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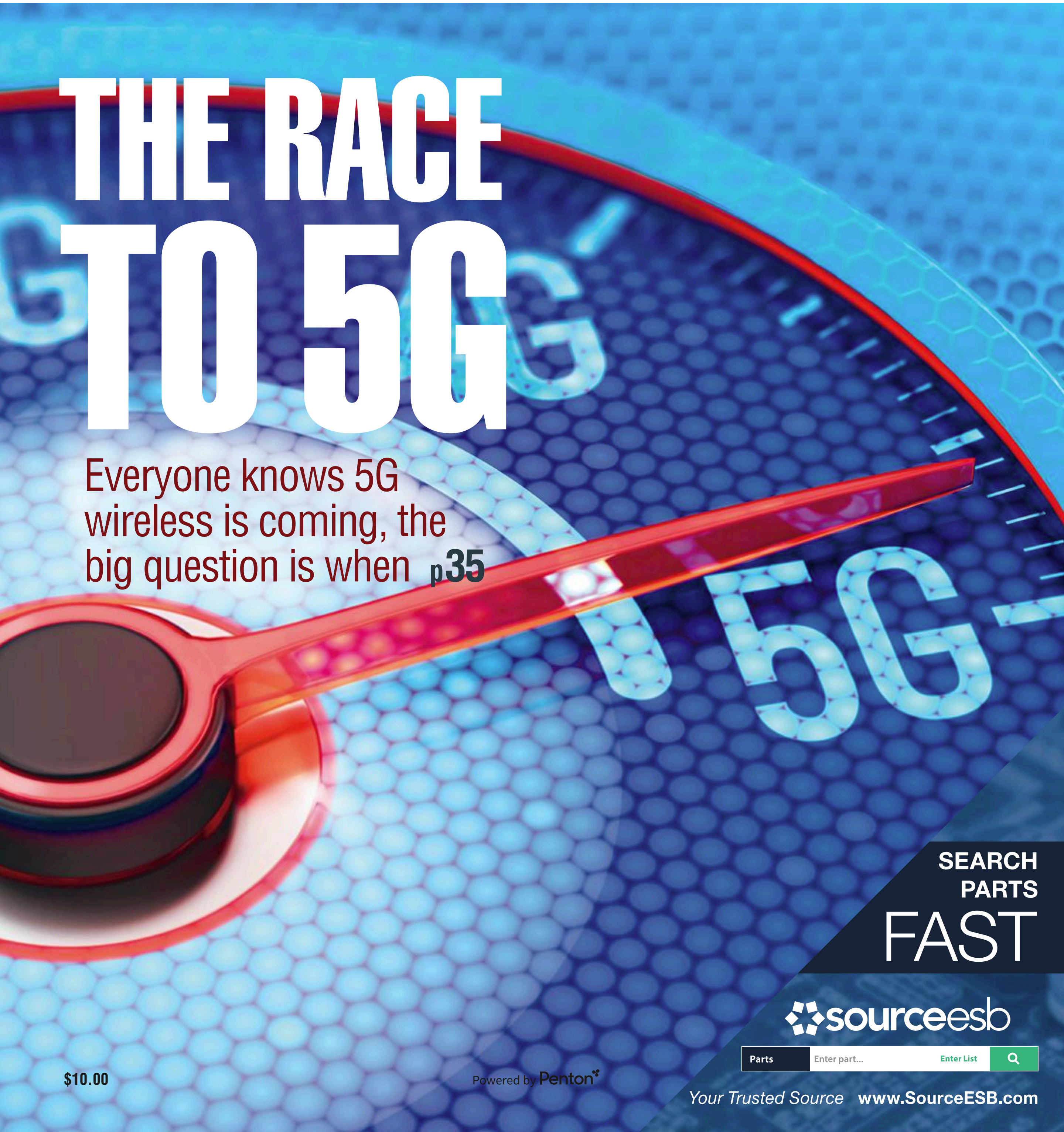

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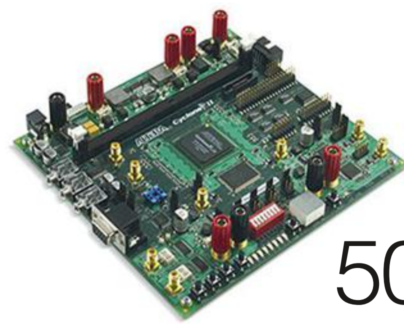

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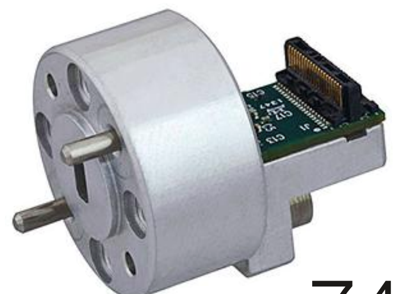

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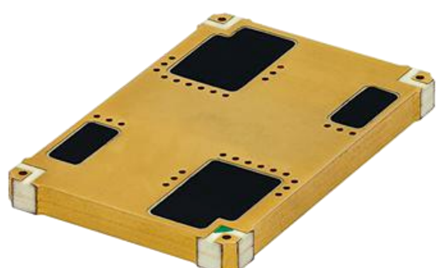

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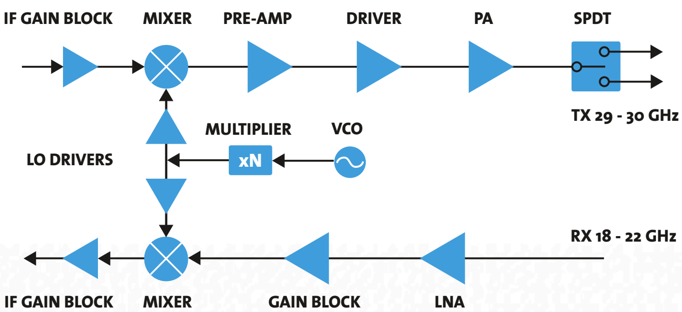

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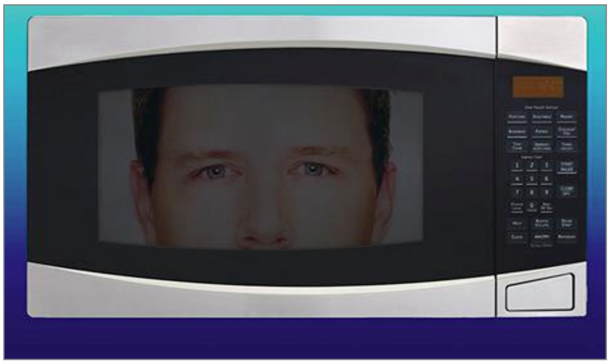

Beware—the Microwave May be Listening!

Tech Editor Jack Browne's latest blog offers a tongue-in-cheek response—but one grounded in microwave technology—to a recent misquote in the media that quickly took on a life of its own: Are our microwave ovens capable of spying on us?

http://mwrf.com/blog/beware-microwave-may-be-listening

Basics of Modulation and Demodulation

Radio waves can carry audio, video, and digital information over great distances by using changes in a carrier wave's amplitude, frequency, or phase to represent the information being transmitted.

http://mwrf.com/systems/basics-modulation-and-demodulation

Tiny Analyzers Scan Millimeter-Wave Frequencies

Barely larger than many smartphones, this line of ultra-portable spectrum analyzers doesn't skimp on performance, with models available for measurements to 110 GHz.

http://mwrf.com/test-measurement-analyzers/pocket-sized-analyzers-scan-millimeter-wave-frequencies

Reversing 25 Years of Antenna Degradation

As mobile communication ramps up in complexity, smarter antenna tuning could prove to be a game-changer in meeting demands.

http://mwrf.com/passive-components/reversing-25-years-antenna-degradation

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Editorial

CHRIS DeMARTINO
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Test Equipment Gets Small

Today, we are clearly seeing a push toward better-performing products in smaller sizes. To prove this, one need only look at how far cellular phones have advanced over the years. Now, smartphones can do almost whatever we want while still being able to fit inside our pockets. But high-performance in small sizes doesn't just apply to smartphones. For example, aerospace and defense systems must yield to today's size, weight, and power (SWaP) constraints.

The smaller-sized product trend also pertains to test-and-measurement equipment, as can be proven by the number of portable test instruments now on the market. Such instruments can offer the performance needed in a portable size—and at prices that are usually lower than benchtop instruments.

Specifically, one can take a look at the current spectrum analyzer market. The spectrum analyzer, which is obviously an essential part of any RF test lab, has traditionally been a large benchtop instrument. When you think of a spectrum analyzer, it is likely that you think of a large box that requires effort to move from one location to another.

However, a number of suppliers are now offering portable spectrum analyzers, which can be connected to a laptop or desktop computer via a USB port. In essence, these analyzers can be held in a person's hand—a stark contrast to a large benchtop instrument. One simply needs a laptop or desktop computer to allow for the display and appropriate user interfacing.

Last year, Tektronix introduced new portable spectrum analyzers, while Anritsu introduced the portable MS2760A millimeter-wave spectrum analyzer earlier this year. Other companies offering portable spectrum analyzers include Signal Hound and Aaronia USA. The availability of portable spectrum analyzers doesn't mean that traditional benchtop spectrum analyzers will disappear anytime soon, but it's clear that test-and-measurement equipment is adapting to the times. Emerging applications like 5G and the Internet of Things (IoT) require innovative solutions from test-and-measurement suppliers. Perhaps tomorrow's RF test labs will look much different than they do today. 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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MICROWAVE MADNESS

I greatly enjoy *Microwaves & RF* magazine, both the print and online versions, and consider it the "industry standard" publication in this field.

I was however, extremely disappointed today to see a well-respected technical journal fall into the same trap so many other "industry" publications have: the insertion of political ideology or commentary into their articles and mailings. For example, today I received this in my inbox (emphasis mine):

"News reports of wiretapped phone lines and microwave ovens used as listening devices **suggest an uncomfortable level of paranoia in the executive branch,** not to mention a **disquieting disconnect from the realities** of modern RF/wireless technologies." (Editor's note: The complete blog is available at *http://mwrf.com/blog/beware-microwave-may-be-listening.*)

If *Microwaves & RF* wishes to run articles addressing technical inaccuracies, that's always welcome, but it's curious that I don't recall seeing any such articles prior to the last presidential election.

Using subjective terms such as "uncomfortable" and "disquieting" speaks volumes to the author's (and perhaps the editors') personal political views, and the article as a whole seems more intended to mock or belittle the current administration than to provide useful technical information...unless your editorial board feels that career RF engineers need reminding that a microwave oven can't (normally) be used as an eavesdropping device.

I have greatly enjoyed many of Mr. Browne's technical articles over many years, but am very disappointed to see politics creeping into areas that should remain (largely) apolitical. "P."

EDITOR'S NOTE

Thank you for your note and for being a reader. I have tried to maintain the highest of standards for *Microwaves & RF* over the years and I appreciate your spending the time with us.

Regarding the "spying microwave ovens," I thought the whole episode of paranoia about microwave ovens was somewhat humorous and decided to write a tongue-in-cheek editorial piece as a commentary, but also to provide a bit of tutorial education, such as what would be required to make a microwave oven a surveillance tool. As you noted, this is not the usual type of editorial piece found in *Microwaves & RF*, but it was never my intention to make any kind of political statement. I hope you will forgive us and continue to look to *Microwaves & RF* for high-quality coverage of the RF/microwave industry.

Jack Browne
Technical Contributor

News

HOW WYOMING IS TESTING CONNECTED VEHICLES on a Major Trucking Route

Commercial trucks will represent almost half the total number of vehicles involved in Wyoming's pilot on Interstate 80. *(Image courtesy of Thinkstock)*

Every year, severe wind on Wyoming's Interstate 80 blows almost a hundred commercial trucks off the road, while the highway's penchant for thick fog and snow storms contribute to thousands of accidents. Wyoming officials say the incidents cause around half a billion dollars in annual property damage.

Officials have imposed variable speed limits and closures to light vehicles during extremely severe winds to curb highway accidents. The state also requires all truck drivers to sign up for an online program that lets them share updates on road conditions from a tablet or smartphone, so that other drivers might know what to expect.

But later this year, Wyoming's transportation agency will convert I-80 into a testing ground for wireless systems that let vehicles talk to each other directly. State officials will retrofit around 400 snow plows, commercial trucks, and patrol cars with on-board units that can send weather updates and collision warnings to other nearby vehicles.

The highway is one of three locations that the Department of Transportation is using to test vehicle-to-vehicle communications, in which cars broadcast their location, speed, and other information so that other vehicles can warn drivers of potential hazards. The National Highway Transportation and Safety Administration says that V2V technology could reduce 80% of crashes that don't involve alcohol or drugs.

The U.S. DoT is spending $4.4 million to bootstrap Wyoming project's on the 402-mile highway. It is also investing around $22 million in another pilot involving 8,000 New York City taxis and buses, as well as $16 million to test V2V communications on a reversible highway in downtown Tampa Bay, Fla.

But the Wyoming pilot is unique in that it will let cars chat about severe weather, using sensors on snow plows, trucks, and fleet vehicles to calculate local weather conditions. It also stands out for focusing on a major commercial trucking route instead of urban transportation: up to 8,000 freight vehicles from 45 states drive on the I-80 every day.

"This is not just a Wyoming issue," said Ali Ragan, a project manager for the Wyoming Department of Transportation, at a recent South by Southwest panel in Austin, Texas. "This isn't even a western United States issue. It really impacts drivers from all over the country."

The pilot is an early test for safety technology based on dedicated short-range communications, which will be required for all new cars and light trucks by 2023 under a proposed federal rule. Cars equipped with DSRC technology send and receive standardized messages 10 times per second over a section of wireless spectrum reserved for automobiles.

Wyoming officials will install 75 roadside units along the highway to collect information from the 400 commercial trucks, snow plows, and other vehicles in the pilot. The project uses fewer vehicles than other pilots, but the technologies that officials are already using to improve safety give it a running start.

Officials have embraced a National Center for Atmospheric Research system that lets cars collect information from temperature sensors and windshield wipers and share it over cellular networks. The Pikalert system combines those data with measurements from satellites, weather stations, and specialized sensors on fleet vehicles to create weather reports that update every fifteen minutes.

The pilot cars in Wyoming will support safety features like forward collision warning and distress signals for emergency responders. When a truck's airbag goes off, for example, the onboard unit will send a distress signal to a roadside unit. If none are close by, then the truck will throw the message to a passing truck, which will toss the message into the next roadside unit.

The pilot is not without its shortcomings. In their application, Wyoming officials worried that spreading only 75 road units over 402 miles of highway would make it difficult to learn anything useful. Because DSRC only works over 1,000 meters, officials are placing the roadside units in places where the most crashes happen, Ragan said.

Those shortcomings are why many wireless carriers and chip makers argue that 5G cellular networks will be better suited for V2V communications. When the final standard is finished, 5G could send message over longer distances and allow for more detailed data like video to be shared, they say.

On the other hand, DSRC is potentially faster than cellular networks because it allows cars to send messages and collision warnings directly, without having to route them through a cellular base station. Another potential advantage is that the hardware can be installed in rural areas with little cellular infrastructure.

But the cost still might be too high for states with shrinking budgets. From that perspective, much is riding on the success of the connected vehicle pilots, said Bob Frey, a project manager at the Tampa Hillsborough Expressway Authority pilot, who also participated in the SXSW panel.

"You have to convince agencies it's worth spending money on," he said. ■

OBSERVING CLIMATE CHANGES from Space

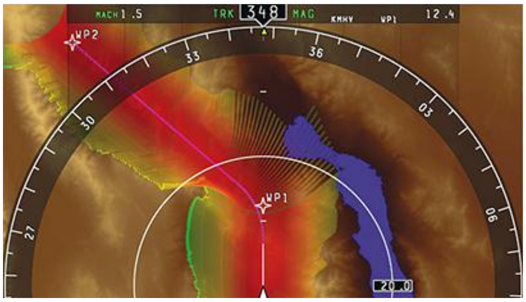
GLOBAL WARMING AND other climate change effects have been a concern for some time, and NASA has been studying the effects for just as long—from outer space. The agency's long-running (since 2002) Aqua satellite mission was initially developed as part of a six-year, Earth observing system (EOS) for studying climate change. The satellite, which has far exceeded its design expectations, has six on-board instruments for collecting data about Earth's water cycle, including water evaporation from oceans, water vapor in the atmosphere, ice movements, and soil moisture *(see figure)*. The satellite and its data-collecting instruments are expected to continue to operate through the early 2020s.

Among the on-board instruments still transmitting high-quality data are an atmospheric infrared sounder (AIRS) and an advanced microwave sounding unit (AMSU) for measuring the daily averaged temperatures around Earth. The AMSU, developed by NASA's Jet Propulsion Laboratories (JPL), is a passive 15-channel radiometer that operates from 15 to 90 GHz. It makes atmospheric temperature measurements from Earth's surface to as high as 40 km above the surface.

The two other instruments still transmitting atmospheric data are the moderate resolution imaging spectroradiometer (MODIS) and Earth's radiant energy system (CERES) unit. The CERES instrument was one of the highest-priority experiments on NASA's EOS project. Managed by NASA's Langley Science Directorate and conducted on several additional satellites, the CERES project measures both solar-reflected and Earth-emitted radiation from the top of the atmosphere to Earth's surface.

Data from CERES and from previous missions, such as NASA Langley's Earth Radiation Budget Experiment (ERBE), provide insights into the role of clouds and the energy cycle in global climate change. The MODIS instrument contributes to the data used in that analysis. ■

This image from NASA's Aqua satellite, which continues to gather atmospheric data to study the effects of climate changes, shows the area around Tunisia.



Using advanced algorithms and synthetic vision technology, NASA's Sonic Boom Display project provides the means to show where the flight of a supersonic aircraft will result in sonic booms on the terrain below.

AVIONICS DISPLAY VISUALIZES Sonic Booms

SUPERSONIC AIRCRAFT HAVE long been known not just for their speed, but also for the sound waves they produce at supersonic speeds. To minimize or even mitigate the effects of sonic books from supersonic aircraft, NASA has been involved in a two-year-long effort, the Sonic Boom Display project *(see figure)*, to enable pilots of such aircraft to visualize any sonic booms they might create. Using advanced algorithms and synthetic vision technology (SVT), NASA hopes to create quiet cockpits in the supersonic aircraft of the future. The results of a recent demonstration show that they are heading in the right direction.

NASA teamed with Rockwell Collins at the NASA Armstrong Flight Research Center for the recent demonstration. The project was developed to help pilots foresee how different flight plans would result in more or less sonic-boom effects. "Important to our progress in reducing the sonic boom impact over land is to have a predictive sonic boom display in supersonic aircraft cockpits that ensures our future quiet supersonic aircraft remain below acceptable noise levels," said Brett Pauer, a subproject manager at NASA's Armstrong Flight Research Center. "We have collaborated with avionics companies like Rockwell Collins to translate our NASA algorithms into an integrated avionics system that is tested and evaluated by pilots."

The project employs NASA's advanced sonic-boom-display avionics algorithm and a worldwide terrain database to predict where a sonic boom from an aircraft will impact the ground. "As a result of this research, we will be able to alleviate noise concerns affiliated with supersonic travel by giving pilots the ability to control boom placement away from populated areas," explained John Borghese, vice president of Rockwell Collins' Advanced Technology Center. ■

MERCURY SYSTEMS BUYS DELTA MICROWAVE for $40.5 Million

MERCURY SYSTEMS IS buying a supplier of microwave components and subassemblies with applications in everything from satellite communications to missile guidance systems. The company's $40.5 million deal for Delta Microwave comes after President Trump's budget blueprint for next year proposed a defense spending hike.

Mercury said that Delta's power amplifiers and filters will complement its wide array of defense electronics, which it sells in modular blocks for applications like electronic warfare, radar systems, and munitions. The company spend around four times Delta's 2016 revenue of $12.8 million.

"Delta Microwave is an excellent fit," said Mark Aslett, Mercury's chief executive, in a statement. "Their strengths in high-power, high-frequency active and passive microwave components and subassemblies—particularly in GaN solid-state power amplifiers—are driving strong backlog and growth."

The deal's timing could also be auspicious. President Trump's proposed budget is seeking $639 million in defense spending next year, up $52 billion from this year. That would reverse the trend of the Obama administration, which made cuts to the defense budget starting in 2011 after spending increased sharply over the previous decade.

