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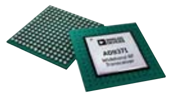

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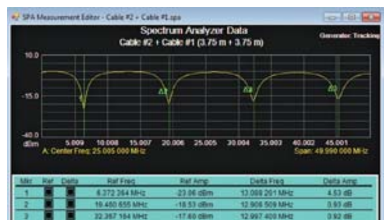

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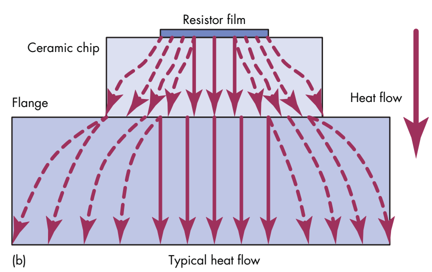

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WIRELESS TECHNOLOGIES FLOOD THE IoT LANDSCAPE

http://mwrf.com/systems/wireless-technologies-flood-iot-landscape

The Internet of Things (IoT) continues to be a major talking point, as many look ahead to the connectivity it may bring to our world. However, an important question remains to be addressed: How will all of these IoT devices be wirelessly connected? Given the vast amount of IoT applications and requirements, it is certain that no single wireless technology by itself will be the driving force behind the IoT.

LAA: LTE AND WI-FI COEXISTENCE OR CONVERGENCE?

http://mwrf.com/services/laa-lte-and-wi-fi-coexistence-or-convergence

Using cellular and Wi-Fi together in a mobile device has now become an expectation. Not only should they work together, but they should be enabled to work together seamlessly at the switch of a button. LTE and Wi-Fi have coexisted and been complementary for years, but researchers have recently proposed new LTE and Wi-Fi coexistence technologies to enhance the user's mobile data experience. As demand for mobile data access continues to escalate, these technologies will likely be commercialized and deployed in the near future.

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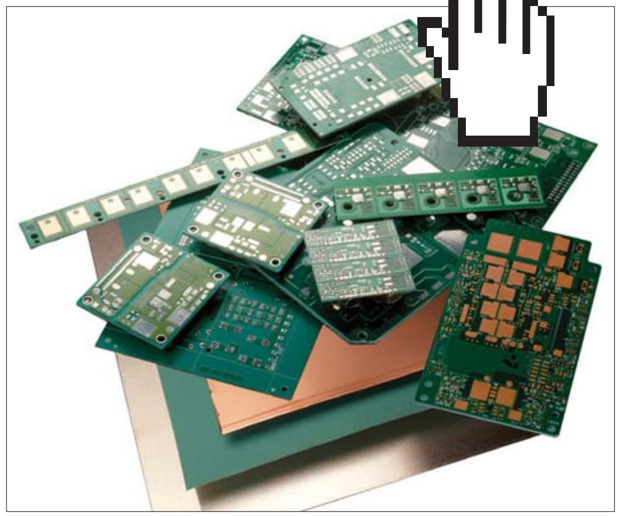

WHAT SUBSTRATE MATERIAL BEST FITS YOUR HIGH-SPEED CIRCUITS?

http://mwrf.com/materials/what-substrate-material-best-fits-your-high-speed-circuits

Printed-circuit-board (PCB) materials contain the transmission lines and components that enable discrete RF/microwave circuits. They consist of numerous materials, including plastics, epoxy, glass, and ceramics, in rigid and flexible forms and with qualities that serve many different circuit designs. Understanding how PCB material parameters relate to circuit performance can simplify the task of matching a PCB material to an application as well as to a circuit fabrication process.

SUMMARIZING ADVANCES IN SDR TECHNOLOGY

http://mwrf.com/systems/summarizing-advances-sdr-technology

Software may be what defines the functionality of a software-defined radio (SDR), but hardware is still a critical part of the radio—whether it is in a smart cellular phone or a tactical radio for military use. The software can only achieve the performance levels made possible by the essential hardware components within the radio, including analog-to-digital converters (ADCs), digital-to-analog converters (DACs), field-programmable gate arrays (FPGAs), and integrated-circuit (IC) radios.

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Editorial

CHRIS DeMARTINO
Technical Editor
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The Continuing Advancement of Wi-Fi

It is pretty clear that nowadays Wi-Fi appears to be everywhere. Unfortunately, such heavy Wi-Fi congestion has also created its own problems. Simply put, high-density environments can cause a poor user experience. Chances are you have experienced slow Wi-Fi at some point—as a matter of fact, chances are pretty good that you have experienced extremely slow Wi-Fi.

The IEEE wireless-local-area-networking (WLAN) standards have continued to progress throughout the years. The latest and greatest Wi-Fi standard is IEEE 802.11ax, which is currently in the process of being standardized. This new Wi-Fi standard promises to increase throughput in dense user environments. In other words, IEEE 802.11ax seeks to remedy today's problem of experiencing slow Wi-Fi in congested areas. The IEEE 802.11ax standard is expected to be officially released in 2019.

A number of features will allow IEEE 802.11ax to achieve better throughput in crowded settings. For one, IEEE 802.11ax utilizes orthogonal-frequency-division-multiple-access (OFDMA) technology. Another feature is 1024-quadrature amplitude modulation (1024-QAM).

Recently, National Instruments (www.ni.com) made news by introducing its test solution for IEEE 802.11ax applications. The WLAN Measurement Suite, which provides users with the capability to generate and analyze a wide range of IEEE 802.11 waveforms, has now been updated to target IEEE 802.11ax. A number of key features of IEEE 802.11ax are supported by the software. Furthermore, as the process of standardizing IEEE 802.11ax develops, engineers will be able to update their existing PXI RF test systems with simple software updates.

LitePoint (www.litepoint.com) is another company that has set its eyes on IEEE 802.11ax. The company's IQxel-MW test solution is intended to accommodate IEEE 802.11ax requirements. With all of this being said, it is clear that the next generation of Wi-Fi is moving along to satisfy our never-ending wireless appetite. Stay tuned! mw

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WHATEVER HAPPENED TO IN-HOUSE FOUNDRIES?

Before everyone gets too excited about all the "newfound" bandwidth waiting within unlicensed frequency spectra around 60 GHz and beyond, let us remember that there are reasons why those frequencies have been relatively ignored for such a long time. Not only are such high frequencies characterized by such small wavelengths (and such short propagation distances, as a result), it is a challenge to fabricate the component and circuit dimensions needed for transmission and reception of millimeter-wave frequencies. This has traditionally been handled by waveguide components.

