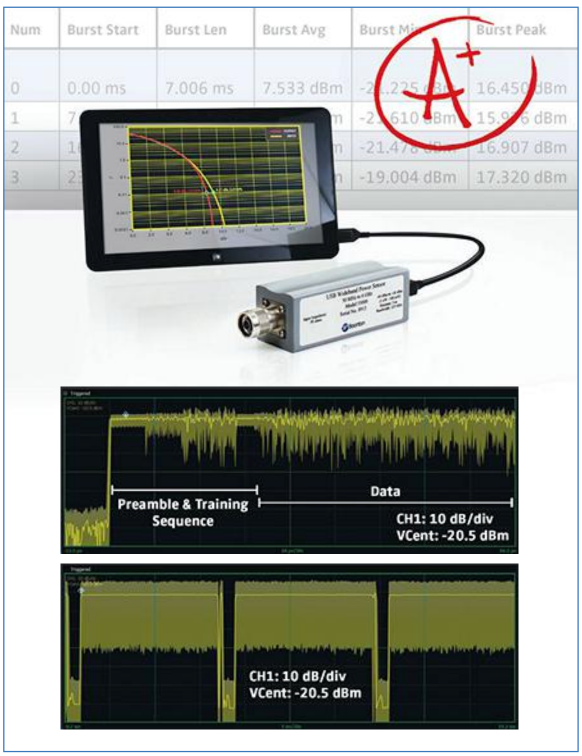
Don't Settle for Average.



Demand Peak Performance.



The 55 Series USB Peak Power Sensor

Real-Time Power Measurements for Complex Communications Signals

Others claim to have fast average measurements, but only the 55 Series measures continuous and burst average power faster than anyone in the industry. It adds wide-band peak and crest factor measurements, allowing you to see all aspects of your device's performance. This USB Sensor delivers results 100 times faster than conventional meters and with its *Real-Time Power Processing*™ technology captures all glitches with 100ps resolution.

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- 3 ns risetime
- 100,000 measurements/sec
- 100 MHz Sample Rate
- Multi-channel synchronized measurements

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Delivered...
MACOM GaN in Wireless Basestations

MACOM™

Partners from RF to Light

The semiconductor technology landscape for wireless infrastructure is undergoing a major transformation, particularly in the power amplifier (PA) market. The multi-decade dominance that laterally diffused metal oxide semiconductor (LDMOS) transistors have sustained in the PA domain is being challenged by Gallium Nitride (GaN), and the implications for wireless basestation performance and operating costs are profound.

The clear technology advantages that GaN provides – improved energy efficiency, greater bandwidth, higher power density, smaller form factors – position it as the natural successor to LDMOS for the next generation of basestations, particularly for cellular bands above 1.8 GHz. While GaN was once prohibitively expensive compared to LDMOS, MACOM's fourth generation GaN on Silicon technology (MACOM GaN) brings their respective cost structures into close alignment.

Here we'll take a closer look at the relative merits of LDMOS, GaN on Silicon Carbide (SiC) and MACOM GaN technologies, assessing their advantages and tradeoffs ranging from performance attributes to costs to supply chain ecosystems. As the only company in the industry to offer both GaN on Si and GaN on SiC technologies – with decades of proven experience and expertise in wireless infrastructure applications – MACOM is uniquely positioned to assess their respective suitability for commercial basestation applications.

MYTH:

GaN on Si power transistors offer negligible efficiency advantages over LDMOS, and can't match the efficiency of GaN on SiC devices.

MACOM GaN-based MAGb power transistors deliver efficiency over 70% and linear gain of 19 dB at 2.6 GHz, with the ability to achieve over 80% peak efficiency when the devices are presented with proper harmonic terminations. This power efficiency profile rivals that of best-in-class GaN on SiC devices, and represents an efficiency improvement of 10% compared to legacy LDMOS offerings.

Properly exploited, this efficiency advantage can make a profound impact on service providers' operating expenses (OPEX) through major savings in the utility bills and savings in the capital expenditures (CAPEX) through minimizing the size of the heat sink, the power supply unit (PSU) and the overall size of the remote radio head (RRH.) The utility bill savings of switching only new macro base stations deployed in a year to GaN can exceed $100M when modeled with an average energy rate of $0.1/KWh.

	LDMOS	MACOM GaN	GaN on SiC	Benefits
Power Amp Efficiency ">2GHz"	–	>10% Improvement	>10% Improvement	*Lower Operating Expense*
Higher Frequency Bands	3.6 GHz	Up to >3.8 GHz	Up to >3.8 GHz	*New Spectrum Deployments*
Wider Bandwidths	100 MHz	200 MHz	200 MHz	*Higher Capacity per Basestation*
Power Density	1-1.5 W/mm	4-6 W/mm	4-8W/mm	*Smaller Antenna, Lower CapEx*
Linearity	DPD Friendly	DPD Friendly	Charge Trapping	*Higher Order Modulation Schemes*
Supply Chain	8"	Up to 8"	4"→6"	*Capacity and Surge Capability*
Cost	Silicon	Silicon	SiC	*LDMOS Like Cost Structure*

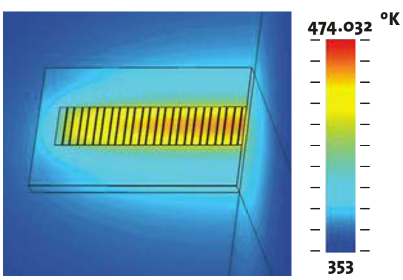
MAGb

MYTH:

GaN on SiC's thermal attributes ensure better PA reliability in the field.