Delta has sold parts for Lockheed Martin's F-35 and Boeing's Rivet Joint aircraft, as well as Raytheon's guided Paveway bombs and MALD decoy missiles. The 36-year-old Mercury has contributed to over 300 military programs, according to its website, including the Patriot missile defense system and Predator drone.

The acquisition is Mercury's third in the last year. Those include a $300 million deal for the embedded security, RF and Microwave, and custom microelectronics businesses of Microsemi. The company also recently bought military embedded computing firm Creative Electronic Systems for $38 million. ■

The Patriot missile defense system is one of many programs that Mercury has been involved with. *(Image courtesy of Raytheon)*

Inside TRACK with Greg Henderson

Vice President, RF and Microwave Business Unit, Analog Devices

Interview by CHRIS DeMARTINO, Technology Editor

DR. GREG HENDERSON, *Vice President of the RF and Microwave Business Unit of Analog Devices, has served in leadership roles in the microwave, semiconductor, and wireless communications industry for more than 20 years. Most recently, Henderson served as Vice President of the RF and Microwave Business Unit of Hittite Microwave Corp.—prior to its acquisition by Analog Devices. Henderson earned a bachelor's degree in electrical engineering from Texas Tech University and was granted a Ph.D. in electrical engineering from the Georgia Institute of Technology. He holds seven patents in wireless communications and semiconductor technologies, and has published over 20 conference and journal papers.*

First, can you tell us a little about your role at Analog Devices?

My role is Vice President of the RF and Microwave Business Unit of Analog Devices. In this role, I am responsible for the creation and execution of Analog Devices' strategy for the full suite of RF and microwave products and solutions.

How are some of the various semiconductor technologies being utilized in terms of applications?

The complex mix of markets that we serve with RF and microwave solutions requires flexibility and careful consideration in terms of semiconductor and packaging technologies. Performance, development costs, margins, time-to-market, and integration levels all play a role in this critical selection.

CMOS is the primary candidate in the very-highest-volume markets, such as automotive and consumer, that require heavy digital and mixed-signal content to complement RF and analog signal processing. Here, high development costs due to design complexity and mask sets are justified by high volumes and revenues, though margins need to be carefully managed.

At the other extreme, for markets and applications that require the absolute best performance, such as military, aerospace, and instrumentation, broader technologies are essential. ADI leverages GaN/GaAs technologies for broadband microwave and millimeter-wave amplifiers and mixers, and SOI technology for low-loss, wideband, small-form-factor switches. These target best-in-class performance and often displace more exotic approaches, such as traveling-wave-tube amplifiers and PIN switches, due to better reliability, smaller size, and/or ease of use.

SiGe BiCMOS offers an important balance of integration and performance when compared to CMOS and GaN/GaAs for medium-volume applications such as cellular infrastructure, satellite communications, and military phased arrays. The improved performance level of SiGe BiCMOS can now address many microwave and millimeter-wave signal chains that were formally implemented with discrete components.

One topic that is not always discussed is packaging. What are some of the more recent developments in regard to packaging?

While ADI has expertise across a wide range of semiconductor technologies, co-packaging of these different technologies is becoming the real differentiator. This approach is not limited to semiconductor technologies, and includes passives, antennas, and waveguide interfaces. Co-packaging redefines system partitioning and enables a "best-of-all" approach in which system-on-chip (SoC) gives way to system-in-package (SiP).

In the microwave and millimeter-wave arena, package performance at the SiP and chip-scale levels is a significant contributor to solution performance. At ADI, we are extending these capabilities up through 100 GHz and can now provide surface-mount, chip-scale package solutions for products up through 70-80 GHz. Two such examples are our DigiMMIC, which is a 77-GHz CMOS integrated automotive radar solution, and our recently released dc-to-30-GHz wideband switch.

In addition, we offer SiP solutions for complete signal-chain integration in cellular infrastructure and point-to-point radio. We recently released a complete E-band SiP radio signal chain in a laminate-based, surface-mount package complete with a waveguide launch embedded in the package. These millimeter-wave markets now require small footprint SiP solutions just like in automotive radar and 5G.

How can today's existing bandwidth be used more effectively?

All wireless communication modes (cellular, point-to-point backhaul, satellite) are going through rapid data-rate expansions to support modern demands such as streaming services and virtual reality. With the scarcity of wireless bandwidth, there is a growing need to maximize throughput in a given channel.

Fundamentally, there are two methods to increase data rates. The first is to move to higher-order modulation. The point-to-point market has taken this to what may be the maximum practical limit by supporting 4096 QAM modulation in the latest-generation systems. These high-order modulations require very low-phase-noise synthesizers and extremely linear Tx/Rx chains.

The second approach is to maximize the use of the channel through multi-antenna systems, often referred to as massive MIMO or phased-array solutions. Massive-MIMO systems rely on the spatial diversity of the physical channel to increase overall system capacity by sending coded data over a large array of antennas (up to 128 channels for current cellular implementations). In phased-array applications, beamsteering technology concentrates and targets RF energy in "beams" for individual users or groups of users. This improves the link budget and allows multiple beams to be sent with data to multiple users simultaneously.

Massive-MIMO and phased-array systems have a big impact on semiconductor content, because they represent a 10X-100X increase in the number of RF channels/radios compared to more traditional alternatives. To address this need, Analog Devices is developing solutions with much higher levels of integration, mostly in SiGe and CMOS technologies. This allows us to support single-chip, multichannel Tx and Rx solutions for next-generation massive-MIMO and phased-array solutions—with channel counts of up to 16 antennas in a single chip.

You have gone on record saying that wireless sensing is a rapidly emerging market. Can you tell us more about this market and where you see it going?

Real-world sensing technology has been advancing steadily, and it's no surprise that, coupled with the Internet of Things (IoT), the development of smarter sensing technology is required to further automate the smarter world in which we live.

ADI's new 24-GHz integrated solution is enabling a new generation of non-contact sensors, which increasingly are being used in mass-market applications such as automotive ADAS, industrial sensing, and consumer products. These wireless radar sensors provide real-time object detection information such as object presence, movement, position, or angle, as well as velocity and range from a few centimeters up through several hundred meters from the sensor.

Until recently, radar sensors at gigahertz frequencies were realized using complex and costly discrete solutions, which limited their broad market adoption. ADI's 24-GHz silicon radar chipset provides a high-performance, small-size, low-cost, easy-to-use solution for object detection and collision avoidance. These sensors have a broad application base and are being adopted in automotive safety systems, traffic-monitoring controls, UAV collision avoidance, security monitoring—even healthcare devices used for vital-signs monitoring.

Radar sensors, compared to optical/vision or ultrasonic-based sensors, provide accurate measurements over a much longer range and wider field of view in very difficult environments that might include dust, smoke, snow, fog, or poor lighting conditions. While radar technology is not a panacea for all sensing requirements, it is being coupled with other sensor technologies to create "sensor fusion" solutions that are reliable, accurate, and robust.

It seems like no interview is complete without mentioning 5G. Can you tell us a little bit about some of the 5G-related activity taking place at Analog Devices?

The possibility of new network topologies, use cases, connectivity scenarios, and the associated technology challenges that we need to overcome—as an industry—is a very exciting place for ADI. We have been making significant investments in both sub-6-GHz and millimeter-wave 5G components, and remain committed to the communications infrastructure market.

In terms of our technology and products, we are in a very strong position to offer customers a complete 5G signal chain. ADI has over a decade of leadership, experience, and success from the digital interface to the antenna. That means we extend from bits all the way to microwave, and now with 28-GHz and 39-GHz waveforms, even to millimeter-wave.

The technology expertise and manufacturing infrastructure that comes from our long history in the communications market are proving vital in the development of our 5G products. We are also finding that we are able to leverage our work in developing integrated solutions for military phased-array radar applications into solutions for 5G. In emerging markets such as 5G, it is important to provide technology leverage from other markets—and ADI is making significant investments in multi-antenna phased-array solutions in the military, 5G, and satellite communications markets.

Currently, we have available a compelling selection of data converters, up- and down-frequency converters, PLL/VCOs, switches, and beamformer/phase-shifter ICs that fit the full range of 5G prototype designs. These products enable our customers to build high-performance, fully functional 5G terminal and base-station systems.

We are actively participating in our customer's trial systems and helping to create the ecosystem for these next-generation solutions. We continue to make investments in each of these product areas, and will offer even higher-performance, more integrated baseband, RF, microwave, and millimeter-wave products in the coming years. We plan to be a big part of the 5G revolution to come. mw

MINIATURE ANTENNA NOURISHES Body Area Networks

WEARABLE SENSORS WILL one day instantly provide physicians with updates on their patients' health conditions, even their up-to-the-moment whereabouts. In support of that goal, a team of students at Ohio University developed a BAN with heart-rate monitor (HRM) and other sensors, such as a fall detector and temperature monitor, integrated into a chest strap. The chest strap includes a low-cost microcontroller to collect and organize the data from the difference sensors also mounted within the chest strap.

The HRM, temperature sensor, and fall detector use a low-frequency data link at 5.5 kHz to communicate with the microcontroller, which in turn makes the collected data available to a smartphone or other monitoring device by means of 2.4-GHz Bluetooth low energy (BLE) communications. The choice of low-frequency 5.5 kHz data link results in less signal attenuation through and around the body of the wearer, using an inter-integrated-circuit (I2C) bus to the microcontroller as the HRM interface (HRMI).

The students designed the system and specified different sensors and components for a prototype system as part of an undergraduate project, a competition in the 2015 IEEE Antennas and Propagation Society Student Design Contest. Since the wearable electronics must be portable and battery-powered, the student designers were constrained in their choice of sensor components, such as the fall detector sensor. It is based on MEMS technology and powered by a +3.3-V dc source and includes a three-axis accelerometer and three-axis gyroscope. This sensor is capable of monitoring changes in acceleration in three axes, taking constant samples to determine when a wearer has experienced a fall by the rapid changes in acceleration.

One of the challenges in completing the BAN design was the development of a compact BLE antenna that could be mounted in the chest strap and radiate outward from the body with sufficient gain. After trying several antenna configurations, an inset-fed patch antenna was developed that was somewhat larger than an earlier planar-inverted-F antenna (PIFA) design, but with good gain and radiation characteristics. Antenna testing was performed at the university's own shielded anechoic chamber and the total cost of parts and labor was tallied at just under $600.

See "Prize-Winning Ohio University Students Present Their Work on an Antenna for Body Area Networks," *IEEE Antennas & Propagation Magazine*, Vol. 59, No. 1, February 2017, p. 116.

FINDING WAYS to Test Massive MIMO 5G

ONE OF THE TECHNOLOGIES seen as a key for optimizing the spectral efficiency of 5G networks is massive multiple-input, multiple-output (MIMO) antenna arrays. But before 5G standards are established and base stations are constructed, wireless network operators must determine an effective way to perform over-the-air (OTA) testing of massive MIMO base stations.

Testing massive MIMO arrays poses much more of a problem than the traditional characterization of an antenna's radiation pattern in an anechoic chamber. Massive MIMO arrays consist of potentially hundreds of antennas in one location, such as a base station, to manage the use of frequencies and time slots for many simultaneous users. A great deal of theory has been presented to this point on the design of massive MIMO systems, but designing, building, and testing such arrays is another issue.

Traditional wireless base stations may have as many as eight separate antennas, and these can be tested individually through the cabled connection to signal generators and spectrum analyzers. The physical size of massive MIMO arrays, with typically 64 or 128 array elements, makes the challenge of performing OTA testing daunting just in providing a test facility that can accommodate the tens of wavelengths of propagated energy that must be measured simultaneously.

For a test facility, such as an anechoic chamber, that is properly equipped to evaluate the performance of a 5G base station massive MIMO antenna array, for example, the number of OTA test antennas needed to characterize a device under test (DUT) must be equal or greater than the number of antenna array elements. Each array element is treated as an individual antenna and expected to perform as such for a designed frequency band of interest. Unfortunately, the costs of providing this many OTA antennas for this type of test facility would be extremely prohibitive. Add to those costs any additional hardware, such as power amplifiers, that might be needed in the testing of a massive MIMO array. Depending on the frequency/wavelength of the array testing, the test facility must also provide the physical dimensions to provide adequate distance between the DUT and the OTA antennas to represent realistic working conditions.

As with much of 5G, the strategies for developing and testing massive MIMO antenna arrays are still in their infancy. However, even based on theory, the concept of using multiple antenna elements in a time-and-frequency-coordinated array for a 5G base station makes sense in terms of achieving optimum spectral efficiency and making the most of the limited available bandwidth.

See "A Step Toward 5G in 2020," *IEEE Antennas & Propagation Magazine*, Vol. 59, No. 1, February 2017, p. 38.

SPECIAL REPORT: 5G

CHRIS DeMARTINO | Technical Engineering Editor

5G Goes Over the Air

For next-generation 5G networks to finally become reality, over-the-air testing must be available—and many companies are working to make that happen.

THE ACTIVITY SURROUNDING fifth-generation (5G) networks is at a fever pitch, as proponents of the technology look to ensure that it becomes a reality in the not-so-distant future. Today, 5G is a hot topic, receiving a great deal of scrutiny in myriad articles, webinars, etc. Those who have been paying attention are probably already aware of the benefits promised by 5G—benefits like faster data rates and greater capacity.

One tantalizing aspect of 5G concerns the prospect of over-the-air (OTA) testing. With 5G expected to utilize antenna arrays at millimeter-wave frequencies, test approaches beyond traditional cable-based methods must be investigated. That's why a number of test-and-measurement companies, including Keysight Technologies *(www.keysight.com)*, National Instruments (NI; *www.ni.com*), and Rohde & Schwarz *(www.rohde-schwarz.com)*, are now focusing on OTA test solutions.

At Mobile World Congress 2017, Keysight's Lucas Hansen gave a presentation titled "mmWave Over the Air Test Challenges and Opportunities." In it, when discussing 5G, he noted the significance of millimeter-wave frequencies along with signal bandwidths that could be as high as 1 GHz. "What this does is drive a fundamental change in the design architecture of the devices that we have," said Hansen during his presentation.

"No longer do you have a traditional cabled environment when you are designing RF front ends," he added. "What you now have at these frequencies is a phased-array antenna, which is bonded directly to an RF integrated circuit (RFIC). Phased-arrays are required at millimeter-waves and, as such, are introducing 'no-connectorized test.' That means that you no longer have the traditional cable that you once had." Expect to hear more from Keysight regarding OTA testing in the near future.

This demonstration system was built on Verizon's 5G specification.

OTA PUBLIC DEMONSTRATION

NI is another company at the forefront of OTA test solutions. At the IEEE Wireless Communications and Networking Conference (WCNC) in March, the company demonstrated a real-time OTA prototype for 5G at 28 GHz *(see photo above)*. The demonstration system, which was aligned with Verizon's 5G specification, contained eight independently configurable 100-MHz component carriers. "The Verizon 5G demonstration system received a lot of attention and was a must-see for the WCNC attendees—which included the top wireless researchers in the world," said James Kimery, director of marketing for RF, communications, and software-defined radio (SDR) initiatives at NI.

The prototype, which was built using NI's mmWave Transceiver System, featured a new version of millimeter-wave heads operating at 28 GHz. Anokiwave *(www.anokiwave.com)* and Ball Aerospace *(www.ball.com/aerospace)* developed the phased-array antennas. Written with LabVIEW system design software, the prototype system features fully modifiable real-time code for both the base station and the user equipment. Stay tuned for more in the days to come. mw

ROGER NICHOLS | Director of 5G Programs, Keysight Technologies
www.keysight.com

Building One 5G Wireless Standard to Rule Them All

Tirelessly working through reams of documentation, the 3GPP marches onward to create a solitary standard for 5G communications.

THE ON-TIME BEGINNING of too many of my business meetings is tarnished by the initial 15 minutes wasted watching three impromptu IT "experts" search for the right port, adaptor, and monitor setting to connect someone's laptop to the projector. If you have never experienced this problem, allow me to suggest that you do not exist.

Are we incompetent operators of IT tools? No. We simply lack a single standard. And while I have little hope for projector convergence, in 5G we are on the verge of something revolutionary: a single and globally deployed standard for mobile communications.

From the earliest days of radio, standards organizations arose to ensure that Marconi's magic could be applied in a manner enabling us to communicate from afar. A quick perusal of the internet will yield fascinating tales surrounding the standardization of Morse code, radio channels, distress signals, and spectrum management. Early standards arose from the predecessors of today's ITU meetings, the results of which read remarkably like those created today.

From 2G forward, we had global standards for cellular communications. But we did not have the potential of a single standard until we reached 4G—and that convergence was forced to cower while the WiMAX/LTE duality threatened the peace of the mobile world for a few tense years.

THE STANDARD BEARER

The 3GPP has been working for over a year to define a fifth-generation standard—the most ambitious development in communications since the advent of analog cellular. Gaining global alignment across all segments of our industry requires difficult technical work hashed out in long meetings, frustrating discussions, email rants, and legal battles. All of this is amongst a demographic of engineers and mathematicians, and our little technical club is not known for its smooth social skills.

I do not mean to belittle standards work. Those not associated with such bodies may be surprised at their scope and breadth. Three technical specification groups exist within 3GPP, each responsible for several technical working groups that develop the details of the specifications. This means approximately 1,500 people in 20 committees meeting up to eight times annually who generate massive amounts of documentation distilled from tens of thousands of technical submissions.

Some perspective: A colleague who attends 3GPP RAN4 recently sent me a copy of "3GPP TR 38.803 v2.0.0," a 200-page, 11-MB feasibility study on radio frequency and coexistence aspects of the new 5G wireless air interface. This work-in-progress document represents just one part of one part of one part of one part of the gestating standard. During this subgroup's last meeting, no fewer than 37 documents were submitted for consideration for the topic of radio testability alone.

The recent 3GPP decision to accelerate the standard comes after a yearlong argument. Without getting into details, this was driven by a discussion of the tradeoffs relating to enabling new business models, standards "fragmentation," and the risk of a standard that falls too far short of the 5G vision originated in the ITU and now beautifully portrayed in every company's 5G presentation.

The technical and commercial demands of creating and deploying these standards are monumental. As a consumer, I look forward to the wireless standards being as unwavering as the color of traffic lights and certainly more consistent than interfacing with display projectors. As a supplier of simulation, design, test, and measurement solutions, I admit that the past 20 years of fragmented standards have created wonderful business opportunities. It is thus difficult for me to find a neutral space. But while it will take a few years, I believe the market forces will drive a common standard to reality. mw

IAN GRESHAM | Distinguished Fellow of Technology, Anokiwave
www.anokiwave.com

5G Makes Major Strides in First Half of 2017

At Mobile World Congress 2017, 5G held court in many circles. Here is one company's perspective on the technology's fast track.

THE CONVERSATION AROUND 5G has reached a crescendo. That was clear at this year's Mobile World Congress (MWC), which saw its largest crowd ever of 104,000 attendees. Discussion at the conference centered around the future of the mobile industry, and one of the main themes was 5G.

From technical tracks on the development of sub-6-GHz spectrum bands to panels posing high-level implications for IoT applications, 5G was both well represented and well received at the show.

A particularly interesting presentation was Keysight's *(www.keysight.com)* wideband real-time beamforming solution, on hardware operating at 28 GHz provided by Anokiwave and the University of California San Diego *(see photo)*. The demonstration clearly showed how researchers can quickly and accurately test analog, digital, and hybrid beamforming systems. As the first true phased-array ever demonstrated at MWC, the booth generated much excitement.

This 5G MIMO beamforming demonstration took place at MWC 2017.

With 5G quickly advancing, another natural topic of interest was the transition path of 4G networks. Most experts agreed that a full 5G rollout is expected by 2020, but pointed to multiple field trials already underway that feature commercially viable RF front ends with beamforming and active antenna solutions. Experts also predicted 2018 and 2019 will bring more field trials with key network providers, underscoring the bottom line—the industry cannot afford to wait for 2020 to begin testing.

The connected car and use of sub-6-GHz spectrum for the Internet of Things stole the show. The market for these technologies is expected to be huge. It's predicted that connected devices will grow to more than 20 billion by 2020, and the push for vehicle-to-everything (V2X) communications in vehicles will cover everything from the smart highway and autonomous driving to continuous connectivity.