For these frequencies to become part of commercial and consumer applications, as in 5G wireless communications systems, it will take much more than just highly integrated semiconductor devices. Innovative engineering in the form of discrete antennas and electronically steered antenna arrays will be needed to make high-data-rate communications at millimeter-wave frequencies possible, let alone practical.

The design method detailed by Anokiwave in your feature article (May 2016), of using the best-suited semiconductor process for a particular device design and/or application, is practical. But it also represents an alternative to the traditional method of investing in a company-owned semiconductor foundry, and refining the fabrication processes as a means of advancing a technology. Unfortunately now it appears that there is more of a "take what you can get" approach from available foundries.

John Avolin

EDITOR'S NOTE

Few companies can afford their own semiconductor foundry as a "division" or auxiliary service without running it as a separate business. But as most companies with their own foundries discovered, it was not possible to give their own foundry enough fabrication business to make running it cost-effective. Success in any semiconductor foundry begins with the quality of the raw materials, whether the starting ingot is silicon, GaAs, GaN, SiC, or even SiGe.

Quality in the process steps generally improves through practice (repetition), which is not possible when performing only sporadic wafer starts. As many electronics manufacturers have discovered, it is possible to achieve repeatable, high-quality results with an outside foundry while side-stepping the enormous operating costs of a semiconductor foundry. The Anokiwave approach frees a company to attempt different processes without these financial risks.

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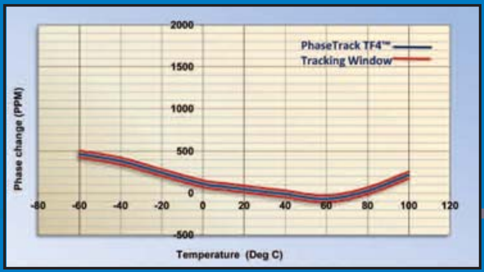

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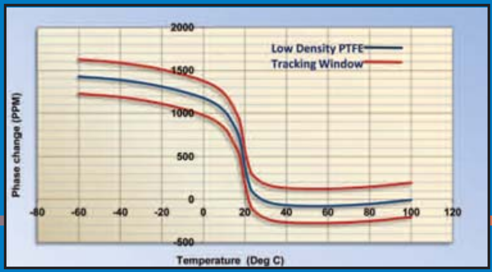

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News

NETWORK ANTENNA Sends Broadcast Television to Mobile Devices

Over the years, televisions have slowly evolved from bales of analog electronics into sleek digital devices. Television broadcast antennas, on the other hand, have seen little innovation. Now, LG Electronics has built a wireless antenna that sends high-definition broadcast signals into smart televisions, smartphones, and other connected devices around the home.

The network antenna, which was revealed at the recent National Association of Broadcasters convention, is designed to process television broadcasts and distribute them around the home using Wi-Fi. The antenna employs a network interface to connect with Wi-Fi routers, sending digital television and internet services over the same path.

The company said in a statement that the antenna was built from directional antenna arrays with electronic steering logic, which points wireless signals directly at connected devices to improve reception. In addition, the antenna can be placed anywhere in the user's house unlike traditional broadcast antennas, which have to be bolted onto the roof.

The antenna has spent nearly two years in research and development at LG's Zenith laboratory, the company said. Inside the antenna is a specialized chip that tunes and demodulates signals based on ATSC 3.0, a digital television standard that provides increased data rates for high-definition television, as well as streaming services like Hulu and Netflix.

ATSC 3.0 is being developed by the Advanced Television Systems Commission in an effort to send television broadcasts like local news programs to mobile devices, set-top boxes, and laptops. The previous generation of the standard, ATSC 1.0, has been used in the United States since 2009, when digital television began to replace analog on the 6 GHz band. The new standard is currently being tested by television stations in Washington, Baltimore, and Cleveland.

The new standard not only provides better video compression and the ability to store information within television and mobile devices, but could also give broadcasters a toolkit similar to those of tech companies like Amazon and Google. ATSC 3.0 will give stations access to data that has helped Google and others provide analytics and advertising services on the web. They would be able to connect with viewers in new ways, including audience measurement, targeted advertising, enhanced programming guides, and streaming services.

LG Electronics, which makes smart televisions and set-top boxes, has invested heavily in the ATSC 3.0 standard, especially as technology companies like Amazon and Apple fight to gain footholds in television. These companies were among the supporters for the Federal Communication Commission's (FCC) recent proposal to open the market for cable set-top boxes. The agency proposed to permit cable subscribers to buy devices, like Apple TV or LG smart televisions, to view both cable programming and internet videos.

"Innovations like the LG smart network antenna will play an important role in accelerating the consumer adoption of ATSC 3.0 by enabling existing devices in the home and reducing the need for multiple converter boxes," Anne Schelle, executive director for industry group Pearl TV, said in a statement. With today's market dominated by large cable companies, people have to lease set-top boxes for cable and buy separate products to access the internet.

Companies that support ATSC 3.0 are trying to seamlessly combine broadcast and broadband services. One example of the benefits could be streaming a soccer game over broadcast with commentary in Spanish, with a separate audio stream in English being delivered via broadband. These kinds of features could become more important in the future, especially as sport leagues sign new streaming deals with social media websites like Twitter and Facebook.

ATSC 3.0 has the potential to lure more television stations into providing services that have been traditionally offered by wireless carriers. Broadcasters could transmit video to smartphones; ads to billboards; and emergency alerts to homes, cars, and other connected devices—all services that wireless carriers have been trying to make money from.

The irony is that the physical layer of the standard is based on the OFDM technology used by wireless carriers as the basis of 4G wireless networks. "There is significant commonality between delivery via broadcast and delivery via broadband," the Advanced Television Systems Commission wrote in a blog post.

LG's network antenna shows the progress behind the ATSC 3.0 standard, but the technology is not expected to appear until at least 2018. South Korea and China have considered using the standard for broadcasts in the next few years. In the United States, many television stations and broadcasters are waiting until the FCC's spectrum auction is finished to start thinking about the standard in more depth. ■

NEW ROUTER GIVES Access to Troublesome Wi-Fi Spectrum

FROM TWO YOUNG ENGINEERS forming Intel nearly 50 years ago, to software programmers at Facebook leaving to build a question-and-answer website, the story of Silicon Valley is largely the story of engineers leaving large corporations to strike it out on their own. One group of engineers was following that script when they departed Qualcomm Aetheros to build a better Wi-Fi router.