MACOM's ***MAG****b* power transistor series has demonstrated MTTF over 10^6 hours at real-world basestation operating temperatures of 200° C. These devices are therefore proven to be every bit as robust and reliable in the field as competing GaN on SiC devices, and match the field longevity profiles of legacy LDMOS devices.

MACOM achieved this thermal performance parity with GaN on SiC devices leveraging advanced transistor and package design techniques. By optimizing the transistor die layout and using innovative heat sinking and die attachment methods, the 15% to 30% delta in thermal conductivity at the Si vs SiC substrate level is effectively negated at the device level.



MYTH:

GaN-based devices introduce linearity issues that are difficult to correct with digital pre-distortion.

Doherty amplifier implementations are popular for their attendant efficiency benefits, but they can magnify signal problems by introducing non-linearity. This can be corrected with digital pre-distortion (DPD), but DPD has proven difficult to implement with GaN on SiC devices. The charge trapping effects in SiC, believed to be caused by crystalline defects in its silicon structure, ultimately yield challenging and less linearizable PAs.

In comparison, MACOM GaN-based ***MAG****b* power transistors are easy to linearize and correct with DPD schemes compared to other GaN technologies. MACOM GaN doesn't exhibit the same levels of the aforementioned artifacts and is therefore a technically superior solution to both LDMOS and GaN on SiC for basestation applications.

MYTH:

GaN's power density benefits are counterbalanced by prohibitively high costs.

TO272S plastic package offers earless TO272-footprint solutions capable of up to 300 W peak power with improved thermal performance

MACOM GaN can produce 4X to 6X more power from the same transistor die size as LDMOS. And while the wafer material costs for MACOM GaN are slightly higher than LDMOS due to GaN epitaxial deposition, MACOM's wafer processing efficiency enables a 50% reduction in the number of processing steps compared to LDMOS fabrication, yielding a negligible difference in cost per wafer. Ultimately, in volume production, MACOM GaN die size will be between 1/4 and 1/6 that of LDMOS, while supporting an inherently lower cost structure.

The high power density provided by MACOM GaN naturally enables smaller device packages. Alternatively, a designer could maintain existing PA form factors while delivering higher power and/or greater integration to accommodate massive MIMO transmit/receive antenna architectures.

MACOM's ***MAG****b* power transistor series exemplifies this power density advantage. Initial entries in this product series include single-ended transistors providing up to 400W peak power, dual-transistors, and single-package Doherty configurations providing up to 700W peak power in both symmetric and asymmetric power options. The physical size of these devices is equal to that of lesser performing LDMOS devices and comparably performing GaN on SiC devices.

continued ⇢

MACOM GaN...Delivered

MYTH:

GaN is simply too expensive for basestation applications.

MACOM GaN is on a trajectory to yield GaN-based devices that are half the semiconductor cost per watt of comparable LDMOS products, and significantly lower cost than comparably performing but more expensive GaN on SiC wafers at volume production levels. MACOM GaN is the clear winner on cost.

4" vs. 8" Wafer

At maturity, GaN on Si stands to benefit from silicon cost structures that are 100X lower cost than today's GaN on SiC technology, owing to the 200X to 300X slower material growth of SiC boules compared to silicon, and the attendant equipment depreciation and energy consumption absorbed by its fabs. GaN on SiC will therefore remain perpetually higher cost and thus prohibitive for mainstream use in commercial basestations.

In contrast, a full year's production of MACOM GaN for the entire RF and microwave industry can be serviced in a few weeks by a single 8-inch silicon factory. MACOM's industry leadership and partner collaboration on 6-inch silicon wafer production, moving to 8-inch production in 2017, enable the capacity and requisite cost structures to break the barriers to mainstream GaN adoption in the commercial basestation market.

MYTH:

GaN can't meet the basestation industry's supply chain requirements.

The high attendant costs of producing SiC dictates that it will be serviced by a small community of high mix, low volume fabs that lack the ability to service commercial scale applications, particularly at peak demand. And whereas SiC is a relatively new material with a correspondingly short history of use in commercial scale applications, silicon has benefited from more than 60 years of industrialization and development. As such, the supply chain for GaN on Si has a host of natural efficiencies aligned in its favor. The industry's ability to support volume production of GaN on Si, maintain inventories, and accommodate surges in demand is firmly established.

Taking all of these factors into account, MACOM GaN strikes the optimal balance of performance, cost effectiveness and commercial supply chain scalability, distinguishing it as the clear technology platform of choice for the next generation of macro basestations.

For more information about MACOM's GaN solutions for wireless infrastructure, visit **www.macom.com/gan**

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