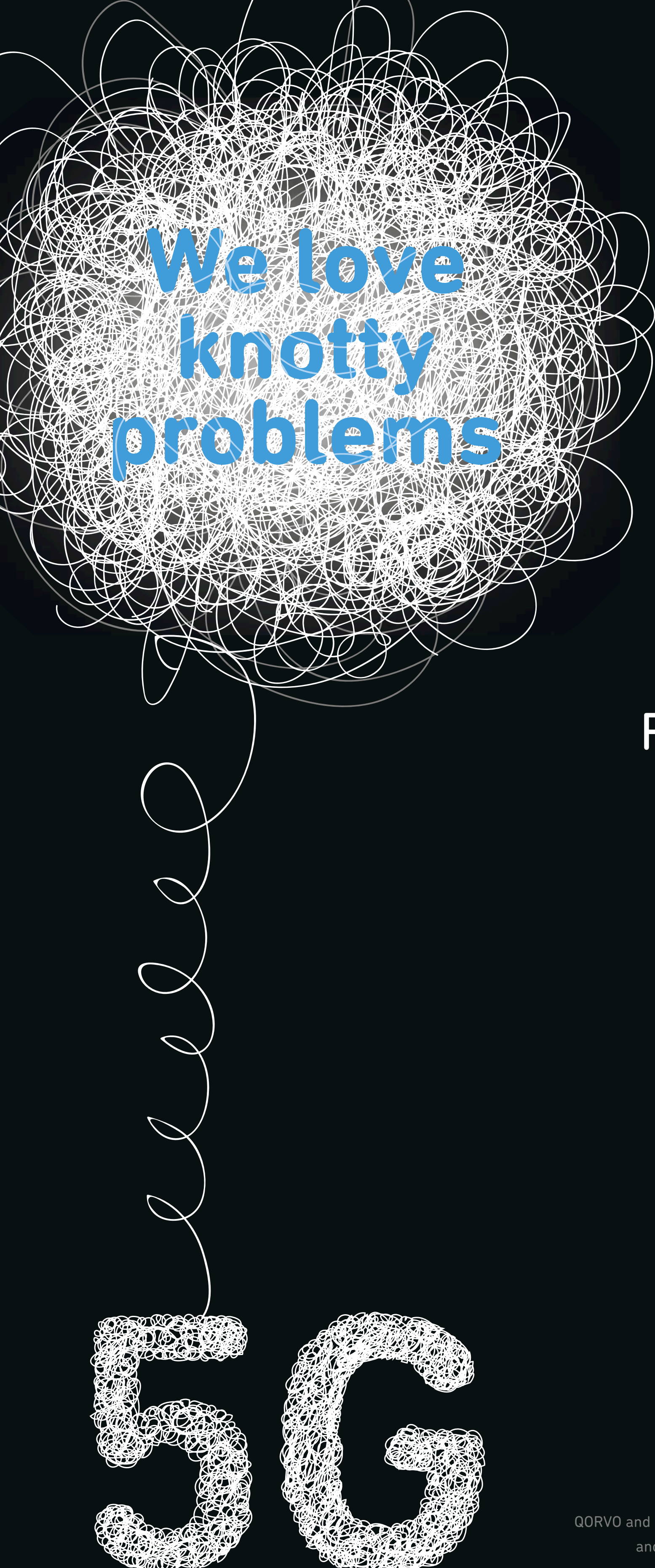
The magnitude of the opportunity demands focus, but resources are limited. Those opportunities that require only slight evolutions of technology will be the priority and focus for stakeholders going forward.

One aspect of 5G arguably neglected at MWC was the consumer end link. While millimeter-wave technology was well represented, solutions for customer premises equipment (CPE) weren't so fully baked out. Speakers and presenters indicated a burgeoning emphasis for 28-GHz spectrum, opening the door for growth and improvement in CPEs moving forward.

On the heels of MWC came two more major announcements. First, international body 3GPP asserted its plans to accelerate 5G deployment to 2019. This is huge news for carriers chomping at the bit to roll out 5G for increasingly data-hungry customers. Device manufacturers and network providers alike have come out in droves to support the plan, including Qualcomm, Nokia, Verizon, Intel, Ericsson, Huawei, and Samsung.

The other announcement came from recently appointed U.S. FCC Chairman Ajit Pai, promising to respond faster to new technology proposals. This commitment is expected to impact the speed and direction of 5G development around the world.

Experts and major industry bodies have spoken—5G will arrive faster than many envisioned. If you're not preparing for it now, you're already behind. As new millimeter-wave frequency bands are allocated by the appropriate regulatory entities for 5G systems worldwide, companies such as Anokiwave will respond with products to help meet emerging needs.


We love knotty problems
5G

JACK BROWNE | Technical Contributor

Underlining the Meaning of Linearity

It can be difficult to achieve the linearity of an RF/microwave component, which is essential for communications systems relying on advanced modulation schemes.

LINEARITY IN AN RF/microwave component or system is fairly easy to understand in concept: It refers to the ability of a component or system to provide an output signal that is directly proportional to an input signal. As a result, the relationship of the signal input to the signal output as a function of frequency is a straight line.

Achieving good linearity, on the other hand, is not quite so simple, even though it is crucial to preserving key pulse characteristics in a radar and modulation quality in a communications system. Whether it is a frequency mixer, an amplifier, or a complete system, many barriers to linearity must be overcome, often at the expense of some other performance parameter.

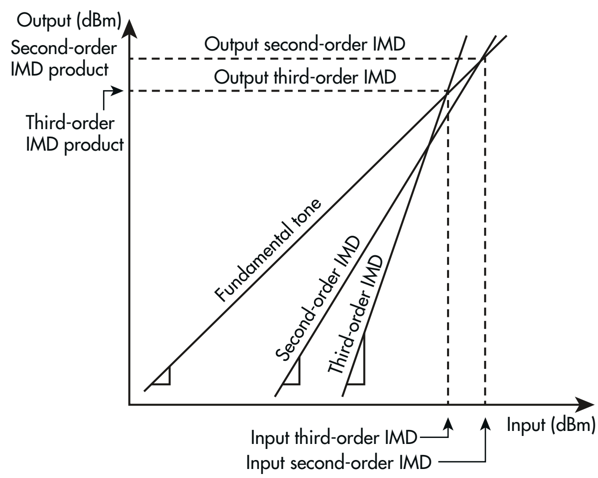
THE ABCS OF LINEARITY

A simple way to think of linearity for any component is a straight line. For an amplifier, this means that a plot of output power as a function of input power will be a straight line, with the slope of the line equal to the gain of the amplifier. If the gain-vs.-frequency response is fairly even, the line will be straight. A line that is not straight indicates an amplifier is not linear. Of course, most RF/microwave amplifiers tend to tail off in gain at the higher frequencies, resulting in a plot where the line curves downward in the direction representing lower gain.

In a wireless communications system, good linearity is essential for both receivers and transmitters, as well as their components. However, poor linearity is most evident when it occurs within the transmitter and a number of its components, including power amplifiers (PAs), frequency mixers, and switches.

Linearity is critical for systems transmitting carrier signals with amplitude modulation (AM) or a combination of AM and phase modulation, such as quadrature amplitude modulation (QAM) or quadrature phase shift keying (QPSK). Nonlinear transmitter performance results in degradation of signal and modulation quality, making it difficult for a demodulator at the receiver to recover the transmitted modulated information.

PAs are usually the first components to check when evaluating a system design for linearity. This is more so than with small-signal amplifiers such as low-noise amplifiers (LNAs), where achieving high output-power levels is less of a concern and the amplifier will not be as apt to go into nonlinear operating conditions.



The intercept points for IP2 and IP3 are mathematical concepts meant to convey input and output power levels for a component or system, beyond which good linearity is left behind.

Because RF/microwave PAs are based on semiconductors, which are inherently nonlinear devices, they fall prey to nonlinear behavior under certain operating conditions. One of these is when boosting the multiple-tone signals commonly used in wireless communications systems. Nonlinear behavior can result in signals mixing and generating unwanted levels of intermodulation distortion (IMD).

The nonlinear behavior tends to worsen as an amplifier approaches saturation, when operating with the highest possible input signals. However, an amplifier operating at saturation is also functioning at its highest efficiency. Thus, using an amplifier in a "backed-off" state at less than peak power to achieve improved linearity represents a classic performance tradeoff—linearity vs. efficiency—facing users of RF/microwave PAs. Various other techniques for higher linearity in RF/microwave amplifiers include the use of feedforward techniques, envelope-tracking technology, digital predistortion (DPD), and analog predistortion to overcome an amplifier's nonlinear tendencies.

INTERCEPTING LINEARITY

Several standard performance parameters help expose an amplifier's potential nonlinearity: 1-dB compression (P1dB)

(Continued on page 44)

IMS

IEEE 5G SUMMIT AGENDA

5-6 June 2017

13:00-13:10 | Welcome Address and 5G Summit Overview

Debabani Choudhury, *Intel Labs*

13:10-13:40 | Keynote Topic on 5G Core and Fog Networking

Keynote Speaker: Flavio Bonomi, *Nebbiolotech*

13:40 -14:00 | 5G: New Spectrum, More Security and Opportunities for New Ideas

Henning Schulzrinne, *FCC CTO*

14:00-14:20 | 5G Operators and Service Providers

Chih-Lin I, *China Mobile*

14:20-14:40 | Advanced Multicarrier Waveforms for 5G and Beyond

Hanna Bogucka, *Poznan University of Technology*

14:40-14:50 | Coffee Break

14:50-15:10 | 5G Views from NTT-DOCOMO and Experimental Trials

S. Suyama, *NTT-DOCOMO*

15:10-15:30 | 5G Channel Modeling for mmW Systems

Andrew Molisch, *USC*

15:30-15:50 | Enabling 5G Densification Utilizing mmW Capable Access and Backhaul

Ali Sadri, *Intel*

15:50-16:30 | Panel Session: 5G Start Up Ecosystem – Network to Components

Moderator: Joy Laskar, *Maja Systems*

Panelists: Nitin Jain, *Anokiwave*; Khurram Sheikh, *Kwikbit*; Farooq Khan, *PHAZR*

16:30 (Adjourn) | REMEMBER TO ATTEND THE IMS2017 PLENARY SESSION

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Exhibition Dates: 6-8 June 2017 • Symposium Dates: 4-9 June 2017

13:00-13:05 | Welcome and Overview on Day 2
Doug Zuckerman, *IEEE COMSOC*

13:05-13:10 | 5G Initiative Overview
Ashutosh Dutta, *AT&T*

13:10-13:40 | Keynote: Emerging Research Tracks in Massive MIMO
Keynote Speaker: Arogyaswami Paulraj, *Stanford University*

13:40-14:00 | Massive MIMO in 3GPP: from LTE to New Radio
Fred Vook, *Nokia NSN*

14:00-14:20 | V2X and 5G
Robert Heath, *UT Austin*

14:20-14:40 | Living on the Edge – How 5G is Going to Enable the Medical Internet of Things Big Time
Christoph Thuemmler, *Edinburgh Napier Univ., UK*

14:40-14:50 | Coffee Break

14:50-15:10 | Full Duplex Wireless: From Fundamental Physics and Integrated Circuits to Complex Systems and Networking
Harish Krishnaswamy, *Columbia University*

15:10-15:30 | RFIC/CMOS Technologies for 5G, mmW and Beyond
Ali Niknejad, *UC Berkeley*

15:30-15:50 | 5G Radio Design for Mobile Products
Kamal Sahota, *Qualcomm*

15:50-16:30 | Panel Session: 5G Test and Measurements
Moderator: Kate Remley, *NIST*
Panelists: Malcolm Robertson, *Keysight*; Jin Bains, *NI*; Chris Scholz, *Rohde Schwartz*; Jon Martens, *Anritsu*

16:30 (Adjourn) | REMEMBER TO ATTEND THE 5G EXECUTIVE FORUM AND RECEPTION FOLLOWING DAY 2 OF THE 5G SUMMIT!

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(Continued from page 41)

point, second-order intercept (IP2) point, and third-order intercept point (TOI or IP3) point. An amplifier's compression point refers to an operating condition at which the output signal level no longer increases by the same amount as the input signal level (with the input signal increased as a function of the amplifier's gain). Amplifiers are usually operated 1 dB below the compression point to preserve linearity and achieve acceptable efficiency.

An amplifier's IP2 and IP3 points are meant to express either input or output power levels beyond which linearity can be expected. Due to nonlinear behavior, an amplifier will generate a certain amount of IMD as a function of input power. When the IMD increases by 2 dB for every 1-dB increase in input power, it is said to be second-order distortion. When the IMD increases by 3 dB for every 1-dB increase in input power, it is referred to as third-order IMD.

The IP2 and IP3 points are mathematical representations of linearity rather than actual physical power levels. IP2 and IP3 are often described in terms of a logarithmic x-y plot of input power vs. output power (*see figure on page 41*).

The desired amplifier performance is represented by equal changes in output power for the changes in input power, or a straight line on the x-y plot with a slope of 1. The plot of an amplifier's second-order IMD products as a function of input power would be a line with slope of 2, while the plot of the amplifier's third-order IMD products as a function of input power would be a line with slope of 3. The points at which these lines intersect with the first line represent the IP2 and IP3 of the amplifier.

CLASSIFYING AMPLIFIERS

The class of a PA is usually a good indicator of its linearity. For example, in a Class A amplifier, the dc input power is constant (always on), regardless of the level of the input signal. While this bias scheme lacks efficiency, it is quite linear and precisely maintains the amplitude and phase characteristics of the input signal, increased by the gain of the amplifier.

Class B amplifiers are designed for higher efficiency. In a Class B amplifier, such as a push-pull configuration with two transistors, the first transistor conducts during the positive half cycle of an input signal waveform while the second transistor conducts during the negative half cycle of an input signal waveform. Less power is consumed than in a Class A amplifier, for higher efficiency, but the switching back and forth between active devices results in higher harmonics and more nonlinearity than the "always-on" Class A amplifier.

A hybrid combination of the two basic amplifier architectures, a Class AB amplifier, provides a compromise in terms of the efficiency and linearity of Class A and B amplifiers. Various other amplifier classes are employed for RF/microwave applications, such as Class C with high efficiency but poor linearity, and all are subject to the basic tradeoff between linearity and efficiency.

Numerous techniques have been developed to improve PA linearity, including approaches that use feedback or distortion to correct for the nonlinear behavior of the amplifier's active devices. More recent approaches are based on envelope tracking—essentially, the use of a dynamic power supply. In a conventional PA, the power supply is constant. In a Class A amplifier with two transistors, both devices are always conducting.

In an amplifier with envelope tracking, the dc bias is varied as a function of the input signal envelope. It is increased or decreased according to the level of the input signal to maintain the amplifier's active devices at a power level that provides optimum balance between linearity and efficiency. This delivers a level of performance that is attractive, for example, to wireless network operators who prefer to minimize the energy costs of their networks.

NONLINEARITY NOT LIMITED TO PAs

Although PAs may often be the culprits of nonlinearities in a communications transmitter, they are not the only RF/microwave component subject to nonlinear behavior. For example, frequency mixers are designed to provide a linear function. They shift an input signal from one frequency to another while preserving its fundamental characteristics, such as amplitude and phase. However, mixers, like amplifiers, are based on semiconductor devices such as diodes and field-effect transistors (FETs), and thus are subject to the nonlinear tendencies of those devices.

Mixer linearity is typically characterized in terms of its third-order intercept, with higher values representing better linearity. RF/microwave frequency mixers are designed in various configurations, such as single-balanced architectures with a pair of diodes and double-balanced mixers with two pairs of diodes. Double-balanced mixers typically provide enhanced linearity compared to single-balanced frequency mixers, although with some performance tradeoffs. With the additional mixing diodes, a double-balanced mixer typically has higher conversion loss and requires more local-oscillator (LO) drive power than a single-balanced mixer.

The linearity of a high-frequency switch can also impact communications-system performance, since a switch that handles higher power levels without distortion will support a higher system dynamic range and signal-to-noise ratio (SNR). A traditional RF switch performance tradeoff often involves linearity vs. dynamic range, or essentially how much power it can handle without distortion.

Component designers are well aware of the need for good linearity in modern high-frequency systems. It has led to the development of many practical solutions in terms of amplifiers, mixers, and switches for both the low-power (receiver) and high-power (transmitter) portions of each system. Maintaining good linearity becomes particular more challenging as systems occupy wider bandwidths and, with the high expectations set for fifth-generation (5G) wireless communications networks, excellent linearity will be required throughout each network's RF/microwave components.

JACK BROWNE | Technical Contributor

Microwave Energy Powers Many Industrial Applications

High-power microwave energy may be best known for a fast, hot meal, but it is also the basis for a wide range of industrial heating, drying, and processing applications.

MICROWAVE ENERGY is well known (and appreciated) by anyone who has used a microwave oven to heat a meal. Such application of high-frequency electromagnetic (EM) radiation for the dielectric heating of materials is also one of the most widely adopted industrial uses for RF/microwave components and systems. Industrial microwave heating systems operate within the unlicensed industrial, scientific, and medical (ISM) frequency bands set aside by the Federal Communications Commission (FCC) for industrial applications in the U.S., such as 915 and 2450 MHz, to prevent interference with other frequency bands.

Many materials are processed by means of microwave heating, and not just for the next meal, although microwave energy is the main component of thermal processing used to eliminate bacteria in commercial food products. In agriculture, microwave energy is exploited for drying of grain and removal of moisture from wood for use as lumber. In the pharmaceutical industry, microwave energy removes the moisture from various powdered substances. In the materials supply industry, microwave energy enables the addition of different types of coatings to rubber and plastic materials.

THESE INNOVATIONS ARE HOT

For industrial applications, such as food processing, power consumption and material processing are key operating parameters toward minimizing the cost of the microwave heating or drying process. As an example, a microwave heating/drying system developed by Max Industrial Microwave (*www.maxindustrialmicrowave.com*) uses only a small percentage of the energy required by other heating/drying systems per liter of water evaporated from the processed material, with reduced thermal processing time

The system is designed in a compact footprint as a form of "microwave tunnel," so that material passing through the system can be exposed continuously to microwave radiation for heating and drying. The tunnel configuration results in predictable and uniform heating of the material with minimal thermal processing times.

The firm supplies systems for microwave drying and sterilization at 915 and 2450 MHz. The systems can process both solid and liquid foods while preserving the essential nutrients within the food, as well as preserve its appearance and flavor. Such microwave heating/drying systems are considered "environmentally friendly" for their lack of exhaust gases and efficient use of electrical energy.

Similarly, Cellencor (*www.cellencor.com*) developed an industrial microwave oven that is about 12 feet in length with a continuous conveyer belt running through the tunnel-like structure for material samples. The system applies microwave energy to the cavity from a high-power source, using a waveguide feed to transfer EM energy to the cavity via two or more high-power, rotating antennas to achieve even heating of material samples.

Advanced Microwave Technologies (*www.advancedmicrowavetechnologies.com*) is another major supplier of industrial microwave heating systems for pasteurization and food-processing applications, as well as for waste treatment and biotechnology research laboratories. Fruits and vegetables processed with the company's systems have yielded increased shelf lives. The firm's industrial systems are designed for fast and efficient heating of materials in a smooth production flow and with clear graphical user interface (GUI) for ease of programming and control.

Autopack Global (*www.autopackglobal.com*), which produces a variety of different material-processing systems, including induction sealers and hot-air dryers, also offers a microwave-based industrial drying system to reduce the moisture content of raw materials. It is applied to the automated drying of fruits, vegetables, meat, and fish, and even to the production of cereals such as corn flakes.

On a smaller scale, Microwave Research *(www.microwaveresearch.com*) has a long track record of supplying microwave heating equipment at 2450 MHz for both industrial and laboratory applications. When a microwave-based heating chamber is needed for experimentation, the company offers standard microwave heating systems with as much as 3.2 kW power, although it has also developed laboratory and industrial

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While the systems used for microwave industrial heating may operate at the same 2450 MHz as the microwave oven that warms a cup of coffee at home, they are considerably larger and more powerful.

processing systems at power levels as high as 12 kW. Many of its systems are designed according to custom requirements.

High-power microwave plasma processing is an industrial application that offers great benefits for the production of several kinds of materials, including semiconductor wafers.

Microwave plasma processing (within a plasma chamber fed by a high-power microwave source) has been employed in semiconductor manufacturing for such operations as material deposition, etching, and photoresist removal. It allows dry etching of photoresist materials at high etch rates and with no ionic damage to the material samples.

Cober Inc. (*www.cober.com*) teamed up with high-power source supplier Muegge GmbH (*www.muegge.de*) to develop microwave plasma ovens that are instrumental in producing advanced ceramic materials in both atmospheric and under-vacuum conditions. Non-oxide ceramic materials such as silicon nitride and tungsten carbide have been fabricated at sintering temperatures to +1700ºC with fine-detail, high-quality microstructures. Cober's engineers also work closely with the members of the materials science department at Penn State University to develop and commercialize new microwave sintering applications.