The router is known as Portal, and the secret to its unique design is an area of wireless spectrum in the 5 GHz range seldom used by other routers. While most routers only access one or two channels in that frequency band, the router grants access to six different channels, helping devices to avoid crowded Wi-Fi by jumping between channels. More channels means that individual devices have more bandwidth to play around with.

(Image courtesy of Ignition Design Labs)

"Our engineers created Portal to fundamentally redefine the consumer Wi-Fi experience," says Terry Ngo, chief executive of Ignition Design Labs, the company behind Portal. "We give you three times more spectrum for faster video downloads, elimination of buffering issues, and an improved overall internet experience."

Ignition Design Labs built its new router under the notion that most other routers fail to address the main problem with Wi-Fi. Billions of devices compete for limited spectrum, especially in cities and apartment buildings, and all that competition causes traffic jams that slow down Wi-Fi. That problem is heightened by the fact that people are using Wi-Fi for applications that consume huge amounts of data, like streaming video and playing video games.

That is one of the reasons that the 5 GHz spectrum has slowly become prime real estate for wireless technologies. Devices like Google's OnHub router are breaking ground in the spectrum to avoid overcrowding in the 2.4 GHz band. Qualcomm and other chipmakers are increasingly using the spectrum to offload cellular data with LTE in the unlicensed spectrum (LTE-U) and Licensed Assisted Access.

Ignition Design Labs was only given regulatory access to the rest of the 5 GHz spectrum—which was originally reserved for weather radar systems—with some caveats. The company had to ensure that wireless signals on the unused lanes would not interfere with radar signals. Normally, devices must use dynamic frequency selection to sidestep radar in these channels, which account for roughly 65% of the entire 5 GHz spectrum in North America, and around 80% in Europe and Japan. But that technology is complex and expensive, and so has been largely ignored by Wi-Fi equipment companies.

Ignition Design Labs, however, did not shy away from that spectrum. Portal contains algorithms that detect and track the channels being used by radar signals, steering Wi-Fi signals around them. That same technology also diverts Wi-Fi onto different channels if certain ones get too crowded. Portal can also optimize your Wi-Fi networks by analyzing data on the cloud. The router can track Wi-Fi networks in your neighborhood to figure out which channels have the most bandwidth for your devices. It can even switch channels based on what time of day certain parts of the spectrum are most crowded.

In one demonstration, Portal clocked around 45 Mbits/s download speeds in an Apple iPad located 33 ft. away from the router. In comparison, a Netgear Nighthawk router showed download speeds of 5 Mbits/s on the same device in the same location. In a video of the demonstration, the company showed that Portal was able to start streaming ultraHD video faster than the Netgear router could even buffer a regular high-definition video.

Portal contains nine advanced antennas. Four of these are wideband 5 GHz antennas that support Multi-user Multi-Input Multi-Output (MU-MIMO), which allows the router to send data to multiple devices simultaneously using a separate stream for each as though each device had a personal router. Three 2.4 GHz antennas allow devices to run on both Wi-Fi frequencies simultaneously. For larger homes, owners can link together two or more Portals for longer range.

Ignition Design Labs revealed its first prototype at the Consumer Electronics Show earlier this year, and now the company is funding the first production run of Portal through Kickstarter. The campaign reached its goal of $160,000 within two days, while over 1,685 backers have pledged almost $280,000 to the project. There are 53 days remaining in the campaign. ■

INTRODUCING THE SOLID-STATE RF Cooking …Thermos?


(Image courtesy of Wayv Technologies)

FOR A LONG TIME, cooking meals with solid-state radio waves seemed little more than a parlor trick to display new wireless power amplifiers. That was until Freescale built a concept oven and offered to license the radio emitters inside to appliance makers—just like it would with wireless chips and processors.

One of the first companies to employ solid-state technology, the startup Wayv Technologies, revealed a new portable oven at the NXP FTF Technology Forum in Austin, Texas. About the size of a thermos, the battery-powered oven directs energy into food more accurately than microwave ovens, the company says.

Known as the Wayv Adventurer, the oven is packed with high-voltage transistors that beam energy directly into the food. That cooks it faster and more evenly than conventional microwaves, which simply fill their cavities with heat. These transistors are the same technology that power RF amplifiers in wireless equipment, sending data signals into smartphones and other mobile devices.

Wayv Technologies has billed the oven—its first product—as an alternative to portable gas stoves for campers and fisherman. It was originally designed for soldiers to cook fast meals at military

> "The Wayv Adventurer oven is packed with high-voltage transistors that beam energy directly into the food."

bases or in the field, but the company has also suggested using it at the office.

The solid-state RF beams are produced by high-voltage laterally diffused metal oxide semiconductor (LDMOS) transistors from NXP Semiconductors. The transistors are contained in a module that delivers 250 watts of power. Wayv contributed an RF antenna to the design that helps deliver high cavity efficiency, quickly transferring energy into the food.

That efficiency is the secret to solid-state RF cooking, and it was one of the most striking aspects of Freescale's concept oven, Sage. The cavity magnetron inside a normal microwave has a supply voltage of around 4,000 volts, while transistors within Sage were vastly more efficient, using between 28 to 50V for cooking meals. That increased energy efficiency translates into a longer device lifespan for Sage, which in turn translates into longer battery life for Wayv.

Part of that efficiency was Sage's ability to control the location, cycles, and levels of cooking within the appliance. In contrast, conventional microwave ovens simply flood the appliance with heat, which removes moisture from the food and results in uneven cooking. In the Adventurer, the transistors provide "maximum power transfer with controllable energy to the food with less wasted heat," Wayv said in a statement. ■

NEW SOFTWARE Targets Phased-Array Antennas with Beamforming

Armed with new software from Keysight Technologies, engineers will have the ability to test antenna arrays that employ algorithms to shoot wireless signals in specific directions. Keysight will include the new tool in the latest version of its popular SystemVue design software for wireless components, which is scheduled for release later this year.

The software is designed for phased-array antennas, in which the phase of the antenna can be calibrated to send signals in one direction and suppress signals in other directions. Though these antenna arrays can be pointed in one direction permanently, other kinds of phased-array antennas can steer narrow beams of radiation using specialized algorithms. This approach is known as beamforming.

Facebook's Terragraph phased-array antennas. *(Image courtesy of Facebook)*

In response to sharp increases in the amount of cellular data that the average person consumes, wireless carriers are turning to phased array antennas with beamforming to make their wireless equipment more efficient. Pointing signals directly at mobile phones and other

handheld devices, wireless carriers have been able to increase the overall capacity of their networks.