In terms of microwave heating systems for a diversified set of applications, few suppliers can come close to Microdry Inc. (*www.microdry.com*). As the company notes, its systems have been used for everything from cooking bacon to drying sludge, typically at frequencies of 915 or 2540 MHz. Although it offers extensive lines of standard industrial microwave systems and high-power microwave energy sources, the firm is perhaps best known for its custom system solutions, which include microwave systems for waste treatment, ore processing, and water-based adhesive drying.

Although EM energy at resonant frequencies of 915 and 2450 MHz is most often used for industrial microwave heating applications, not all suppliers of industrial EM-based heating systems subscribe to the use of those frequencies. The "Macrowave" heating systems from Radio Frequency Co. (*www.radiofrequency.com*) use RF rather than microwave heating to take advantage of the more uniform heating properties of the longer wavelengths. The low-frequency systems have been used to eradicate tobacco beetles when drying tobacco, and remove salmonella when pasteurizing fishmeal prior to packaging it as pet food.

For example, the company promotes the efficiency of its RF heating systems, such as its Macrowave Pasteurization Systems that operate at 40 MHz. Compared to higher-frequency microwave heating systems, the long wavelengths of these lower-frequency systems provide good depth of EM energy penetration into the material to be heated, with excellent uniformity of heating. This effectively eliminates microbes without damage to the material being heated due to prolonged exposure to high temperatures.

SOURCES OF POWER

While the systems used for microwave industrial heating may operate at the same 2450 MHz as the microwave oven that warms a cup of coffee at home, they are considerably larger and more powerful. Oftentimes, conveyer belts feed a continuous flow of materials to be processed to a large, EM-shielded chamber, where the materials are subjected to microwave energy for heating and drying. The source of that microwave energy is usually one or more continuous-wave (CW) magnetrons, using air- or water-cooled architectures to control the heat generated by the tube.

A line of CW magnetrons from the Econoco Div. of Communications & Power Industries (*www.cpii.com*) includes models operating at fixed frequencies of 896, 915, 922, and 929 MHz (with ±10 MHz frequency variation) and as much as 100 kW output power. The magnetrons run on +19.5 to +20.0 kV anode voltage and 5.8 to 6.0 A anode current, using water cooling to maintain thermal stability even with the enormous amount of output power. With high typical efficiency of 83% to 88%, these magnetrons help achieve good operating economy in a microwave heating system by turning most of the dc input power into microwave output power.

In addition to providing the high-power microwave sources for Cober's microwave plasma systems, Muegge GmbH is a major supplier of magnetrons that drive many other industrial microwave heating/drying applications. Suppliers of high-power CW magnetrons for industrial microwave heating applications at 915 and 2450 MHz include e2v (*www.e2v.com*), Hitachi High Technologies America (*www.hitachi-hta.com*), L-3 Technologies (formerly L-3 Communications, Electron Devices, *www.l3t.com*), and the aforementioned Communications & Power Industries, Econoco Div.

For repair of industrial microwave heating systems, the aptly named Industrial Microwave Systems (*www.industrial-microwave-systems.com*) provides replacements for many original-equipment-manufacturer (OEM) magnetrons. It offers tubes with as much as 120 kW output power at 915 MHz and 3 kW output power at 2450 MHz. mw

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Digital Approach Generates AM-VSB and 8VSB Signals

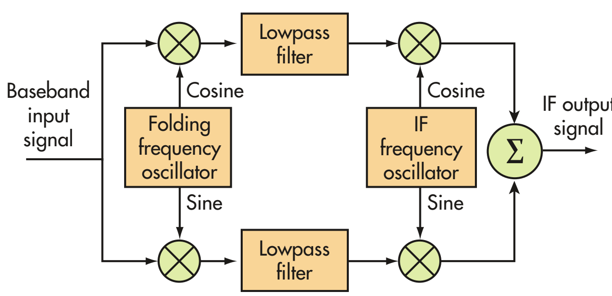
Through the use of DSP techniques, a single modulation platform can generate both analog AM-VSB and digital 8VSB broadcast television signals.

Digital television broadcast standards employ various forms of amplitude-modulated (AM) signals with suppressed sidebands to reduce emissions and interference. An example is the Advanced Television Systems Committee (ATSC) 8-level vestigial sideband (8VSB) American standard for digital broadcast television in the United States, as well as its analog predecessor, the National Television System Committee (NTSC) standard. High-power high-definition-television (HDTV) transmitters require stringent emission masks to reduce sidebands and to achieve spectrally pure signals.

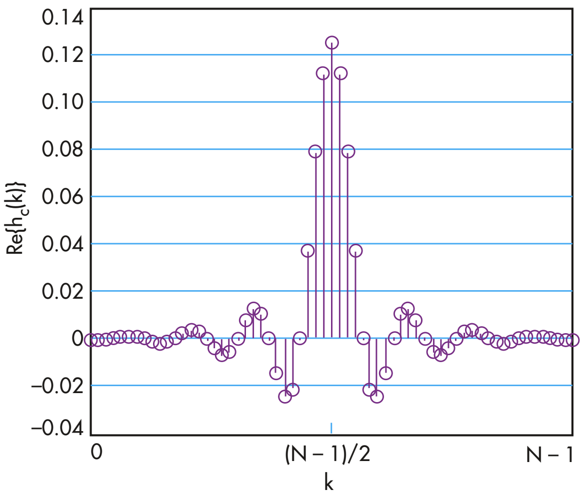
To accomplish this, many 8VSB modulators have incorporated surface-acoustic-wave (SAW) filters for high sideband attenuation. Unfortunately, such filters are often plagued by excessive passband amplitude ripple, high passband insertion loss, and high cost. However, the use of digital modulation techniques, such as field-programmable gate arrays (FPGAs) and digital signal processors (DSPs), has made it possible to implement digital television modulators that overcome the limitations of SAW filters. Through the use of DSP techniques, it is possible to generate both analog AM-VSB and digital 8VSB television signals with a single platform.

A modulation method known as Weaver modulation has been used to generate single sideband (SSB) signals with arbitrary sideband shape.[1-4] Because the approach requires two precisely matched filters and signal paths, it has rarely been implemented in analog circuitry. However, such matching is routinely possible with DSP circuitry. *Figure 1* depicts a Weaver modulator, which begins by multiplying the modulating signal with a pair of quadrature phased sinusoidal signals.[5, 6] When generating a SSB signal, the frequency of the sinusoidal is one-half the modulation bandwidth.

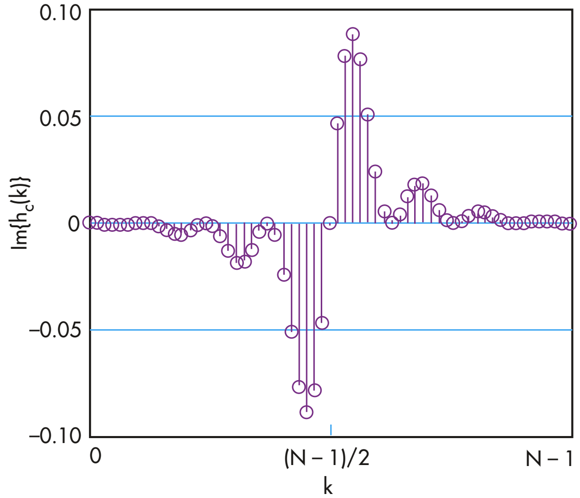
The frequency of these two signals is called the folding frequency, and the signal multiplication produces a pair of orthogonal baseband signals. A lowpass filter following each modulator restricts the bandwidth of each output to one-half of the bandwidth of the original modulating signal. At this point, the modulating signal has been folded in such a way that the folding frequency is translated to DC, while both the upper and lower band edges are translated to the highest frequencies in the folded spectrum.



1. This block diagram shows the components and architecture of a Weaver modulator.



2. The plot shows the real part of the impulse response.



3. This is a visualization of the imaginary part of the impulse response.

The two baseband signals are then applied to a quadrature mixer. If the quadrature phases are accurate; if the two lowpass filters are matched; and if the gain, phase, and delay of the two signal paths are matched, the sum of the two signal paths is a SSB signal.

Discrete analytic signals yield a null in Fourier transform values for frequencies of $-\pi \leq \omega < 0$. The Hilbert transform is a mathematical method for describing the analytic signal $s_a(n)$ (sometimes known as the complex envelope) of a real-valued baseband signal s(n) as:

$$s_a(n) = s(n) + jH[s(n)],$$

where H[s(n)] is the Hilbert transform of baseband signal s(n).[7] The definition of this linear operator has the convolution form of $H[s(n)] = s(n) * h(k)$. This transformation can be implemented as the output of a linear time-invariant system with input s(n), and an impulse response represented in the form $h(k) = 2\sin^2(\pi k/2)/\pi k$. The Hilbert transform has the effect of shifting the frequency components $-\pi \leq \omega < 0$ of s(n) by 90 deg., as well as the frequency components $0 \leq \omega < \pi$ by –90 deg. This occurs because of the frequency response behavior of the Hilbert transform linear system: $F\{h(k)\} = H(\omega) = -j\,\mathrm{sgn}(\omega)$ where $H(\omega)$ is the discrete-time Fourier transform of h(k).[6]

The lower sideband from an AM signal is produced due to the presence of the negative part of the spectrum, and this must be eliminated. These negative frequencies may be cancelled by applying the modulating baseband signal in a system with suitable frequency response, where the transmitting bandwidth is represented by ω_m. To obtain the impulse response for this system, consider a discrete-time Fourier transform (DTFT). Let x(n) be a real-valued signal with a DTFT defined by Eq. 1:

$$X(\omega) \equiv F[x(n)] = \sum_{n=-\infty}^{+\infty} x(n).e^{-j\omega.n} \quad (1)$$

According to the symmetry property, if x(n) is real, $X(\omega)$ is a conjugated symmetric, which satisfies all of the equations for even and odd symmetry with the relationship expressed by Eq. 2:

$$\begin{gathered} \mathrm{Re}[X(-\omega)] = \mathrm{Re}[X(\omega)],\ \mathrm{Im}[X(-\omega)] = -\mathrm{Im}[X(\omega)] \\ |X(-\omega)| = |X(\omega)|,\ \angle X(-\omega) = -\angle X(\omega) \end{gathered} \quad (2)$$

The desired system cannot be achieved using a real-valued impulse response, since symmetry around the zero frequency makes it impossible to discriminate positive and negative frequencies. To generate the desired system response, it is necessary to use a complex-valued impulse response, in the process departing from the frequency shifting property of the DTFT function. This can be done by using a lowpass filter with cutoff frequency of $\omega_m/2$ and a real-valued impulse response $h_r(k)$ with N taps and $0 \leq k \leq N - 1$.

As a direct consequence, the desired frequency response can be obtained by multiplying the $h_r(k)$ response by the complex function with frequency $\omega_m/2$, $\omega_m/2$, resulting in a complex-valued impulse response $h_c(k)$, in the form of Eq. 3:

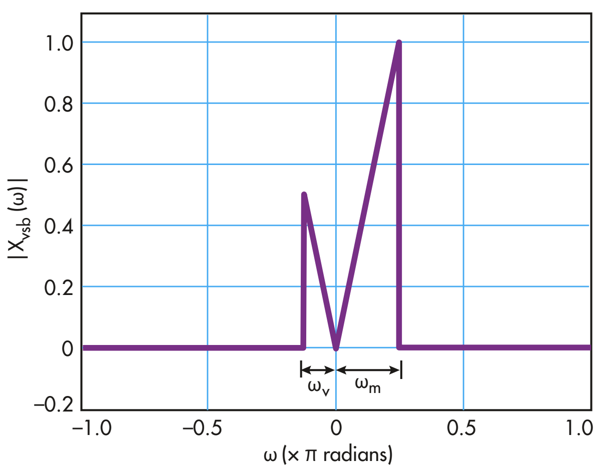
$$h_c(k) = h_r(k) \cdot e^{j\cdot\left(\left(\frac{\omega_m}{2}\right).k+\phi\right)} \quad (3)$$

Digital television 8VSB modulation is considered to be a vestigial-sideband signal because actual filters differ from ideal ones, so that the vestigial sideband corresponds to the filter rolloff. Ideally, this system could be called 8-SSB. But in analog broadcast television systems like NTSC, a large amount of the sideband is intentionally transmitted.

Thus, $H_r(\omega)$ presents a passband from $-\omega_m/2$ to $+\omega_m/2$, while function $H_c(\omega)$ provides a passband from 0 to ω_m due to the $\omega_m/2$ shifting. It can be proven that there is an optimum initial phase value ϕ for the complex function that will avoid phase distortion of the complex envelope to be generated.[2] The initial phase ϕ is used to guarantee an optimization criterion where both real and imaginary parts of the complex impulse response $h_c(k)$ must present an even and odd symmetry, respectively.[7]

Following this criterion, the complex function at the instant $k = (N - 1)/2$, which corresponds to the $h_r(k)$ symmetry point, must be null. This results in an initial phase to applied in Eq. 3, where $\phi = -(1/2)[(\omega_m/2) \bullet (N - 1)]$. *Figures 2 and 3* illustrate both real and imaginary parts of $h_c(k)$, with the phase correction. If a signal s(n) is applied into this complex filter, the output is a band-limited analytic signal, s_a.

Digital television 8VSB modulation is considered to be a vestigial-sideband signal because actual filters differ from ideal ones, so that the vestigial sideband corresponds to the filter rolloff. Ideally, this system could be called 8-SSB. But in analog broadcast television systems like NTSC, a large amount of the sideband is intentionally transmitted. As a result, what was shown earlier for SSB signals can be generalized for AM-VSB signals.

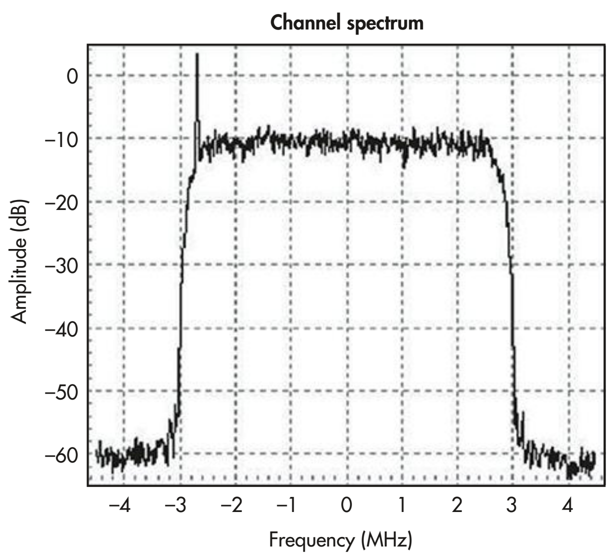


4. This is a representation of an AM-VSB signal.

This can be done by considering ω_m as the bandwidth from one sideband and ω_v as the bandwidth from the vestigial sideband, as shown in *Fig. 4*. If $h_{r\text{-}vsb}(k)$ represents the real impulse response of a lowpass filter with cutoff frequency equal to $(\omega_m + \omega_v)/2$, with $0 \le k \le (N - 1)$, then a baseband signal that describes the AM-VSB channel can be generated by filter having the complex impulse response $h_{r-vsb}(k)$ which is defined by Eq. 4:

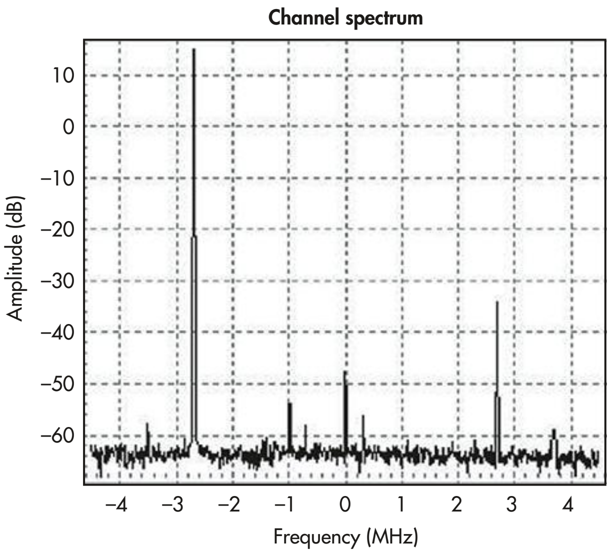
$$h_{c-vsb}(k) = h_{r-vsb}(k)\cdot e^{j\cdot\left[\left(\frac{\omega_m-\omega_v}{2}\right)\cdot k-\left(\frac{\omega_m-\omega_v}{2}\cdot\frac{N-1}{2}\right)\right]} \quad (4)$$

By performing a comparative study between the Weaver method and the complex filtering method proposed here using an 8-VSB modulator implementation, almost no difference exists in performance, as shown in *Fig. 5*.[8] At this measurement, the lower sideband had been attenuated by 50 dB due to the orthogonal phase relationship between both baseband signals. Analysis of the channel spectrum generated by the complex filter method reveals no differences from previous modulation methods.

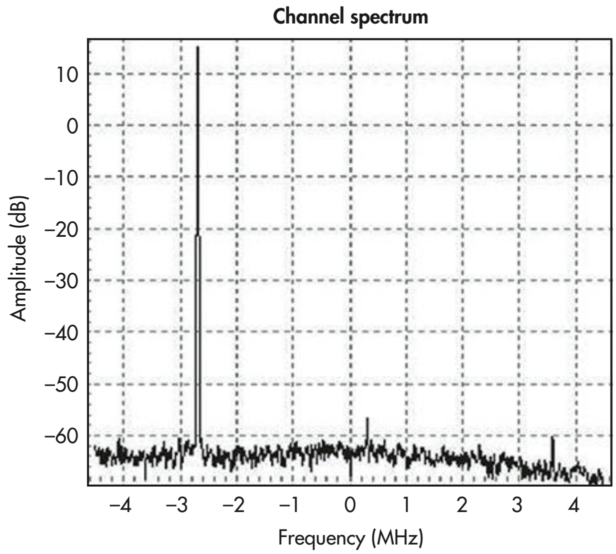


5. The plot shows the 8VSB spectrum for both signal generation methods.

However, if a single symbol is transmitted continuously, which means transmitting a pure carrier, differences will appear in terms of in-channel spurious content. This can be seen in the measurements presented in *Figs. 6 and 7*. By using the Quartz II programming platform to implement the inside the FPGAs, *Fig. 8* presents the architecture designed for all experimental measurements made over the modulator block for modern HDTV transmission systems.



6. This is a representation of the carrier resulting from the Weaver filtering method.



7. This is a representation of the carrier resulting from the complex filtering method.

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Quite possibly, the original, complex filtering approach presented here provides the flexibility needed to apply DSP techniques to modern broadcast television systems.

8. The photograph shows the Quartz II programming platform used to validate the complex filtering approach for AM-VSB signal modulation.

The FCC has mandated a period which ATSC and NTSC signals will be multicast. Transmission equipment that is suitable for both systems will provide the greatest degree of flexibility for the broadcaster. Quite possibly, the original, complex filtering approach presented here provides the flexibility needed to apply DSP techniques to modern broadcast television systems. mw

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are focused in applied research of new technologies involving electromagnetism and broadcast telecommunication systems.

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CVD Diamond Manages Device Heat Effectively

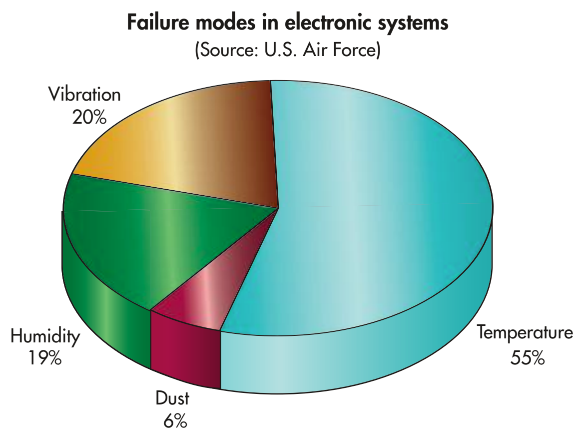
Synthetic diamond materials provide the mechanical stability and outstanding thermal conductivity needed to dissipate heat from GaN and other high-power semiconductor devices.