Several internet companies trying to muscle into wireless service have started using phased-array antennas. Facebook, which has plans to expand wireless access in cities and the developing world, built its millimeter-wave Terragraph system around phased-array antennas. The company's engineers have said that beamforming helps to steer the millimeter wave around walls and buildings and protect signals from being absorbed into the atmosphere.

Keysight's Phased Array Beamforming Kit helps engineers working on these systems to model interference and power consumption. Using the software, engineers can model parallel wireless architectures, testing single beams or tracking individual signals passing through phased arrays. It can also be used to validate 3D conformal arrays using active signaling between multiple transmitters and receivers.

The ability to model antenna behavior on the system level can be helpful for engineers dealing with the huge amount of antenna elements in phased arrays. One type of phased-array antenna known as active electronically scanned arrays can contain from 16 to 256 elements in experimental 5G systems. That number grows to hundreds of elements in satellite systems, and thousands of individual baseband and RF signal paths in military systems.

"Organizations delivering products with phased-array subsystems typically use five to 10 different, unconnected design tools, not counting spreadsheets," says Daren McClearnon, system-level marketing manager with Keysight's Electronic Design Automation division.

The toolkit combines algorithmic research and application references for communications and radar, allowing users to "cross-validate both the RF and baseband from proposal to test, using a common framework." SystemVue 2016.08, the simulation software that will support the phased array toolkit, is expected to be released later this year.

Keysight is also building new software tools for technologies related to beamforming, such as multiple-input, multiple-output (MIMO), which segments the narrow signal beam into multiple strands. Not long before it revealed the new phased-array software, Keysight said that it would partner with the China Mobile Research Institute on testing Massive MIMO systems. The work will focus on developing channel measurement and modeling tools. To that end, the companies will test CMRI's Massive MIMO antenna array to generate channel models. ■

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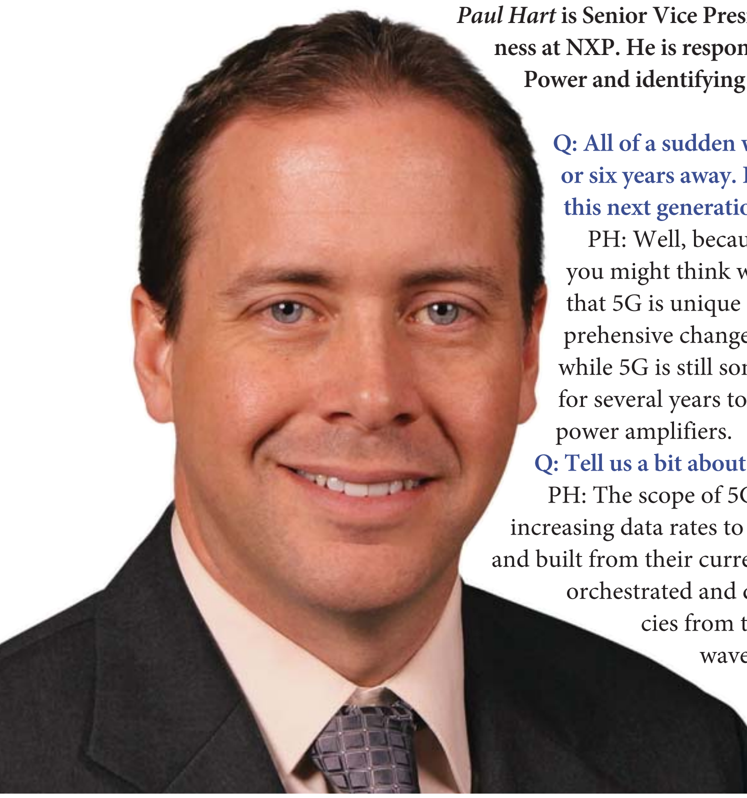
Inside TRACK with Paul Hart, *Senior Vice President and General Manager RF Power Business, NXP Semiconductors*

Interview by MICROWAVES & RF



Paul Hart **is Senior Vice President and General Manager of the Radio Frequency business at NXP. He is responsible for maximizing NXP's leadership position in RF Power and identifying new market opportunities to drive growth.**

Q: All of a sudden we're hearing a lot about 5G, even though it's probably five or six years away. Is NXP already concentrating on meeting the demands of this next generation of wireless?

PH: Well, because 5G standards aren't likely to become formal until 2019, you might think we have lots of time, which is far from reality. The reason is that 5G is unique in comparison to its predecessors, as it's the most comprehensive change in wireless communication since cellular's inception. So while 5G is still some way off in terms of deployment, we have been working for several years to address its immense challenges for RF power devices and power amplifiers.

Q: Tell us a bit about why this is the case.

PH: The scope of 5G is truly immense and incredibly ambitious. In addition to increasing data rates to at least 1 Gb/s, it changes the way networks are designed and built from their current focus on hardware to software-defined and virtually orchestrated and dynamically controlled. It also expands operating frequencies from their current limit of about 3 GHz through the millimeter-wave region up to 60 GHz, and requires signal bandwidths of hundreds of megahertz.

Also, 5G effectively aggregates all of the wireless standards competing for supremacy in the IoT arena, providing an umbrella of sorts based on cellular communications. Hopefully, this will fully address the needs of machine-to-machine (M2M) communications—IoT—that will finally allow it to achieve its full potential.

"5G effectively aggregates all of the wireless standards competing for supremacy in the IoT arena, providing an umbrella of sorts based on cellular communications."

And last, but surely not least, is the need to decrease round-trip latency from its current 50 ms or so in 4G to 1 ms or less, which basically pits it against the laws of physics. But such performance will be essential in order to enable autonomous vehicles, next-generation robotics, high-end gaming, augmented and virtual reality, telesurgery, and other applications requiring near-instantaneous response times. Any one of these changes alone would put 5G in a class by itself. Collectively, they're essentially a wholesale revision of wireless communications in general.

Q: Can you provide some details as they relate to RF power and RF in general?

PH: Every succeeding wireless generation has placed greater and greater demands on designers of RF power devices and amplifiers, and 5G takes this to a whole new level. Take signal bandwidth. Expectations are 5G will have theoretical maximum download data rates of at least 1 Gb/s, which requires a huge increase in signal bandwidth, potentially as high as 400 MHz. This cannot be achieved without advances from the die level through packaging and amplifier architecture, while simultaneously increasing efficiency and other metrics.

Higher frequencies—especially 60 GHz—have characteristics that make them useful only over short distances. They also are limited in terms of RF power levels, will require lots of new infrastructure, and demand truly massive MIMO in order to achieve very low latencies. It will be absolutely essential to reduce the size, weight, power consumption, and cost of small cells through increasingly high levels of integration.

Q: Since the new company was formed, has the integration of Freescale's RF and microwave products within NXP been fairly smooth?

PH: Yes it has, especially considering the breadth of the two companies' product lines. The reason is that the technologies represented are largely complementary. For example, the RF Power business, for which I'm responsible, targets applications requiring higher power levels than those required in battery-powered devices. Our technologies in the RF Power business are LDMOS transistors and RFICs and GaN transistors. However, other business lines focused on applications like millimeter-wave vehicle radar that rely on SiGe. So there's a pretty clear delineation between technologies and the applications they serve.

Q: Will NXP continue to pursue the defense sector?

PH: Since we first entered the defense marketplace in 2013, our products have been enthusiastically received by prime and subprime contractors—especially in the areas of L-band radar and IFF with our LDMOS and GaN transistors. We've just expanded our LDMOS line for defense, including an RF power transistor for L-band applications that delivers very high output. We've also introduced new GaN devices.

"We've just expanded our LDMOS line for defense, including an RF power transistor for L-band applications that delivers very high output. We've also introduced new GaN devices."

Q: After using vacuum tubes for decades, the industrial market finally seems to be embracing solid-state devices. Is this a significant sector for NXP?

A: Absolutely. There are a remarkable number of applications in which RF is used for heating, welding, sealing, etching, lighting, lasers, and, of course, in MRI and other medical equipment. LDMOS in particular offers many advantages when compared to magnetrons and other "legacy" devices as well as bipolars and MOSFETs, so we're actively involved in helping manufacturers make the transition from older technologies to LDMOS.

Q: Land-mobile and public-safety communications has been a mainstay at Freescale for decades. I assume this will continue to be a primary focus now at NXP?

A: The land-mobile radio market is one of the most important to us, as it was for Freescale and for Motorola before that. This sector is undergoing considerable changes so we're ensuring that OEMs have the devices they need to accommodate them.

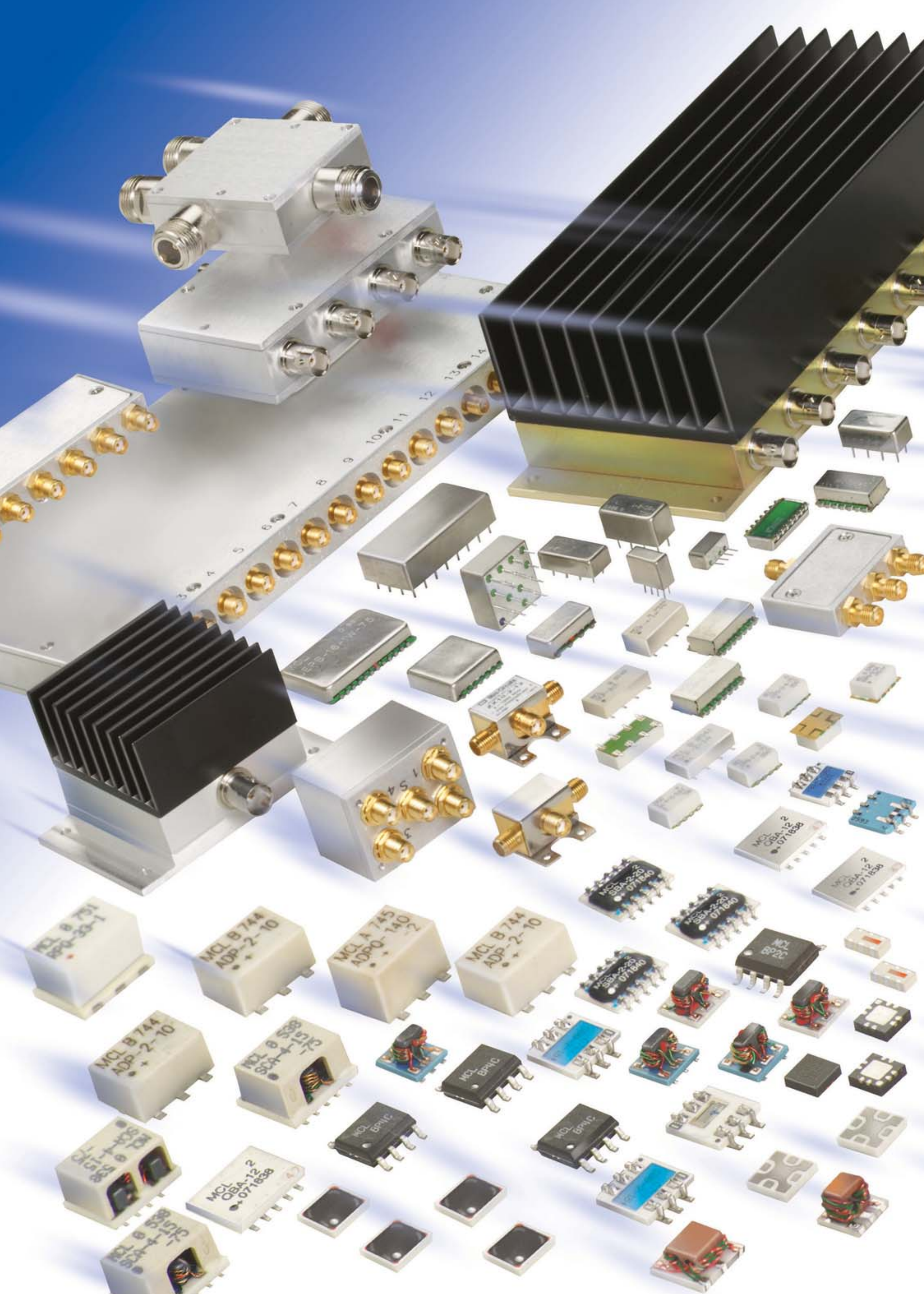
Q: I saved RF cooking for last, because it's so much different than your traditional markets, and potentially lucrative as well.

PH: The real story here is not just transitioning from magnetrons to solid-state devices for the generation of RF power, but creating an entirely new appliance with capabilities that no other cooking technology can achieve. At the same time, it takes people out of the control loop in the cooking process.