Heat can be damaging to the semiconductor devices that produce it, unless it is allowed to flow away from those devices. Solid-state devices such as GaN transistors continue to advance in terms of increased power densities at higher operating frequencies, but they also generate large amounts of heat in small areas, and their performance levels and reliability will be limited by how quickly and completely the heat can be dissipated. Quite simply, higher-power levels are possible with a large-signal semiconductor when the right heat-spreader material is used. In terms of thermal management, diamond is that optimum heat-spreading material, offering thermal conductivities up to 10× those of other commonly used heat-spreading ceramics.

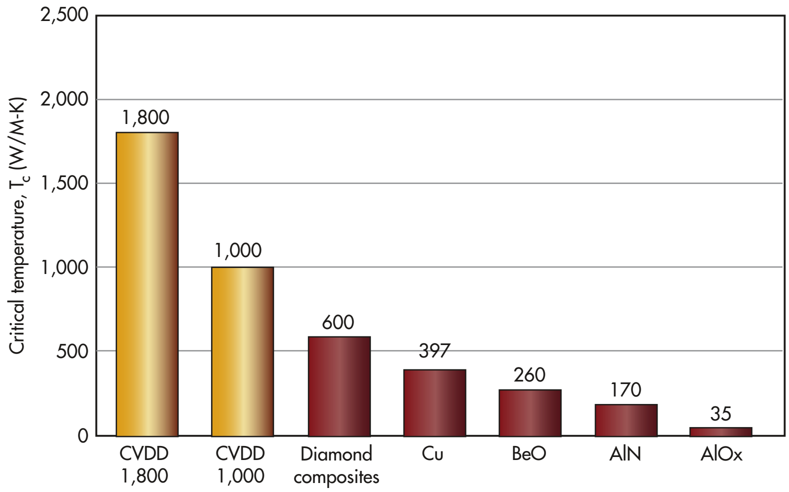
Commercial GaN transistors and integrated circuits (ICs) have been fabricated on various heat-spreading base substrates, such as silicon (Si) and silicon carbide (SiC), with fair results in terms of thermal management. Still, the heat spreading capabilities of these materials can put a ceiling on the maximum output power that can be achieved from a GaN-based solid-state device. The thermal conductivity of SiC, at 400 W/m-K, has been considered suitable for dissipating heat from GaN devices. Single devices capable of high power levels at RF/microwave frequencies have been developed on GaN-on-SiC processes for commercial, industrial, and military applications.

Modern electronic systems often fail due to lack of adequate thermal management *(Fig. 1)*. The choice of materials for a thermal management design and the methodology of the application are essential to minimizing channel temperatures and ensuring reliable long-term device operation. Until now, GaN-on-SiC devices have demonstrated the most effective management of heat in high-power discrete transistors and monolithic-microwave-integrated-circuit (MMIC) components. Still, the heat-spreading capabilities of SiC are limited and typically the maximum power dissipation of GaN-on-SiC devices is derated to protect long-term reliability. To achieve higher power levels with less heat, especially for circuits with densely packed active (heat-generating) GaN devices, chemical vapor deposition (CVD) diamond enables much higher power densities than conventional approaches.

Diamond is a versatile material for many industries, with excellent mechanical and electrical characteristics. It has many useful properties for electrical applications, including the highest known thermal conductivity,[1] stiffness, and hardness, combined with high optical transmission across a wide wavelength range, low expansion coefficient, and low density.



1. Of the causes of failure in electronic systems, heat is the most damaging.



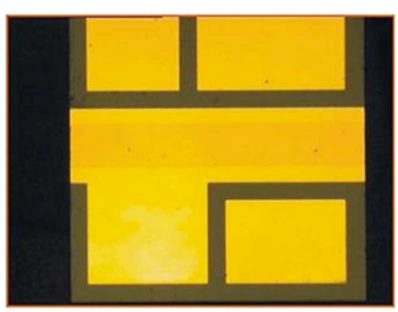
2. Shown is a comparison of CVD diamond with "traditional" heat-spreading materials.

These exceptional characteristics can make diamond the ultimate solution for thermal management problems.

To synthesize diamond for this purpose, the first step is choosing the most suitable deposition technology. Microwave-assisted CVD enables the best control of grain size and grain interfaces for producing high-quality, high-repeatability, polycrystalline diamond with the thermal conductivity needed for particular applications. CVD diamond is now commercially available in different grades with thermal conductivities between 1,000 and 2,000 W/m-K. CVD diamond has fully isotropic characteristics, so that heat will spread in all directions. *Figure 2* shows a comparison of CVD diamond with other materials traditionally used for heat spreading purposes.

To harvest the maximum heat-spreading effectiveness of diamond for semiconductor device applications such as GaN semiconductors, both package integration issues and functional requirements must be considered. Since the surfaces of electronic components are typically very smooth and flat, an effective heat spreader should match, forming a gap-free interface. For a diamond heat spreader, the surface deviations or roughness, R_a, should be no greater than 50 nm.

This minimal roughness is typically achieved by means of polishing. Any surface defects, such as protrusions or bumps, should be removed since they can impede the transfer of heat from device to thermal substrate. Otherwise, any lack of flatness must be overcome by an effective mounting technique of device and thermal substrate.



3. This is an example of a heat-spreader design metallized on CVD diamond.

In general, flatness is of lesser importance to smaller devices such as laser diodes or RF/microwave transistors, with edges measuring 1.5 mm in length. However, for larger devices such as laser diode arrays, RF MMICs, or discrete power transistors having dimensions of around 3 to 5 mm on a side, a typical flatness of $R_a = 1\ \mu m$ should not be exceeded.

The use of high-quality, sputter-deposited, thin-film metallization is strongly recommended for any advanced device-level thermal solutions.[2] Since the thermal barrier resistance between the device and the heat spreader must be minimized, additional metal interfaces should be avoided. Sputtered layers, particularly those formed of titanium (Ti), can form a very effective chemical bond with CVD diamond, achieving high long-term stability at elevated temperatures. For chemical separation of the gold termination layer and the titanium adhesion layer, a platinum or titanium/tungsten (Ti/W) barrier layer is recommended.

The layer thicknesses for the adhesion and barrier layers should be typically in the range of 80 to 200 nm. The gold termination layer is usually thicker, from 500 to 1,000 nm, for soldering purposes, and sometimes as thick as 2,000 to 3,000 nm for devices requiring high current levels. With the inherent insulating property of diamond, the generation of patterned metallization is possible, allowing a wider functionality of the heat spreader to also act as a submount for additional device mounting and/or wire-bond termination pads. *Figure 3* shows an example of a CVD diamond heat spreader with patterned metallization.

As with the metallization layers, soldering layers for attaching devices to the heat spreader should be kept at minimum thicknesses for optimum thermal dissipation. This is particularly true for the primary interface (TIM1) between device and heat spreader, again to minimize thermal resistance. For good results, predeposited solder materials, such as eutectic gold/tin (AuSn, at $T_m = +278°C$) or gold/germanium (AuGe, at $T_m = +361°C$), can be used. They are typically sputter-deposited or evaporated onto the heat spreaders at thicknesses of 2 to 4 μm. With a suitably designed die-attach process, the resulting solder layers should be void free and only a few microns in thickness.

Lastly, since diamond is capable of extreme heat transfer with an optimized primary interface, even the secondary

The thickness of CVD diamond can be important for thermal management. For a range of applications, a thickness of 250 to 400 μm is sufficient for thermal dissipation—particularly for small devices with high power densities. The isotropic characteristics of the diamond material help spread the heat efficiently, hence reducing the maximum operational temperature for a constant power output.

thermal interface (TIM2) between the heat spreader and submount surface or package is important. The use of thermal pads or epoxy-type bonds, which have high thermal resistance, would impede the flow of heat. As a result, lower-melting-temperature solder materials like indium (In) or indium/tin (InSn) should be used. The soldering sequence is usually designed so that the most critical TIM1 interface is formed first, so as to mount a semiconductor chip on a heat spreader, which is then soldered into a package in a second step at a lower soldering temperature.

An alternative assembly approach is to use the same solder material for both sides of the heat spreader and attaching the device/heat-spreader package stack in one operation. In any case, when soldering, the mismatch in the coefficient of thermal expansion (CTE) between the CVD diamond and the semiconductor material must be considered. Gallium-arsenide (GaAs) semiconductor devices to an edge length of 2.5 mm can be attached with hard solder material to CVD diamond without CTE-mismatch problems. For larger devices, the use of soft solder material is recommended to avoid excessive stress that could jeopardize device performance or reliability. The *table* shows a wide range of solder materials commercially available for device soldering processes.

The thickness of CVD diamond can be important for thermal management. For a range of applications, a thickness of 250 to 400 μm is sufficient for thermal dissipation—particularly for small devices with high power densities. The isotropic characteristics of the diamond material help spread the heat efficiently, hence reducing the maximum operational temperature for a constant power output. However, for applications with larger heat spots on the order of 1 to 10 mm in diameter, the diamond thickness must be increased for better results. As an example, for disk lasers, which can generate several kilowatts of optical output power, the use of diamond with thickness of several millimeters has proven beneficial.

The electrical conductivity of the heat spreader can play a part in a device application. For some devices, the simplest design may involve running current through the device and the heat spread for a path to ground, as is often done with laser diodes. For other devices, the heat spreader may be used as an insulator. Since CVD diamond is an intrinsic insulator, its insulation properties can be maintained by keeping the side faces of the material free of metallization. This is required for RF/microwave amplifiers and transistors, especially at higher frequencies (greater than 2 GHz).

AN OVERVIEW OF SOLDERING MATERIALS

Solder material	Composition (wt%)	Soft/Hard	Liquidus temp. (°C)	Solidus temp. (°C)
InSn	52/48	soft	118	eutectic
InSn	50/50	soft	125	118
InAg	97/3	soft	143	eutectic
In	pure	soft	156.6	156.6
InPb	70/30	soft	171	162
SnPbAg	62/36/2	soft	179	eutectic
SnPb	63/37	soft	183	eutectic
SnPb	60/40	soft	191	183
AgSn	3.5/96.5	soft	221	eutectic
AuSn	80/20	hard	278	eutectic
AuSn	75/25	hard	356	278
AuGe	88/12	hard	361	eutectic
AuSi	82/18	hard	363	eutectic
AuSn	73/27	hard	370	278
AuSn	70/30	hard	390	278
InCuSil	5/27/68	hard	760	743
TiCuSil	28/72	hard	780	eutectic

Significant improvements in the thermal design of electronic systems can be realized by using advanced materials such as CVD diamond. Integration of the material is relatively straightforward, since diamond heat spreader can serve as a direct replacement for aluminum nitride (AlN), BeO, or other ceramic materials.

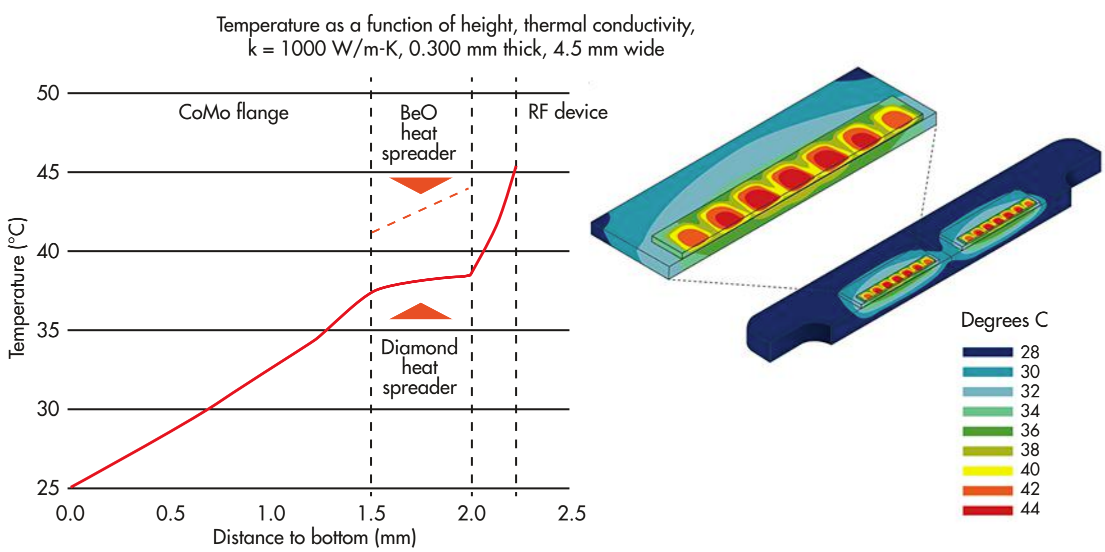
MODELING THERMAL FLOW

A head-spreader configuration is typically optimized for performance for a given power level by means of thermal simulation. Software simulation can help find the best solution based on output power, material thickness, metallization scheme, the geometry of the source of heat, and the package configuration.[3] For best simulation results, it is important to model the complete system, including device details, interfaces, materials, and subsequent heat-sink approach, in performing a full junction-to-case thermal analysis.

To demonstrate the impact of a diamond heat spreader in a practical example, an RF amplifier design was analyzed. In this example, a VDMOS power amplifier package was initially made with a beryllium-oxide (BeO) heat spreader on a copper/molybdenum (CuMo) flange. The end user was interested in lowering the overall thermal resistance of the system design, as well as avoiding the use of BeO due to its toxicity. Modeling was performed with parameters for heat-spreader thermal conductivity and thickness using various soldering solutions.

Figure 4 shows one of the key findings of this modeling and analysis. It demonstrates the junction-to-case temperature profile for one of the optimal designs. The CVD diamond heat spreader solution exhibited 30% lower thermal resistance at 0.300 mm thickness with thermal conductivity of 1,000 W/m-K (the original solution used a 1.00-mm-thick BeO heat spreader). Note the almost-horizontal, constant temperatures within the CVD diamond, which indicate that the heat spreader is not even employed to its full capability. But even so, the improved thermal resistance of the diamond heat spreader has led to this device functioning with better linearity and with improved reliability due to its reduced junction temperature.

One important finding was the need to modify device architecture for improved thermal flow. The main temperature rise is within the device itself. A thinning of the device substrate, to bring it closer to the diamond heat spreader, would enhance the thermal design significantly. Also, mounting such devices with the active layers facing the diamond heat spreader would provide even further benefit, such as mounting laser diodes p-face down with the quantum well structures soldered directly against the heat spreader.



4. Thermal modeling revealed the effectiveness of CVD diamond heat-spreader materials compared to other materials in an example application.

Another way to bring the device gate junction closer to the diamond is the use of a different substrate altogether. This has been demonstrated by using GaN-on-diamond wafers, which remove both the Si substrate and transition layers, replacing them instead with CVD diamond. The result brings the diamond material within 1 μm of the heat-generating gate junctions. Initial users of GaN-on-diamond wafers for RF HEMT devices have demonstrated as much as 3.5 times the power density compared to equivalent GaN-on-SiC devices.

Diamond materials can also be a useful allay in removing heat as part of package designs. CVD diamond can be embedded in copper/tungsten (CuW), copper/molybdenum (CuMo), or other packaging materials for enhanced thermal dissipation. This package design improvement cost-effectively decreases the thermal resistance of the thermal path between the device gate junction and the package case.

Significant improvements in the thermal design of electronic systems can be realized by using advanced materials such as CVD diamond. Integration of the material is relatively straightforward, since diamond heat spreader can serve as a direct replacement for aluminum nitride (AlN), BeO, or other ceramic materials. Attention to detail at the interfaces is important to keep overall thermal resistance low and optimize the effectiveness of the diamond for thermal dissipation. For example, once the thermal resistance of the TIM1 (primary thermal interface material) is minimized, attention must be turned to the secondary thermal interface (TIM2) as the limitation to the overall system performance.

Improved synthesis and processing techniques are making CVD diamond materials more available and affordable as head spreaders for electronic circuits. The trend in building denser electronic circuits with higher power levels per square inch is expected to continue, adding to the need for better thermal materials to prevent heat from degrading performance and reliability. MW

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Study the Loss of Microstrip on Silicon

By understanding their loss mechanisms, microstrip transmission lines on silicon substrates offer potential for low-cost passive microwave components.

Microstrip transmission lines serve high-frequency circuit designs on a wide range of substrate materials, but CMOS-grade silicon may not be the first to come to mind. Still, silicon is a low-cost foundation for analog and digital integrated circuits (ICs), and it may provide a useful starting point for miniature microstrip-based passive components, such as filters and antennas. But first, it is necessary to understand the loss characteristics of microstrip on silicon dielectric material, whether working on lower-frequency RF, microwave, or digital circuits. Proper analysis of the loss mechanisms can yield more accurate predictions of final circuit performance levels.

In microstrip circuits, the electromagnetic (EM) fields propagate mostly through the conductive metal circuit traces and the dielectric material, such as silicon. But a small portion of the EM energy also travels through the air above the microstrip circuit's conductors, resulting in an inhomogeneous medium and quasi-transverse-EM (quasi-TEM) mode propagation. The inhomogeneous nature of a microstrip circuit structure makes quasi-static approximations of analyzed TEM-coupled transmission lines difficult and limits its accuracy.[1]

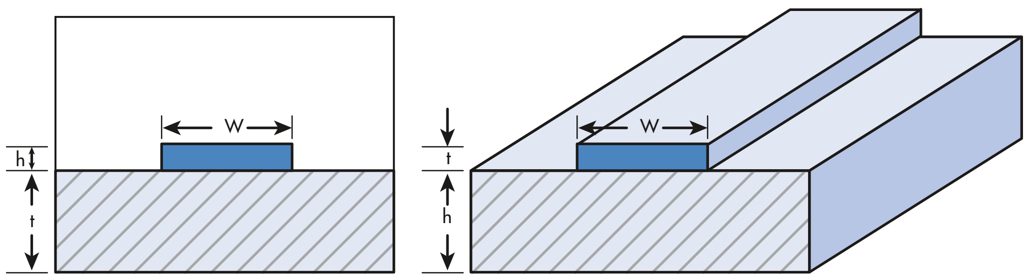
Most of the signal attenuation in a microstrip transmission line is due to the finite conductivity of the conductor metal and the dielectric loss of the substrate material.[2,3] The amount of signal attenuation depends on a number of factors, including the properties of the substrate material, the properties of the conductor metal, and the operating frequency range. Microstrip transmission lines can also exhibit radiation losses, as well as losses at any air-dielectric interfaces without conductors. Radiation loss can be minimized by the use of thin and high-dielectric-constant circuit materials.

Conductor losses are typically greater than the other losses exhibited by microstrip circuits. However, as the operating frequency increases, dielectric losses become a larger part of the loss budget. In the case of a substrate material with high loss, such as CMOS grade silicon, the effects of dielectric and surface-wave propagation are more dominant than conductor losses. Simulation software based on the finite-element method (FEM) can model many of the parasitic effects that affect microstrip losses, but FEM software may not account for all attenuation mechanisms in microstrip circuits, resulting in the possibility of differences between measured and simulated results.

Analysis of microstrip loss mechanisms can provide guidance on using microstrip with silicon substrate materials. Equation 1 presents phasor notation for the frequency-domain signal propagation in a transmission line:

$$\bar{E}(f,z) = E(f,z)e^{-[\alpha(f)+\beta(f)]z} \quad (1)$$

where $\bar{E}(f,z)$ is the Fourier transform of the time-domain waveform at a distance z; $\alpha(f)$ is the frequency-dependent



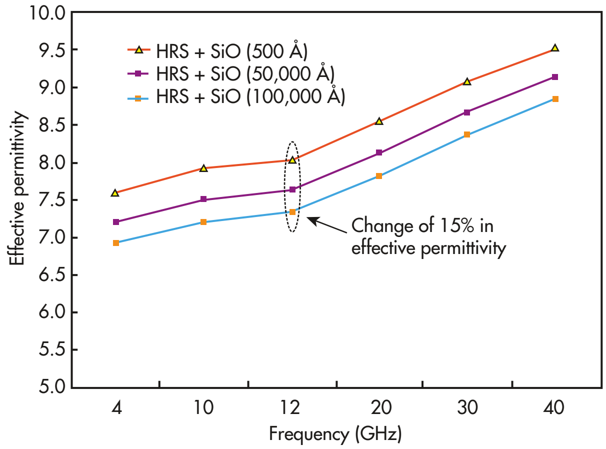
1. The diagram depicts a microstrip transmission line with conductor width w and height h, enclosed in a box not considered as part of the loss analysis.

attenuation; and β(f) is the frequency-dependent phase responsible for signal dispersion. By focusing on the attenuation mechanism represented by α(f), involving conductor, dielectric, and radiation losses, the impact of substrate permittivity on loss can be understood. Substrate selection is critical for a circuit design, since dielectric constant will dictate the required circuit dimensions for a target line impedance along with frequency. But it is not simply a matter of choosing a material with higher dielectric constant to design smaller circuit dimensions: Substrates with higher dielectric constants typically exhibit greater losses than materials with lower dielectric constants.