For example, the infinitely variable output power of LDMOS RF power transistors along with beamforming and other techniques allow nutrients and moisture content to be much better preserved. Because the entire cooking process is performed autonomously, you will no longer need to periodically peek into the oven to make sure the food is being properly cooked. It also offers the possibility of cooking different types of food at the same time.

Q: What are the challenges in developing this market?

PH: Building a microwave oven is well understood by appliance manufacturers, but creating a solid-state RF cooking appliance is not. So our goal is to provide the tools that allow them to speed this type of product to market. For companies with RF expertise, we can provide the LDMOS RF power transistors, reference designs, and other tools. For others, we can provide a cooking module that includes the RF power source and its power supply, as well as computational and signal-processing hardware in addition to control software. mw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LOG-PERIODIC MONOPOLE ARRAY SPANS 1.5 TO 6.8 GHz

COMMUNICATIONS FOR AIRCRAFT and ground vehicles require low-profile antennas capable of relatively broad bandwidths. To fill this need, researchers from various institutions in China developed a low-profile, log-periodic monopole array with end-fire radiation and vertical polarization. Using conductor-backed coplanar stripline feed and a broadband transition from coaxial cable to the stripline to facilitate measurements, the antenna array achieves a wide impedance bandwidth of 1.5 to 6.8 GHz for a VSWR of less than 2.30:1. The antenna array also provides more than 4.5 dBi gain over that same wide bandwidth. In spite of the outstanding performance, the design has a low profile equal to only 0.047 λ_L (the free-space wavelength at the lowest operating frequency).

The antenna consists of 15 monopoles of different sizes/resonant frequencies printed on the top layer of a conductor-backed printed-circuit-board (PCB) substrate. The monopoles have the same height and are mounted in a straight line for a nearly symmetric radiation pattern in the end-fire direction. The monopole top hats feature an elliptical shape to avoid overlaps in radiation patterns of adjacent monopoles at lower frequencies. In addition, the coplanar stripline is bent slightly to alternately feed the monopoles and achieve a phase difference of 180 deg. between adjacent monopoles across the slot in the stripline. A pair of lumped-element resistors are included to absorb the residual power at the end of the coplanar stripline. The antenna design was simulated using High Frequency Structure Simulator (HFSS) commercial electromagnetic (EM) simulation software from ANSYS (www.ansys.com).

A prototype antenna array was fabricated on a low-dielectric-constant ($\varepsilon_r = 2.2$) PCB substrate material and characterized with commercial test equipment. Only slight differences were found between measurements and simulations, which the authors attributed possibly to fabrication and assembly errors. The low profile, wide bandwidth, and planar structure of the antenna make it an attractive candidate for vehicular and airborne communications systems.

See "Low-Profile Log Periodic Monopole Array," *IEEE Transactions on Antennas & Propagation*, Vol. 63, No. 12 December 2015, p. 5484.

MODELING THE WAY TO A BETTER ANECHOIC CHAMBER

ANECHOIC CHAMBERS ARE useful test environments for many RF/microwave systems designs, including radar, for their absence of ambient radio waves. They are constructed with different dimensions and using radar-absorbing materials (RAMs) to reduce the levels of reflected RF/microwave energy within the chamber. A challenge in constructing such chambers is in optimizing performance with different RAMs and room sizes and configurations. For that purpose, researchers from various institutions in China applied geometric optics (GO) to the design and optimization of anechoic chambers in a number of different configurations. They validated their simulation solutions by comparison with several actual semi-anechoic chambers to compared simulations with measurements, with fairly close agreement.

One goal established by the researchers was to develop an effective system-level computer-aided-design tool to describe the characteristics of the RAM without losing accuracy or efficiency. The far-field pattern of the test antenna is used as an excitation source rather than a three-dimensional (3D) model of the antenna as typical in full-wave simulations. In GO analysis, the electric (E) field is assumed to propagate in an anechoic chamber much like light, and the researchers developed forward and inverse algorithms to model electromagnetic (EM) propagation in the anechoic chamber as if it were emanating from an optical source. Algorithms were developed with the aid of MATLAB mathematical simulation software from The MathWorks (www.mathworks.com) and the chamber was modeled by means of ASCII stereo lithography (STL) file.

Modeling involved determining the forward propagation paths in all directions from an antenna source using the forward algorithm, and then back tracking the reverse paths by means of the inverse algorithm. To validate the models, several semi-anechoic chambers were used for measurements, including a compact chamber measuring 22.0 × 13.5 × 8.0 m. This chamber contained half-wave dipole antennas for receive and transmit functions, both at a height of 2 m. Different types of RAM were used and each type of RAM was characterized and the complex reflection coefficients for different angles were determined. The work led to a systematic solution for the analysis and design of, hopefully, a better anechoic chamber.

See "Building a Better Anechoic Chamber: A Geometric Optics-Based Systematic Solution, Simulated and Verified," *IEEE Antennas & Propagation Magazine*, Vol. 58, No. 2 April 2016, p. 94.

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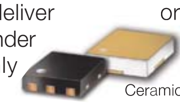

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CHRIS DeMARTINO | Technology Editor

Passive Components Punch Through Walls

Designers bank on passive components to help deliver the performance needed to satisfy ever-tougher demands.

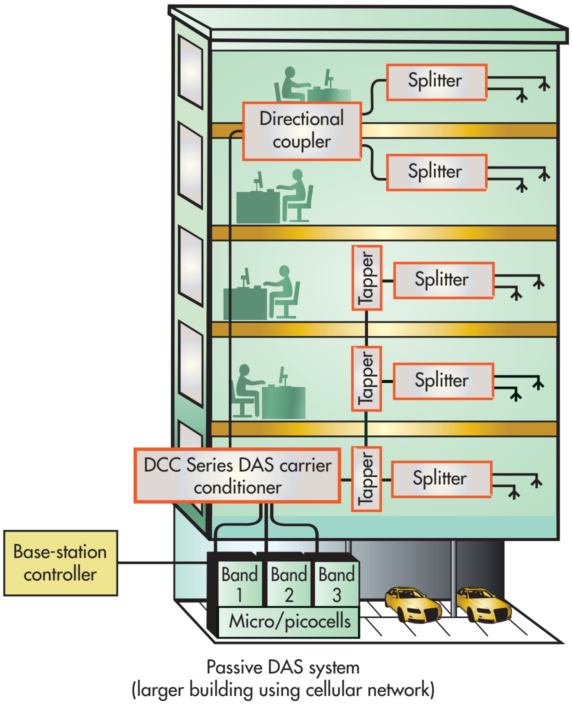
High-frequency passive components may lack the glamour of their active counterparts, but they play crucial roles when trying to meet system performance requirements. Such components, which include power dividers/combiners, directional couplers, hybrid couplers, and more, are needed to enable critical functionality for numerous applications. A distributed antenna system (DAS), for instance, relies heavily on high-performance passive components.