Figure 1 shows a microstrip transmission line with conductor width w and height h, enclosed in a box not considered as part of the loss analysis. Dielectric constant is the key material parameter involved in quantifying the intrinsic capacitance between conductors. In time-varying electric fields, dielectric loss represented by the substrate material's loss tangent is taken into consideration. Due to the field distribution in microstrip, the effective dielectric constant, ε_{eff}, has a lower value than the relative permittivity or relative dielectric constant, ε_r, of the substrate material. The effective dielectric constant, ε_{eff}, can be found by means of

$$\varepsilon_{eff} = C/C_a = (c/v_p)^2$$

where C is the capacitance of the microstrip on a dielectric material and C_a is the capacitance of the microstrip structure considering vacuum in place of the dielectric.



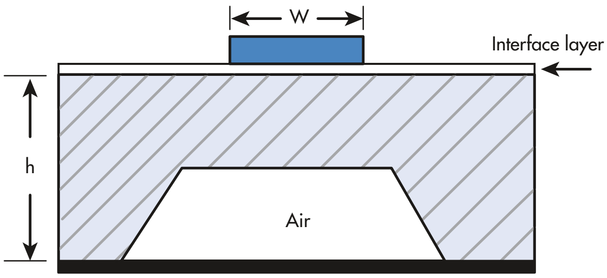
2. The passivation layer thickness has a determination of the effective permittivity of silicon substrate.

A general expression for ε_{eff} is

$$\varepsilon_{eff} = [(\varepsilon_r + 1)/2] + [(\varepsilon_r - 1)/2]\{(1 + 10(h/W)^{-0.5} + 0.041[1 - (W/h)]^2\}$$

for W/h >> 1. The equation for effective dielectric constant has been generalized in considering only a perfect dielectric constant (with $\sigma = 0$ and $\omega = 0$). The influence of frequency on effective permittivity is shown in Eq. 2:

$$\varepsilon_{eff}(f) = \varepsilon_r - (\varepsilon_r - \varepsilon_{eff})/[1 + G(f/f_t)^2] \qquad (2)$$



3. Micromachining allows the removal of small amounts of silicon beneath active devices for microstrip circuits fabricated on silicon substrates.

where

$$G = [(Z_0 - 5)/60]^{0.5} + 0.004Z_0 \text{ and } f_t = 15.66(Z_0/h)$$

with f_t in GHz, h in mils, and Z_0 in Ω.

At higher frequencies, the value of ε_{eff} approaches the value of ε_r for a microstrip substrate, implying that most of the energy propagates through the substrate (and less through the air) at higher frequencies. Considering finite metal thickness, Eq. 2 can be rewritten as Eq. 3:

TABLE 1: LOSS VARIATIONS WITH FREQUENCY FOR TFG SUBSTRATES

Frequency (GHz)	ε’	ε”	tanδ × 10-3
6.45	2.61	0.0025	0.958
6.91	2.65	0.0035	1.321
7.42	2.64	0.0036	1.364
8.54	2.61	0.0034	1.303
9.14	2.59	0.0034	1.313

$$\varepsilon'_{eff} = \varepsilon_{eff} - [(\varepsilon_r - 1)/4.6][(t/h)/(W/h)^{0.5}] \quad (3)$$

where $t/h \leq 0.2$; $0.1 \leq W/h \leq 20$; and $\varepsilon_r \leq 16$. *Figure 2* shows the influence of the substrate passivation layer thickness on the effective permittivity, and how variations increase with frequency. High-resistivity silicon substrates with various oxide thicknesses were used in this analysis.

It is important to note that ε_r for a given materiaal is a complex quantity. Equations 4 and 5 represent the complex value of the dielectric constant:

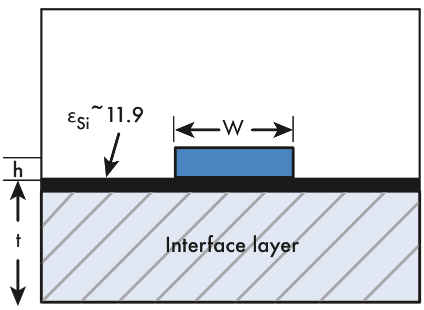
$$\nabla \times H = J = J_D + J_C = j\omega D + J_C = j\omega[\varepsilon' - j\varepsilon'' - j(\sigma/\omega)]E = j\omega\varepsilon^* E \quad (4)$$

$$\varepsilon^* = [\varepsilon' - j\varepsilon'' - j(\sigma/\omega)] \quad \text{(complex dielectric constant)} \quad (5)$$

for $\sigma = 0$, where

$$D = \varepsilon E = [\varepsilon + \varepsilon_1(\partial/\partial t) = \varepsilon_2(\partial^2/\partial t^2) + \ldots]E \rightarrow D = (\varepsilon + j\omega\varepsilon_1 - \omega_2\varepsilon_2 + \ldots)E \rightarrow (D/E) = \overline{\varepsilon}(\omega)$$

$$\text{and } \overline{\varepsilon}(\omega) = \varepsilon' - j\varepsilon'' = |\varepsilon|e^{-j\delta}$$



4. This is a depiction of a silicon substrate with an interface layer.

TABLE 2: EFFECTIVE PERMITTIVITY OF STANDARD COMBINATIONS ON SILICON

Substrate	Combination	ε_T (total permittivity)
Silicon (675 µm)	oxide (1 µm)	11.763
Silicon (675 µm)	oxide (2 µm)	11.727
Silicon (675 µm)	oxide (5 µm)	11.620
Silicon (675 µm)	oxide (500 Å) + nitride (1500 Å)	11.796
Silicon (675 µm)	micromachined silicon (50-µm membrane)	1.035

Parameter ε' is known as ac capacitance of the dielectric material; ε'' is the dielectric loss factor and represents dielectric absorption; and δ is the dielectric loss angle associated with molecular motion and relaxation. This relation assumes matter to be linear, having time lag for atomic particles to respond to frequency variations. Furthermore, it shows that the electric and magnetic fields in the dielectric material are no longer in time phase. mw

EDITOR'S NOTE: This represents the first one-third of this article, with the remainder of the article exploring how various material characteristics can influence the high-frequency performance of microstrip transmission lines fabricated on a particular substrate, such as silicon. For the full version of the article, please visit *http://mwrf.com/components/study-loss-microstrip-silicon.*

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CHRIS DeMARTINO | Technology Editor

The Differences Between Transmitter Types, Part 2

Though older transmitters were based solely on analog technology, digital technology now plays a major role in today's most commonly used transmitters.

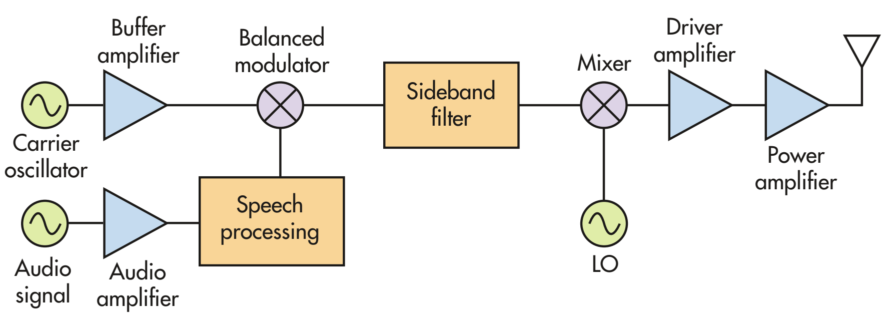
THIS TWO-PART SERIES investigates various types of transmitters that are found within myriad applications. Part 1 provided a general overview before examining classical AM and FM transmitters. In Part 2, we discuss single-sideband transmitters and then examine more modern transmitter types.

SINGLE-SIDEBAND TRANSMITTERS

With AM modulation, both an upper and a lower sideband are transmitted. The upper sideband frequency is equal to the sum of the carrier signal frequency and the modulating signal frequency, while the lower sideband frequency is equal to the carrier signal frequency minus the modulating signal frequency. A single-sideband (SSB) transmitter differs from an AM transmitter in that it only transmits either the upper or lower sideband—not both. Thus, an SSB transmitter uses less bandwidth than an AM transmitter.

Figure 1 shows one implementation of a SSB transmitter. An oscillator generates the carrier signal, which is then amplified before entering a balanced modulator. In addition, the audio signal is amplified and processed before also entering the balanced modulator.

Subsequently, the signal generated at the output of the balanced modulator enters a sideband filter. This filter allows the desired sideband to pass while rejecting the unwanted one. After the filter, the signal—which is now an SSB signal—enters a mixer, along with a local-oscillator (LO) signal. Next, at the mixer's output, a higher-frequency signal is generated; then it gets amplified and launched.



1. This SSB transmitter makes use of a filter to remove the unwanted sideband.

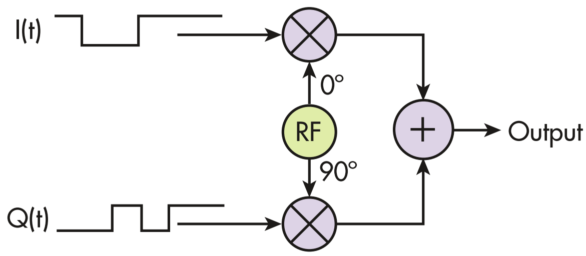
MODERN WIRELESS TRANSMITTERS

The modulating signal in AM and FM transmitters is purely analog. However, more modern transmitters utilize digital technology. In essence, today's transmitters often take advantage of digital-signal-processing (DSP) technology to process the information to be transmitted.

I/Q SIGNALS

Before discussing transmitters any further, it is helpful to explain in-phase/quadrature (I/Q) signals (also simply known as quadrature signals). I/Q signals are at the core of the complex modulation techniques implemented in many transmitters. Essentially, I/Q signals can be defined as a pair of signals that differ in phase by 90 degrees. The in-phase (I) signal is the reference signal, while the quadrature (Q) signal shifts 90 degrees in phase from the I signal.

A cosine wave and a sine wave differ in phase by 90 degrees. The cosine wave would be considered the I signal (phase equal to 0), while the sine wave represents the Q signal. When adding together a cosine wave and a sine wave with equal amplitudes, the result is a sinusoid that shifts in phase by 45 degrees from the I signal. Combining I and Q signals is an important concept with regard to complex modulation.



2. Shown is a simple representation of QPSK modulation.

PHASE SHIFT OF OUTPUT SIGNAL WITH RESPECT TO I/Q VALUES	
I/Q values	Phase (degrees)
1 1	45
0 1	135
0 0	225
1 0	315

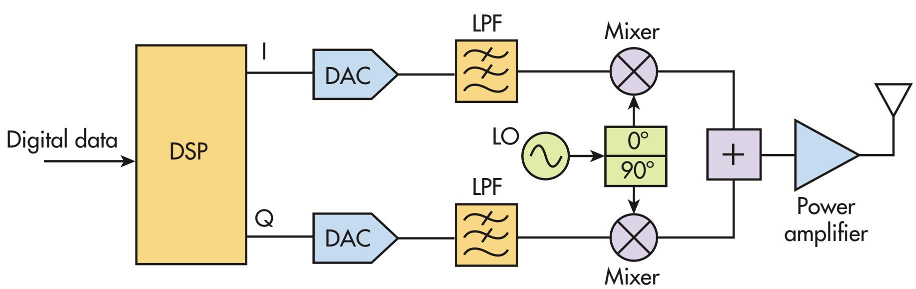
Figure 2 is an illustration of quadrature phase-shift-keying (QPSK) modulation, including the I/Q signals as well as the RF carrier signal. The I and Q signals shown are actually digital bit streams. The *table* denotes that the phase shift of the output signal is determined by the I and Q values. As can be seen, QPSK has a total of four states.

Many other modulation techniques exist, but describing them all would go beyond the scope of this article. However, the concept discussed here demonstrates that a carrier signal can be modulated by controlling the amplitude of the I/Q signals. It is an essential factor in understanding the functionality of many of today's transmitters.

DIRECT-CONVERSION TRANSMITTER

One often-used transmitter is the direct-conversion transmitter, which has the benefit of being simple and cost-effective *(Fig. 3)*. Here, the digital data that contains the information to be transmitted is processed, resulting in baseband I/Q signals. The I and Q signals are then each fed to respective digital-to-analog converters (DACs). Next, the DAC output signals are each applied to respective lowpass filters. After passing through these filters, both signals subsequently enter corresponding mixers.

Meanwhile, an LO generates an RF signal. This signal is then split into two signals that are 90 degrees out of phase. Each of these signals drive the other input port of the aforementioned mixers, respectively. At this stage, the output signals from both mixers are combined, and the resulting modulated signal is amplified, fed to an antenna, and launched. The transmitted signal eventually arrives at a receiver, which demodulates the received signal to recover the I/Q signals.

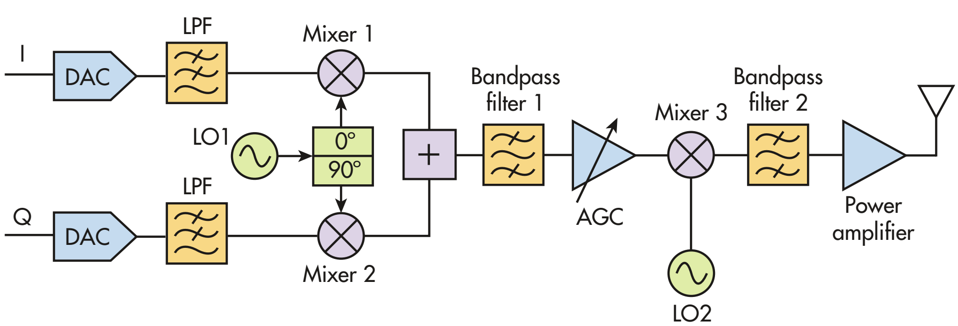


3. The direct-conversion transmitter is widely used in wireless communication systems.

SUPERHETERODYNE TRANSMITTER

Figure 4 shows a block diagram of a superheterodyne transmitter, which has greater complexity than the direct-conversion transmitter. Its process is similar to that of the direct-conversion transmitter up until the first bandpass filter, shown as Bandpass Filter 1. The signal that reaches this filter is known as the intermediate-frequency (IF) signal.

(Continued on page 83)



4. A superheterodyne transmitter functions similarly to the direct-conversion transmitter until reaching the first bandpass filter.

LEARN TO OVERCOME PHASE NOISE

PHASE NOISE IS A CRITICAL parameter in sophisticated radar systems, as well as other types of communication systems. For example, a receiver's sensitivity can be improved by minimizing phase noise. In the tech brief, "Addressing Phase Noise Challenges in Radar and Communication Systems," Custom MMIC discusses the importance of phase noise, and breaks down various approaches to overcome the problem.

Initially, the tech brief explains how phase noise is commonly used to define an oscillator's frequency stability. The phase-noise performance of an oscillator ultimately affects the performance of the system in which it is incorporated. Phase noise can impact the performance of many RF/microwave systems, but the document focuses two in particular: direct-downconversion receivers and radar systems.

Optimizing the phase noise of an oscillator will obviously help to achieve the required system performance. However, the paper points out that an amplifier is often used to increase an oscillator's output power level in order to sufficiently drive a mixer's local-oscillator (LO) port. Unfortunately, the amplifier increases the phase noise of the LO signal—all devices add noise power to an input spectrum due to 1/f noise, or pink noise. No doubt, then, that the presence of this amplifier could lead to problems.

A phase-noise plot of a low-noise amplifier (LNA) is provided in the paper. If this noise level is greater than the phase noise of the input signal, the amplifier noise would actually have a greater effect on the output noise spectrum. Therefore, the benefit of using an oscillator with low phase noise is essentially negated due to the phase noise generated by the amplifier.

Amplifier phase noise can be overcome by looking into the device's physics. Specifically, the document explains why gallium-arsenide (GaAs) bipolar devices are beneficial in terms of phase-noise performance. It goes on to mention several of Custom MMIC's low-phase-noise amplifiers based on GaAs heterojunction-bipolar-transistor (HBT) technology. The tech brief concludes by discussing how frequency multipliers also can impact phase-noise performance.

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MINIATURIZING WILKINSON POWER DIVIDERS

WILKINSON POWER DIVIDERS, commonly used in RF/microwave applications, can achieve high isolation between output ports while also maintaining a good match on all ports. In the application example, "Design of a Reduced Footprint Microwave Wilkinson Power Divider With EM Verification," National Instruments presents how its AWR Design Environment was utilized to design a Wilkinson power divider with a compact footprint.

The design flow consists of three steps. First, a design is created using ideal transmission lines. The next step involves updating the ideal schematic with the actual microstrip lengths and widths. The final step is generating the design's physical board layout.

As mentioned, the first step took advantage of ideal transmission-line models. The electrical lengths of these transmission lines were derived by specifying a frequency of 2 GHz, which is the intended center frequency. After identifying the properties of the chosen substrate, the physical attributes of the ideal transmission lines can be determined. Those attributes were obtained via the TX-LINE transmission-line calculator.

Next, an updated schematic was created that incorporated the microstrip lengths and widths. The schematic contains both *MTEEX$* and *MTRACE2* elements. The *MTEEX$* is a microstrip tee-junction element, and the *MTRACE2* element is a microstrip meander line element. The *MTRACE2* elements are employed so that the quarter-wavelength microstrip lines can be bent in the layout environment.

The last step involved creating the physical board layout, with a goal of minimizing the board area without compromising performance. The application brief explains how to add bends to microstrip lines in the layout. The document also discusses how to account for coupling between sections by utilizing automated-circuit-extraction (ACE) technology. ACE is a tool that can extract high-frequency models of the layout—including coupling effects.

After completing the layout, the next step was to further miniaturize the layout. The AXIEM 3D planar electromagnetic (EM) simulator was used for final EM verification.

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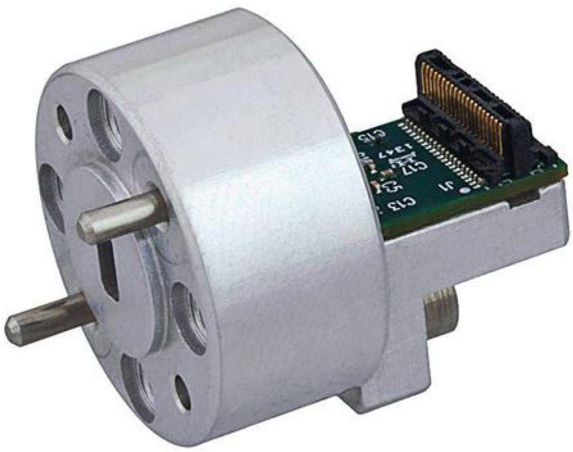
COMPACT TRANSMITTER Module Targets 60-GHz

The 60-GHz band is now in the spotlight, as designers attempt to provide cost-effective transmitters and receivers for high-data-rate, short-range links.

THE 60-GHZ FREQUENCY BAND is viewed as a solution for "last-mile" wireless communications links as well as for short-range communications in potential fifth-generation (5G) wireless networks. Achieving such solutions will require cost-effective components at frequencies that were once considered for experimental or military purposes, or for such "exotic" applications as radio astronomy or vehicle collision-avoidance radar systems.



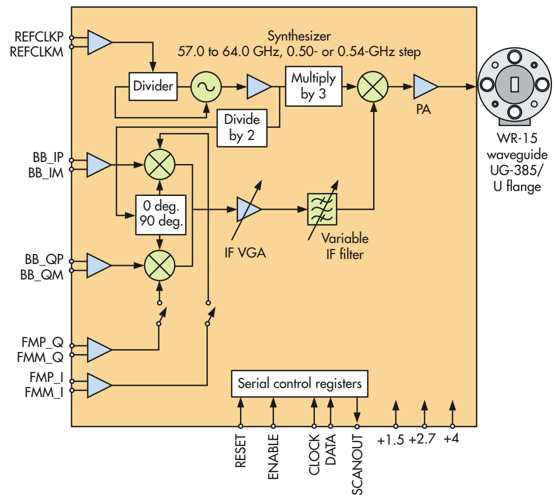
1. The PEM101 transmitter module covers a frequency range of 57.0 to 68.4 GHz with RF output power of +12 dBm.

A COMPACT SOLUTION

The model PEM010 is a waveguide transmitter module that is tunable across a frequency range of 57.0 to 64.8 GHz (*Fig. 1*). It provides +12 dBm output power at 1-dB compression across that frequency range, with saturated output-power levels slightly higher (*see table*).

The transmitter module is based on a double-conversion superheterodyne architecture (*Fig. 2*) with a sliding intermediate frequency (IF) at one-seventh the carrier frequency. The module uses silicon-germanium (SiGe) monolithic-microwave-integrated-circuit (MMIC) components for the power amplifier (PA) and frequency synthesizer, which achieves low phase noise at millimeter-wave frequencies.

The transmitter's voltage-controlled oscillator (VCO) operates at two-sevenths the carrier frequency and the local oscillator (LO) at three times the VCO frequency. LO and IF generated by the synthesizer produce step sizes of 500 MHz or 540 MHz, depending on which of two reference clocks is used. The 540-MHz step size supports IEEE channels for 802.11ad wireless systems.



2. The transmitter module employs a SiGe MMIC for its frequency synthesizer and RF power amplifier, achieving low phase noise even close to the carrier.

Inputs to the transmitter module can be either in-phase (I) and quadrature (Q) analog baseband signals or frequency-shift-keying (FSK) and minimum-shift-keying (MSK) modulated signals through different interfaces, which are upconverted to the IF at the input mixers. The IF signal is fed to a variable-gain amplifier (VGA) with a range of 20 dB and then to a variable IF filter, after which the resulting signal is mixed with the LO signal. The output of the mixer is fed to the SiGe PA that connects to the antenna using a low-loss UG-385/U WR-15 waveguide transition. A multipin ST4 connector is used for power, reference clock, digital control port, and baseband signals.

Typical PEM010 performance includes 38-dB gain, image rejection of 34 dB, a modulation bandwidth as wide as 1.8 GHz, and phase noise of −111 dBc/Hz offset 10 MHz from 308 MHz. Phase noise and I/Q balance specifications are sufficient for

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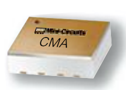

3 x 3 x 1.14 mm

Model	Freq. (GHz)	Gain (dB)	P_{OUT} (dBm)	IP3 (dBm)	NF (dB)	DC (V)	Price $ ea. (qty 20)
CMA-81+	DC-6	10	19.5	38	7.5	5	8.95
CMA-82+	DC-7	15	20	42	6.8	5	8.95
CMA-84+	DC-7	24	21	38	5.5	5	8.95
CMA-62+	0.01-6	15	19	33	5	5	7.45
CMA-63+	0.01-6	20	18	32	4	5	7.45
CMA-545+	0.05-6	15	20	37	1	3	7.45
CMA-5043+	0.05-4	18	20	33	0.8	5	7.45
CMA-545G1+	0.4-2.2	32	23	36	0.9	5	7.95
CMA-162LN+	0.7-1.6	23	19	30	0.5	4	7.45
CMA-252LN+	1.5-2.5	17	18	30	1	4	7.45

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THE MODEL PEM010 TRANSMITTER MODULE AT A GLANCE	
Parameter	**Value**
Frequency range	57.0 to 64.8 GHz
Architecture	Double conversion superheterodyne with sliding IF
Modulation bandwidth	1.8 GHz
Step size	500 or 540 MHz
Clock rate	285.7 MHz (500-MHz step) 308.5 MHz (540-MHz step)
Gain	38 dB
Gain step size	1.25 dB
RF output power (P1dB, saturated)	+12 dBm, +15 dBm
Image rejection	34 dB
Sideband suppression	20 dB
Phase noise at 308.5 MHz 100 kHz offset 1 MHz offset 10 MHz offset 100 MHz offset	–72 dBc/Hz –85 dBc/Hz –111 dBc/Hz –125 dBc/Hz
I/Q balance Phase Amplitude	± 3 deg. ± 1 dB
Input	Serial, Samtech ST4-20 connector for dc power, clock reference, control, and baseband signals
Output port	WR-15 waveguide, UG-385/U flange
Operating voltages	+1.5, +2.7, and +4 V dc
Other features	Analog I and Q or FSK/MSK modulation, extensive filtering, over-temperature protection

modulation formats to 16-state quadrature amplitude modulation (16QAM). Additional performance specifications are shown in the table.

For those in search of a complete 60-GHz link solution, the PEM101 transmitter module is compatible with other modules in Pasternack's 60-GHz development system. The development system includes a 60-GHz receiver and five horn antennas. The horn antennas cover various portions of the 60-GHz band with as much as 42-dBi gain and coverage patterns ranging from omnidirectional to very narrow beamwidths. A 60-GHz baseband I and Q signal source, model PEM004, is also available as part of the development system.

The complete development system includes the transmitter and receiver modules, transmit and receive printed-circuit boards (PCBs), two tripods, mounting brackets, ac-to-dc power adapters, USB cables, and control software. Various accessories, including phase-matched baseband coaxial cables, can be added to complete the development-system package. In this way, 60-GHz technology, which has been "just around the corner" for many years, can be quickly and easily implemented. mw

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Compare Phase-Locking Methods of RF Sources

Several different design approaches, such as leveraging a programmable PLL or even an integrated PLL/VCO, can be taken to meet performance requirements for RF/microwave sources.

THE DESIGN OF PHASE-LOCKED MICROWAVE sources typically involves one of two approaches: direct synthesis or indirect synthesis. Direct synthesis uses a very stable reference source, such as a temperature-compensated crystal oscillator (TCXO) or oven-controlled crystal oscillator (OCXO), and multiplies up to the desired frequency. With indirect synthesis, a coupled portion of the voltage-controlled oscillator's (VCO) output is fed back and its frequency is divided to match that of a stable reference source.

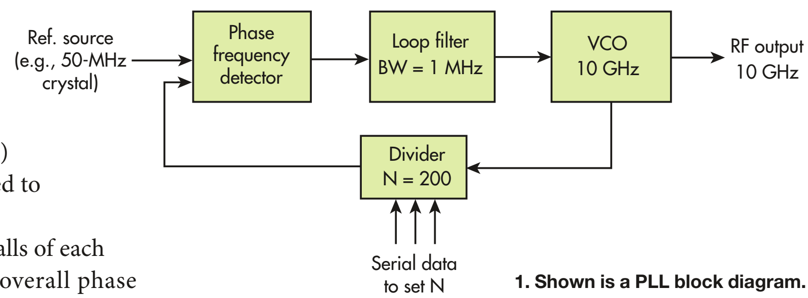
This article discusses the benefits and pitfalls of each method, and explains how they affect the overall phase noise. For instance, when close-to-carrier phase noise is critical, direct synthesis is often the favored approach.

Radical changes have occurred in the design and manufacturing methods of phase-locked RF sources, thanks to advances in programmable phase-locked loops (PLLs) and integrated PLL/VCOs that now enable a more flexible and cost-effective approach. The phase noise of these integrated devices is also comparable to that of discrete devices used with traditional methods. For example, a phase noise of –100 dBc at 100-kHz offset—across a 20-GHz bandwidth—is achievable.

INDIRECT SYNTHESIS

Indirect synthesis, also commonly known as the PLL approach, couples off a portion of an RF oscillator's (e.g., VCO) output and divides its frequency to precisely match that of a stable reference source (such as a TCXO). If the frequency of the fed-back signal is ever-so slightly different than that of the reference source, the phase frequency detector (PFD) generates an error signal, which then retunes the frequency of the VCO to the correct value. This continuous feedback arrangement ensures that the error signal is always zero and the frequency is therefore locked at a fixed frequency.

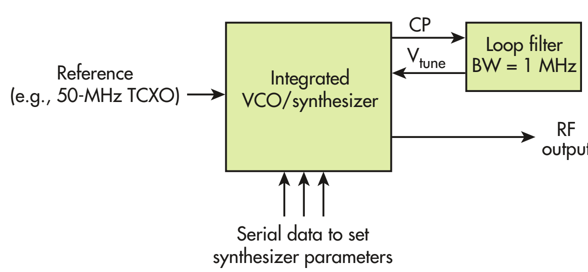
Figure 1 shows an example where an X-band microwave source at 10 GHz requires a divider of exactly 200 to be matched to a 50-MHz reference. In this example, a programmable divider is used because it provides the flexibility of output frequency selection.



1. Shown is a PLL block diagram.

Traditionally, before programmable devices, fixed frequency sources were commonly used. This was particularly the case in military applications, such as local-oscillator (LO) sources in up/down converter modules. These applications would use a fixed frequency divider.

Nowadays, both the PFD and the programmable frequency divider are integrated into a single PLL monolithic microwave integrated circuit (MMIC). Recent synthesizer developments have enabled very precise frequency selection and fine steps (e.g., 1 Hz). Synthesizer technology has progressed further to include the VCO in the MMIC (*Fig. 2*).



2. This figure illustrates an integrated PLL/VCO.

The external components required are a stable reference source (e.g., a TCXO), a carefully designed loop filter, regulated power supplies, and a means of programming or interfacing with the synthesizer.

In addition, synthesized frequencies of up to 20 GHz can be generated with very low phase noise (e.g., −100 dBc at 100-kHz offset) with these new packaged PLLs. As a result, they are well-suited for either commercial or military applications. The other advantages of MMIC-based synthesizers include added flexibility for a variety of applications, lower-cost materials/products, and reduced production time.

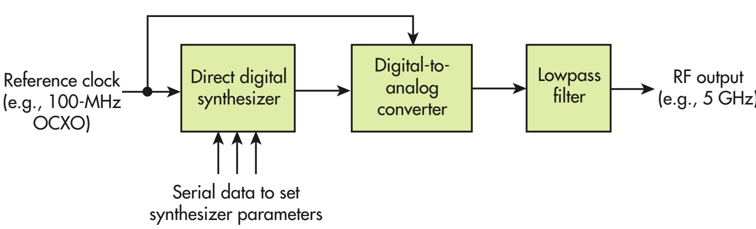
Many PLL/synthesizer MMIC devices contain volatile memory, since they are devoid of EPROMs. Information is sent via serial peripheral interface (SPI) to the synthesizer chip, which sets a variety of control parameters—such as the number of frequency divisions. The output frequencies of the synthesizer are phase-locked to precise values within the frequency range of the VCO. All of this required data can be programmed onto an EPROM chip so that the SPI data is triggered and sent to the PLL/synthesizer chip as the unit powers up.

To improve the noise performance of an N-integer PLL, it is desirable to minimize the N counter value and maximize the phase detector frequency, f_{pd}. If N is an integer, the maximum value of the phase detector frequency is limited to the size of the channel spacing, Δf.

If N is a fractional value, Δf can be further reduced, improving the frequency resolution. Fractional–N synthesizers can also have very low phase noise with very fast switching speeds. In the past, their drawback has been fractional spurs, but today, methods such as analog compensation are able to suppress them.[1] For high-frequency applications with low channel spacing, fractional-PLL synthesizers are the preferred option.[2]

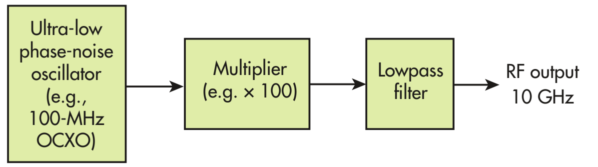
DIRECT DIGITAL SYNTHESIZERS

Major developments of late in direct-digital-synthesizer (DDS) technology have led to significant performance improvements. DDS requires a digital-to-analog converter and a lowpass filter to remove the unwanted products and harmonics of the output signal (*Fig. 3*). This can often be complex to set up and a problematic option if spurious emissions are undesirable.

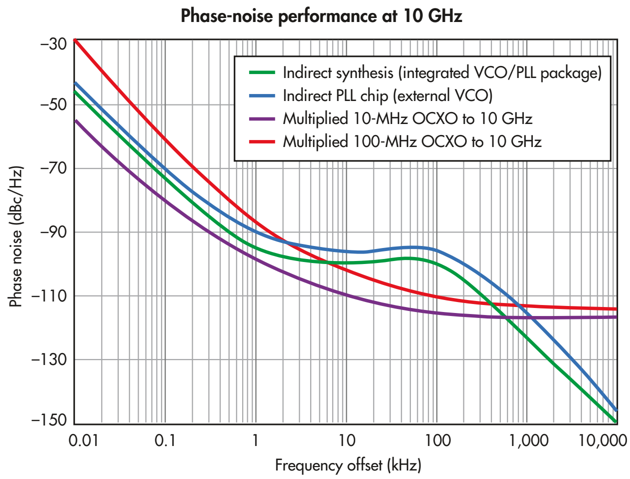


3. Shown is a representation of direct digital synthesis.

However, it's possible to achieve fine frequency steps, making the close-to-carrier phase noise more desirable in comparison to indirect synthesis. A simpler but less flexible method that has the same benefits and pitfalls as DDS is to multiply a very clean crystal source, such as an OCXO (*Fig. 4*).



4. This image depicts an OCXO being multiplied up to a higher frequency.



5. These plots compare phase noise performance of direct and indirect synthesis.

PHASE-NOISE PERFORMANCE

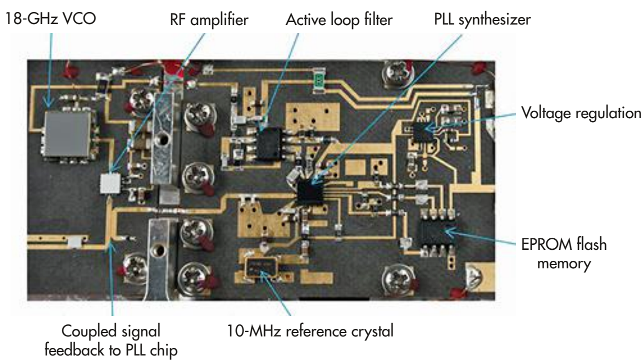
Figure 5 shows the phase-noise performance of direct synthesis by multiplication compared with the indirect (PLL) method. The chart reveals that improved phase noise is achieved by multiplying the 10-MHz OCXO—currently available 10-MHz OCXOs feature ultra-high stability. The graph also shows that the direct multiplication method can attain lower phase noise than PLL methods at close-to-carrier offset frequencies up to 500 kHz. At offsets greater than 500 kHz, the phase noise of the VCO dominates in the PLL method. This results in lower phase noise for the PLL technique at these larger offset frequencies.

DESIGN AND MANUFACTURING

Figure 6 shows a PLL/VCO board designed and manufactured at Specialist Microwave Solutions

The correction signal generated from the PLL device then passes through an active loop filter back to the tuning port of the VCO to ensure that the VCO's output is continuously locked at a predefined frequency.

Ltd., U.K. The unit outputs a fixed-frequency phase-locked signal from an amplified VCO (left-hand side of the figure). Some of this signal is fed back to a PLL device, which divides the 18-GHz signal down to be compared with that of a clean 10-MHz reference source (courtesy of a PFD).



6. Shown is the board layout of a PLL/VCO-based design.

The correction signal generated from the PLL device then passes through an active loop filter back to the tuning port of the VCO to ensure that the VCO's output is continuously locked at a predefined frequency. This circuit shows a phase-locked 18-GHz source. However, the circuit can be adapted to output a wide range of phased-locked frequencies by changing the VCO, loop filter components, and software instructions. Low phase-noise frequency synthesizers that can output many frequency channels across a predefined bandwidth are also designed and manufactured at Specialist Microwave Solutions Ltd.

CONCLUSION

The development of programmable PLLs and integrated synthesizer chips provide a flexible and cost-effective approach to the design of a frequency source. Comparing the phase-noise performance of some of these approaches can help pinpoint the best solution for your design. The methods discussed here include utilizing a PLL synthesizer chip along with an external VCO; using an integrated PLL/VCO; and direct multiplication.

The first approach mentioned above can offer added flexibility, as it can be used to phase-lock a range of VCOs, dielectric-resonator oscillators (DROs), etc. Recent advances of integrated synthesizer MMICs have resulted in phase-noise performance that meets commercial and military specifications. Whenever a new requirement for a microwave source arises, the final decision on the appropriate design approach will be based on a range of specifications, such as the allocated cost, size, frequency resolution, and phase noise. mw

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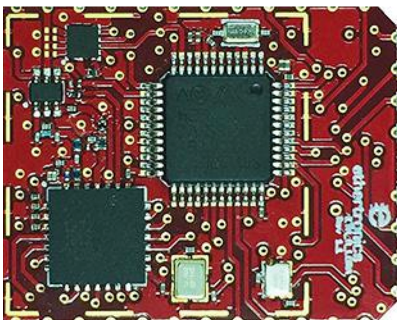
CHRIS DeMARTINO | Technical Editor

New Module Meets LoRa Challenges

To meet the needs of LoRa applications, one company decided to develop its own unique solution.

LoRa TECHNOLOGY IS REGARDED as a key player for Internet of Things/machine-to-machine (IoT/M2M) applications. Based on spread spectrum technology, LoRa allows for long-range, low-date-rate communications. In North America, LoRaWAN networks operate in the 902-to-928 MHz frequency band, while Europe uses 867 to 869 MHz. Some of the various applications that can be enabled by LoRa technology are intelligent buildings, agriculture, and logistics.



1. This LoRa module operates in the 868- and 915-MHz bands.

One company, Ethertronics, recognized the need for antennas for LoRa-based products. Hence, Ethertronics—which is a member of the LoRa Alliance—essentially decided to create its own solution. Those efforts have resulted in the new ETH-LORA-M-AX-0110 LoRa module (*Fig. 1*).

The ETH-LORA-M-AX-0110 is a plug-and-play LoRa module that enables low-power-wide-area-network (LPWAN) connectivity. It operates in the unlicensed 868- and 915-MHz frequency bands. The module combines Semtech's SX1272 LoRa transceiver with Ethertronics' Active Steering and impedance matching solutions. Ethertronics' EC686 chipset, which is a single-pole, four-throw (SP4T) for antenna tuning applications, is utilized in the module's architecture (*Fig. 2*).

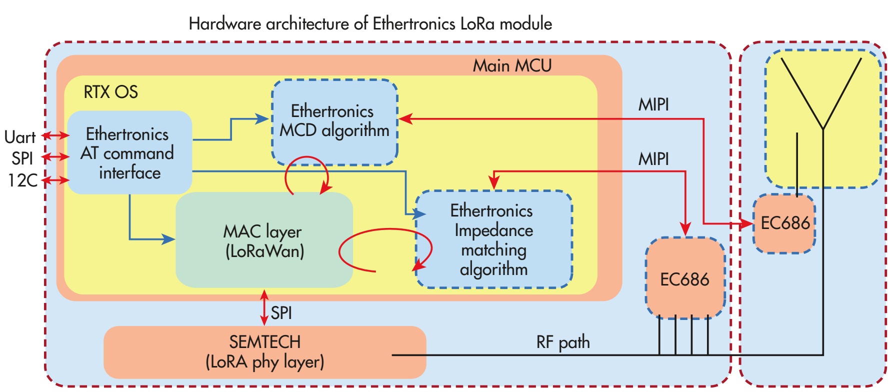
Ethertronics' motivation, essentially, is to deliver a complete LoRa device solution. This solution includes a LoRa module, antennas, testing, software integration support, and pre-certification. "We want to be a one-stop shop to allow customers to bring a LoRa application to market," explained Jeff Shamblin, the company's chief scientist.

MODULE FEATURES

One key feature of the ETH-LORA-M-AX-0110 module is its impedance matching capability. This capability allows power transfer between the radio and antenna to be maximized. The company maintains that this impedance-matching capability helps to overcome potential antenna detuning caused by the surrounding environment.

In addition, Active Steering technology offers the capability of generating three radiation patterns. This technology essentially enables a communication link to be optimized dynamically. IoT/M2M applications can benefit from real-time adjustments, which are made possible by Active Steering technology. Thus, customers can place their IoT/M2M device in virtually any location, according to Ethertronics.