In addition, some suppliers offer passive components with superior power-handling capability to support high-power applications. This article takes a look at some of these passive-component solutions designed to meet the growing array of demanding requirements.

DISTRIBUTED ANTENNA SYSTEMS

A DAS uses a network of antennas connected to a common location to provide wireless coverage to a specific area *(Fig. 1)*. As a result, wireless coverage and capacity can be enhanced in areas that need a boost in service. A DAS can be deployed indoors or outdoors; settings include office buildings, convention centers, subways, airports, sports arenas, etc.

Passive components are an extremely important aspect of a DAS. For instance, power dividers and directional couplers allow signals to be distributed as required by the DAS. Because such an antenna system may incorporate numerous passive components in its architecture, it's important they provide adequate performance to satisfy the demands of the entire system.



1. Implementation of a DAS will ultimately improve wireless coverage. ***(Courtesy of Microlab)***

Passive intermodulation (PIM) can occur due to the nonlinear mixing of two or more frequencies in a passive component, such as a cable, connector, or power divider. Causes of PIM range from ferromagnetic materials and corrosion to loose connections.

PIM can degrade the performance and reliability of a DAS. Specifically, unwanted intermodulation products generated by multiple signals in the downlink may appear in the uplink, thereby reducing quality of service. Thus, to help ensure reliable DAS performance, its passive components must have superior PIM characteristics.

One company focused on DAS applications is Radio Frequency Systems (RFS; www.rfsworld.com). "Growing demand for reliable wireless communications wherever people go, at all times, is driving network improvements to provide connectivity in even the most challenging environments," says Eileen Januszkiewicz, commercial product manager of cables at RFS.

"These environments include stadiums, airports, metro transportation systems, and hotels," she continues. "The world will be watching the upcoming Summer Olympics, which will require unprecedented coverage capacity for millions of athletes, vendors, event managers, and spectators."

Januszkiewicz adds, "Meeting communication needs in such venues requires cutting-edge infrastructure solutions. Passive DAS systems and components provide the flexibility for multi-band, multi-technology, multi-operator support. A single passive DAS solution can be shared by several operators delivering different wireless services using different technologies and frequency bands, including mission-critical (380-520 MHz), commercial wireless (698-2,700 MHz), and broadband and ultra-broadband (380-2,700 MHz) in 2G, 3G, 4G LTE, and TETRA."

RFS has already delivered several DAS solutions, including its deployment of a passive DAS for the 2014 FIFA World Cup. Januszkiewicz explains, "RFS deployed a passive DAS solution that enabled wireless connectivity at four stadiums for the 2014 FIFA World Cup in Rio de Janeiro. The sophisticated, multi-operator solution used a new RF sectoring concept for each network, delivering a considerable increase in capacity when processing calls and ensuring 2G, 3G, 4G (LTE), and iDEN wireless communications throughout the venue for customers of five Brazilian operators. The networks were built with state-of-the-art indoor wireless infrastructure, including RF corrugated coaxial cables, RFS's HYBRIFLEX hybrid cable, indoor and outdoor antennas, jumpers, and accessories."

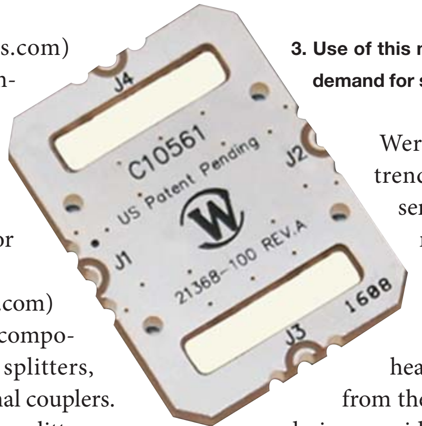
Earlier this year, the company unveiled a range of new passive RF components for DAS applications *(Fig. 2)*. These products are intended to satisfy wireless in-building commercial and mission-critical communications requirements.

"RFS recently expanded its product portfolio of passive components," says Januszkiewicz. "These components include couplers, power splitters, tappers, and hybrid combiners, complementing our comprehensive line of low-loss RF feeder cables and jumpers for DAS to help customers deploy future-proof solutions. All our passive DAS products share harmonized PIM specifications (–161 dBc) to maintain a high level of repeatability and reliability of services."

Many other companies offer passive components for DAS applications. Among them is Microlab (part of the Wireless Telecom Group; www.microlab.fxr.com), which offers a variety of passive components such as tappers, power splitters, and directional couplers.

2. These components, which include couplers, tappers, power splitters, and hybrid combiners, are intended for DAS applications. ***(Courtesy of Radio Frequency Systems)***

R&D Microwaves (www.rdmicrowaves.com) maintains its own line of DAS passive components. Covering a frequency range of 380 to 2,700 MHz, these products include tappers, hybrids, and combiners/dividers. In addition, the company offers these components with different connector options, such as Type-N and 7/16 DIN.



3. Use of this new dual directional coupler helps satisfy the demand for smaller PAs. *(Courtesy of Werlatone)*

For its part, Werlatone (www.werlatone.com) supplies a range of DAS-targeted passive components, which includes even and uneven splitters, unidirectional couplers, and dual directional couplers. All ports of non-isolated even and uneven splitters can communicate with one another. These components allow users to split a single run of a 50-Ω coaxial cable that simultaneously carries multiple service bands. By utilizing non-isolated even power splitters, one signal is able to be evenly split into two, three, or four signals, which can then enter corridors, tunnels, shafts, or rooms. Uneven splitters can be utilized to unevenly split a signal so that a shorter corridor, tunnel, shaft, or hallway is provided with a smaller portion of the power on the main coaxial run.

Also sparking interest is Westell (www.westell.com), which offers a line of standard passive components as well as its ClearLink PIM-rated passive components. Standard passive components include power dividers, directional couplers, and cross-band couplers. The ClearLink lineup features power dividers, directional couplers, hybrid couplers, and power tappers.

Not to be outdone, Innowave RF (www.innowaverf.com) supports DAS applications with products such as low-PIM power combiners/dividers. The company offers 2-, 3-, and 4-way power combiners/dividers, each covering a frequency range of 698 to 2,700 MHz. These components achieve a PIM of –153 dBc when measured with two 20-W output tones.