In terms of performance, the ETH-LORA-M-AX-0110 module has a performance range in excess of nine miles. It also has an expected battery lifetime of 2 to 10 years—depending on the application. The module takes advantage of a real-time, multi-task operating system (RTX OS). Its command interface is intended to increase flexibility and speed integration. The module measures 20 × 25 mm. Samples are available now. mw



2. Shown is the LoRa module's hardware architecture.

ETHERTRONICS INC., 5501 Oberlin Dr. Ste. 100, San Diego, CA 92121; (858) 550-3820; *www.ethertronics.com*

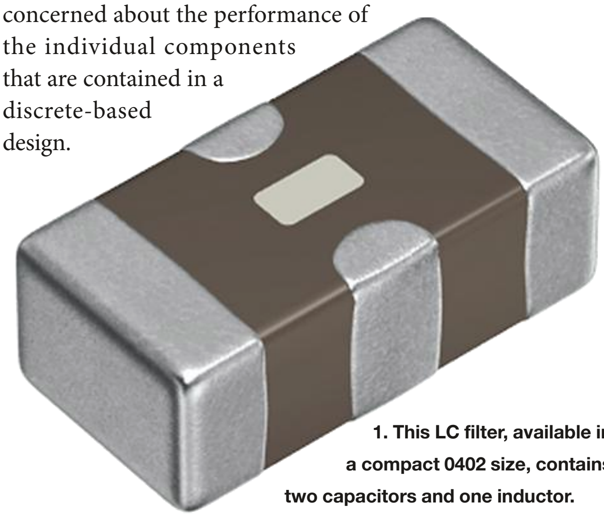
CHRIS DeMARTINO | Technical Editor

MINIATURE FILTER Takes Aim at EMI

A new compact lowpass filter has been introduced to overcome interference.

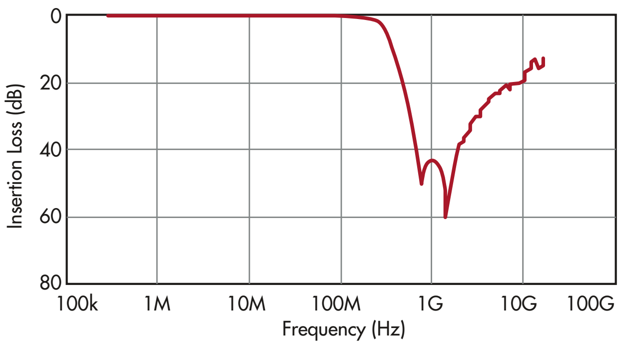
WITHOUT QUESTION, electromagnetic-interference (EMI) is something that designers must be mindful of when designing circuits for wireless products. Proper filtering is key when it comes to overcoming potential EMI problems. Discrete capacitors and inductors are commonly used to suppress interference in communication frequency bands. However, TDK Corporation recently introduced a new integrated component that is intended to help designers defeat EMI: the MEM1005PP251T LC filter, intended for signal lines.

As mentioned, discrete capacitors and inductors are often used to suppress EMI. However, the MEM1005PP251T LC filter actually contains two capacitors and one inductor in a standard 0402 case size (*Fig. 1*). These elements together form a lowpass Pi filter. Taking advantage of the MEM1005PP251T therefore enables a designer to avoid building filters with discrete parts. Those who use this filter no longer have to be concerned about the performance of the individual components that are contained in a discrete-based design.



1. This LC filter, available in a compact 0402 size, contains two capacitors and one inductor.

The small size of the MEM1005PP251T allows the required board space to be reduced by about 61% in comparison to using discrete components. This space reduction is significant in terms of meeting today's smaller-size requirements. In particular, portable products demand high performance in small sizes.



2. This plot shows the filter's typical insertion loss.

The filter has a specified cutoff frequency of 250 MHz. Its specified insertion loss is 30 dB across a frequency range of 700 MHz to 3 GHz (*Fig. 2*). The company asserts that this insertion loss performance allows for well suppressed interference and increased reception sensitivity in the wireless communication frequency bands. Moreover, the MEM1005PP251T has a dc resistance of 0.8 Ω, which contributes to low-loss operation.

In addition, the MEM1005PP251T has a maximum rated voltage of 10 V and a maximum rated current of 350 mA. This rated current is 3.5 times greater than the maximum rated current of the company's MEM1608P series, which is actually offered in a larger 0603 case size. Furthermore, the filter has an operating temperature range of –55°C to +125°C.

In terms of applications, the MEM1005PP251T is intended to be used in designs for products like smartphones, tablets, computers, cameras, and gaming consoles. Base stations represent another potential market. Volume production of the MEM1005PP251T has already begun. On a final note, TDK Corporation also has plans to expand the series to meet a wider range of requirements. mw

TDK CORPORATION, *www.global.tdk.com*

(Continued from page 70)

Transmitters come in various shapes and sizes. While AM and FM transmitters are still in play, current wireless communication systems extensively use other types—in particular, direct-conversion and superheterodyne implementations.

After passing through Bandpass Filter 1, the IF signal is amplified and then upconverted to the final output frequency by a mixer. After that, the signal is filtered, amplified, and launched.

Referring to Fig. 4, one drawback of the superheterodyne transmitter is the generation of unwanted signals at the output of Mixer 3. To explain, the frequency of the desired output signal could be equal to the sum of the LO2 and IF frequencies. However, an unwanted signal with a frequency equal to the difference of the LO2 and IF frequencies will also appear at the output of Mixer 3.

Alternatively, the reverse could be true: The desired output frequency could be equal to the difference of the LO2 and IF frequencies; thus, an unwanted signal with a frequency equal to the sum of the LO2 and IF frequencies will appear at the output of Mixer 3. No matter the case, Bandpass Filter 2 is employed to remove the unwanted signals.

CONCLUSION

Transmitters come in various shapes and sizes. While AM and FM transmitters are still in play, current wireless communication systems extensively use other types—in particular, direct-conversion and superheterodyne implementations. And let's not forget that DSP technology is a key enabler of the communications that prevail today. mw

REFERENCES

1. Frenzel, Louis E., *Principles of Electronic Communication Systems,* Fourth Edition, McGraw Hill, 2016.

2. Tektronix, What's Your IQ—About Quadrature Signals, April, 2013.

LEARN THE DIFFERENCES BETWEEN RECEIVER TYPES

INTERESTED READERS CAN also find online "The Differences Between Receiver Types, Part 1" *(http://mwrf.com/systems/differences-between-receiver-types-part-1)* and "The Differences Between Receiver Types, Part 2," *(http://mwrf.com/active-components/differences-between-receiver-types-part-2)* from the March 2016 and April 2016 issues of Microwaves & RF, respectively. PDF downloads of both articles are available.

This two-part series of articles complements this series, as it provides an overview of receivers. As stated in this series, transmitted signals ultimately arrive at a receiver. The referenced articles describe receiver performance, with block diagrams to illustrate their functionality. Direct-conversion and superheterodyne receivers are described. In addition, the newer direct-RF sampling technique is discussed. Some of the performance tradeoffs between different receiver variations are described. ■

CHRIS DeMARTINO | Technical Editor

Q&A: Roland Carter,

President of Smiths Interconnect

It was recently announced that EMC Technology, Hypertac, IDI, Lorch, Millitech, RF Labs, Sabritec, TECOM, and TRAK would unify under a single brand identity: Smiths Interconnect. In this brief interview, Roland Carter, president of Smiths Interconnect, discusses this brand transition.

First, can you tell us the reasoning behind this brand transition?

Carter: Over time, interactions among our brands have increased across many of our markets. Aligning all this activity under the Smiths Interconnect name will make us a more streamlined partner, enhancing our customers' access to the combined strength of our products, expertise, and application knowledge. This brand transition supports a recent strategic reorganization focused on creating a more agile structure that can better anticipate and respond to customers' evolving needs.

How will this transition impact customers of these brands?

Carter: Unifying these technology brands under the single brand identity of 'Smiths Interconnect' will simplify customer access and interactions across multiple applications, making it easier to navigate between and communicate about the entire offering.

Where do you now see Smiths Interconnect positioned in the RF/microwave industry?

Carter: As a single brand that represents a breadth of solutions across connectors, microwave components, and microwave subsystems technologies, Smiths Interconnect is positioned as a comprehensive solutions provider. The shared expertise and market knowledge across our technology brand foundation paves the way for enhanced innovation and technology partnerships with customers.

smiths interconnect
bringing technology to life

INSIDE SMITHS INTERCONNECT

HERE ARE THE brands that make up the new Smiths Interconnect:

EMC Technology: Board-level components incorporating resistive and signal distribution technologies.

Hypertac: Hyperboloid contact technology, electrical connectors, and interconnect solutions.

IDI: Spring probe contacts, interposers, connectors, and semiconductor test solutions.

Lorch Microwave: RF/microwave conditioning products using multiple topographies.

Millitech: Millimeter-wave components, antennas, assemblies, and integrated subsystems for SATCOM, test & measurement, radar, and scientific applications.

RF Labs: Microwave cable assemblies and coaxial components.

TECOM: Ground and airborne antenna systems for SATCOM, radio link, radar, telemetry, and high-bandwidth connectivity.

TRAK Microwave: Integrated microwave assemblies and subsystems, time and frequency systems, and ferrite components.

Product SPOTLIGHT

The latest product information presented by

Mini-Circuits®

www.minicircuits.com

Power Splitter/Combiner Goes Two Ways to 6800 MHz

Mini-Circuits' model SCRP-2-682W+ is a two-way, 0-deg., 50-Ω power splitter/combiner with excellent amplitude and phase unbalance from DC to 6800 MHz. The typical insertion loss (above the 3-dB power split) is 0.5 dB from DC to 5000 MHz and 0.8 dB or less from DC to 6800 MHz. Isolation between ports is typically 19 dB across the full frequency range. The power splitter/combiner maintains typical amplitude unbalance within 0.3 dB across the full frequency range and typical phase unbalance within 1 deg. from DC to 5000 MHz and within 3 deg. from DC to 6800 MHz. The typical full-range VSWR is 1.50:1 or better at all three ports. The power splitter/combiner is supplied in a rugged, RoHS-compliant surface-mount package and is designed for operation from -40 to +85°C.

75-Ω Directional Coupler Channels 5 to 1218 MHz

Mini-Circuits' model TCD-16-12W-75X+ is a 75-Ω, surface-mount directional coupler suitable for use from 5 to 1218 MHz, including in VHF/UHF, CATV, and cellular communications applications. The nominal full-band coupling is typically 16.0 ± 0.5 dB, with ±0.8 dB typical coupling flatness across the full frequency range. The directivity is typically 16 dB to 870 MHz and 12 dB to 1218 MHz. The mainline insertion loss (above the 0.1-dB coupling loss) is typically 0.7 dB for the full frequency range. Input return loss is typically 19 to 22 dB and output return loss is typically 19 to 25 dB. The compact, RoHS-compliant directional coupler is designed for operating temperatures from -40 to +85°C and is available in tape-and-reel packaging for automated assembly.

Four-Channel Attenuator Programs 63-dB Range from 1 to 6000 MHz

Mini-Circuits' model RC4DAT-6G-60 is a USB/Ethernet-programmable attenuator that operates from 1 MHz to 6 GHz. It controls 0 to 63 dB attenuation in 0.25-dB steps across four independent channels, with more than 100-dB isolation between channels. Typical attenuation accuracy is ±0.70 dB or better for all attenuation settings and all frequencies. Insertion loss is typically 3 dB to 2 GHz and 6.2 dB or less to 6 GHz. The input IP3 is typically +53 dBm to 3 GHz and +51 dBm to 6 GHz. Full software support is downloadable at any time from the Mini-Circuits' website, including user-friendly Windows-based GUI applications. The programmable attenuator includes female SMA input and output RF connectors and is a good fit for laboratory as well as production-line testing.

Power Splitter/Combiner Routes 10 W to 2750 MHz

Mini-Circuits' model ZN8PD-272SMP+ is an eight-way, 0-deg., 50-Ω power splitter/combiner that handles as much as 10 W input power as a splitter (and as much as 6 W input power as a combiner) from 690 to 2750 MHz. For the full frequency range, the typical insertion loss (above the 9-dB eight-way split) is 0.8 dB while isolation between channels is typically 23 dB. The typical full-band amplitude unbalance is 0.1 dB while the typical full-band phase unbalance is 2 deg. The compact power splitter/combiner measures just 6.60 × 3.26 × 0.30 in. with snap-on SMP connectors to fit dense packaging requirements. It is well suited for applications in automatic test systems, satellite distribution systems, and terrestrial wireless communications systems.

MMIC SPDT Switch Handles High Power to 2.7 GHz

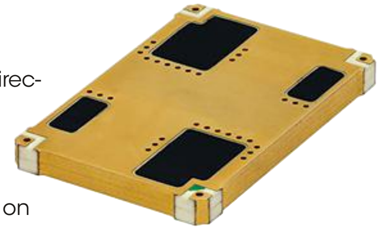
Mini-Circuits' model HSW2-272VHDR+ is a high-power single-pole, double-throw (SPDT) MMIC reflective switch with high power handling, low loss, and high isolation from 30 to 2700 MHz. It handles as much as 25.1 W pulsed input power and as much as 15.8 W CW input power, across the full frequency range. Typical insertion loss is 0.7 dB or less and typical isolation is 24 dB or better between the common port and the two RF ports, and 26 dB or better between the two RF ports, across the full frequency range. The rugged switch exhibits low harmonics and has on-state return loss of typically 20 dB or better. It is equipped with an internal driver and is well suited for communications, defense, and test applications. The switch operates with a single supply from +2.3 to +5.5 V dc with typical current consumption of only 120 µA.

E-PHEMT Dual Amplifier Achieves High Dynamic Range to 1250 MHz

Mini-Circuits' model MPGA-122-75+ is a dual matched monolithic amplifier with high dynamic range and low noise figure from 40 to 1250 MHz. Well suited for CATV applications, the 75 Ω dual amplifier is based on E-PHEMT technology and features a positive gain slope with frequency: typical gain is 14.9 dB at 40 MHz and 15.3 dB at 1250 MHz. With 15 dB gain at 1500 MHz, the amplifier provides usable gain and even amplitude response to 1800 MHz. The wide-dynamic-range dual amplifier has typical noise figure of 2.9 dB at 500 MHz, 2.9 dB at 40 MHz, and 3.6 dB at 1250 MHz. It is capable of typical output power at 1-dB compression of +30.1 dBm at 40 MHz and +28.2 dBm at 1500 MHz. It features excellent linearity, with typical IP3 of +51 dBm at 500 MHz and typical IP2 of +68 dBm, also at 500 MHz. The RoHS-compliant dual amplifier is supplied in a thermally conductive 4 × 4 mm 24-lead MCLP package. It draws typical current of 391 mA from a +9 V dc supply.

New Products

Dual-Directional Coupler Channels 300 W to 520 MHz



FOR COUPLING HIGH-POWER signals in tight spaces, the model DDCH-50-521+ dual-directional coupler handles 300-W maximum mainline power from 20 to 520 MHz and provides 50-dB coupled signals with 13-dB typical return loss. It also passes as much as 4 A current from mainline input to output and boasts typical mainline input and output return loss of 35 dB to 150 MHz and 30 dB to 520 MHz. The tiny 50-Ω coupler is supplied on an open printed-circuit laminate measuring 1.0 × 1.5 × 0.128 in. with wrap-around terminations for ease of mounting on high-frequency PCBs. It features low typical insertion loss of 0.10 dB across the full frequency range, with typical fullband directivity of 21 dB, and typical fullband coupling flatness of ±0.65 dB. Suitable for commercial and military applications, the dual-directional coupler is designed for operating frequencies from –55 to +105°C.

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

Phase Shifters Steer 360 deg. from 0.5 to 18 GHz

A SERIES OF 8-B PROGRAMMABLE phase shifters covers frequency bands from 500 MHz to 18 GHz with 360-deg. control. Three new models adjust phase in 1.4-deg. increments in as many as 256 tuning steps and with phase shift error minimized from ±0.9 to ±4.5 deg. The phase shifters handle CW input levels from +13 to +30 dBm and have fast switching speeds of 30 to 265 ns. They incorporate TTL control and are supplied with field-replaceable SMA or 2.92-mm coaxial connectors. The digitally controlled analog phase snifters are suitable for radar, communications, and EW applications working with phased-array antennas that require exact phase control.

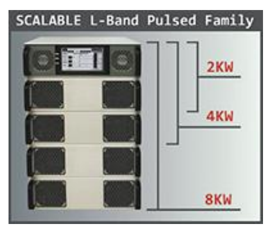
FAIRVIEW MICROWAVE, INC., 17792 Fitch, Irvine, CA 92614, (949) 261-1920; *www.fairviewmicrowave.com*

Low-Noise VCO Tunes 10.5 to 11.0 GHz

OPTIMIZED FOR X-BAND applications from 10.5 to 11.0 GHz, model DXO10701095-5 is a low-noise voltage-controlled oscillator (VCO) with low harmonics and phase noise. It exhibits typical phase noise of –82 dBc/Hz offset 10 kHz from the carrier with harmonic content of typically –22 dBc. The oscillator delivers minimum output power of +2 dBm and offers 40 to 68 MHz/V tuning sensitivity for a tuning range of 0.5 to 15.0 V. The frequency pushing is typically 10 MHz/V while the frequency pulling is typically 20 MHz for a 1.75:1 VSWR. The VSO typically draws 25 mA current from a +5-V dc supply. It is designed for operating temperatures from –40 to +85°C.

SYNERGY MICROWAVE CORP., 201 McLean Blvd., Paterson, NJ 07504; (973) 881-8800, *www.synergymwave.com*

L-Band Pulsed Amps Add Power As Needed



A FAMILY OF SCALABLE pulsed L-band amplifiers features an expandable, modular architecture that allows users to add 3U blocks to add power as needed. The amplifiers operate from 1 to 2 GHz with a starting pulsed output-power level of 2 kW, which can be expanded to 4 kW and 8 kW with the additional modules. The rack-mount pulsed amplifiers include automatic-gain-control (AGC) and automatic-level-control (ALC) blocks to simplify system integration. They are equipped with a host of protection functions, including output power limit, fault shutdown, and VSWR protection for shutdown on faults. The amplifiers can be supplied with RS-232 or RS422 interface.

EMPOWER RF SYSTEMS, INC., 316 W. Florence Ave., Inglewood, CA 90301; (310) 412-8100, *www.EmpowerRF.com*

Differential Amplifier Offers Unity Gain to 1 GHz

MODEL LTC6419 is a dual broadband differential amplifier with low input noise and gain-bandwidth product of 10 GHz. It features unity-gain response past 1 GHz, with gain of 100 for a 100-MHz bandwidth. The spurious-free dynamic range is 85 dB at 100 MHz while driving 2-V peak-to-peak signals. The input voltage noise density is 1.1 nV/(Hz)0.5. The channel-to-channel isolation is 95 dB at 100 MHz. The differential gain of each amplifier can be set with four external resistors. The maximum gain is 400 for a bandwidth of 30 MHz. The dual differential amplifier, which allows DC coupling, is available with different grades and operating temperature ranges for different applications, including driving high-sample-rate analog-to-digital converters (ADCs). It is supplied in a 4 × 3 × 0.75 mm, 20-lead LQFN plastic package.

LINEAR TECHNOLOGY CORP. (NOW ANALOG DEVICES), McCarthy Blvd., Milpitas, CA 95035; (408) 432-1900, *www.linear.com*

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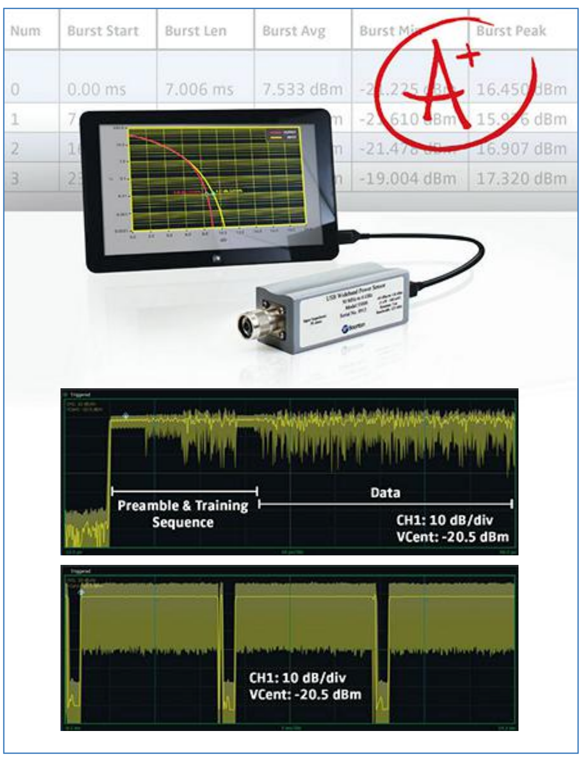

The 55 Series USB Peak Power Sensor

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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