4. This drop-in hybrid coupler covers a frequency range of 20 to 1,000 MHz. *(Courtesy of Innovative Power Products)*

HIGH-POWER PASSIVES

Suppliers of power-amplifier (PA) modules are feeling the pressure to deliver efficient PAs in smaller sizes. Utilizing smaller surface-mount passive components inside these PA modules can help accomplish that task. To demonstrate this, Werlatone developed a new dual directional coupler in response to the need for smaller PAs *(Fig. 3)*.

"We have identified several market trends targeting smaller, more robust, and more efficient high-power RF amplifier modules," says Glenn Werlau, president of Werlatone. "One transformation that is currently ongoing is the use of smaller surface-mount directional couplers within the modules, rather than larger connectorized devices."

Werlau adds, "As a response to this market trend, we have introduced the first in a new series of surface-mount, 20- to 1,000-MHz, mismatch-tolerant, dual directional couplers, conservatively rated at 250 W continuous-wave (CW). Our new design offers enhanced insertion loss, with less heat dissipation, resulting in a lower demand from the system power supply. Additionally, this design provides near-perfect main-line voltage standing wave ratio (VSWR) and a coupled port VSWR of less than 1.2:1, assuring near-optimum flatness. The first product is a 50-dB coupler. Further releases will be available with coupling values of 30 and 40 dB."

Innovative Power Products (www.innovativepp.com) also specializes in high-power passive components. The company's products include power dividers, directional couplers, hybrid couplers, and others. One of its newer products is the IPP-2315, a drop-in hybrid coupler that covers a frequency range of 20 to 1000 MHz *(Fig. 4)*. This model has a maximum insertion loss of 0.8 dB along with a maximum VSWR of 1.35:1. Furthermore, the IPP-2315, which can handle as much as 50 W of CW power, maintains an amplitude balance of less than ±0.30 dB across the entire band.

TRM Microwave's (www.trmmicrowave.com) line of high-power passive components achieves power-handling capability into the kilowatt range. Components include directional couplers, power combiners/dividers, and hybrid couplers. The company builds its range of products to satisfy a number of commercial and military requirements, such as those for combat radar systems, military radio communications, weather radar, RF jamming and countermeasures, aviation communications, and medical imaging and radiology.

No doubt, passive-component performance is a critical "component" in satisfying higher-level requirements. DAS applications represent one example, with suppliers having to adhere to stringent PIM requirements. And PA modules can benefit greatly from using high-performance passive components in small surface-mount packages. These are just two examples, but passive components take on great importance in a host of other applications, too. All that said, it is incumbent on passive-component suppliers to deliver products that can meet the increasingly demanding requirements of today's wireless world. mw

JACK BROWNE | Technical Contributor

Preventing PIM in Microwave Systems

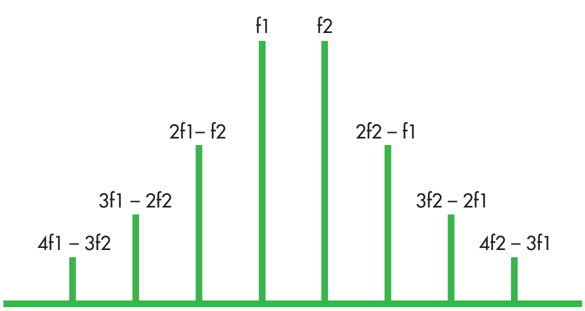
Passive intermodulation stems from a poor mix of components and materials in a transmitter, when resulting signal products fall within the operating bandwidth of a receiver sensitive enough to detect them.

MULTICARRIER COMMUNICATIONS SYSTEMS have become commonplace, squeezing more and more signals into increasingly limited frequency bands. Having transmitters and receivers loosely spaced in frequency is never easy, especially when intermodulation distortion from one more or transmitters can cause interference that degrades the performance of a receiver. Signals sharing the same transmission path can mix together, causing intermodulation not only in active devices and components, but in passive components as well.

Passive intermodulation (PIM) can originate from almost any passive component, including antennas, cables, connectors, and power dividers. Knowing how and why it starts can help to stop it, or at least minimize PIM to acceptable levels below a receiver's sensitivity.

PIM is caused by the nonlinear behavior of different materials and how they are assembled to form passive components. Levels of distortion become more significant at higher power levels because of their increased current densities. Components with high ferromagnetic material content (such as iron, nickel, and steel) are particularly susceptible to PIM, exhibiting nonlinear voltage/current relationships.

That being said, even low-PIM materials are subject to PIM; this can occur whenever the RF/microwave transmission path through them is not clean and clear. Any poor mechanical junction in a transmission path, such as gaps in conductors or loose connectors, can cause PIM. In addition, surface defects on transmission paths, like rust or oxidation, can also be a starting point for PIM.



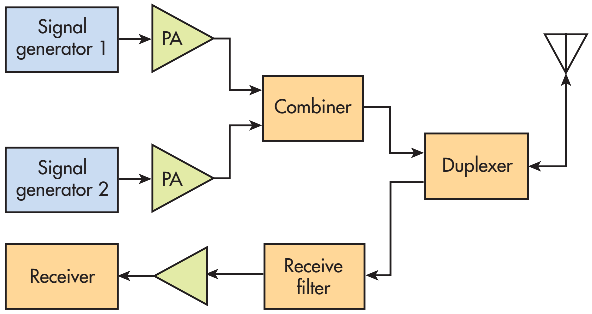
1. PIM is produced by the mixing of two signals and their harmonics as they share a transmission path, commonly the case in wireless base stations.

PIM is a concern when it falls within the frequency range of a receiver with sufficient sensitivity to detect it. As newer wireless carriers attempt to provide more customers with more service over limited bandwidths, they employ base stations in which transmitters and receivers are diplexed, or where two or more transmit frequencies may share the same antenna. Both cases are invitations to PIM, especially for poorly fitted or matched components and dirty or corroded transmission paths (e.g., poor connections to the antenna).

At higher power levels, such as those used by cellular base-station transmitters, PIM can reach levels that are above the sensitivity of a nearby receiver—a cellular handset, for instance—and can block the reception of desired signals carrying voice, data, or video information. Fourth-generation (4G) cellular communications networks using frequency-division-duplex (FDD) techniques require high levels of signal fidelity and can suffer performance degradation, with loss of audio quality on cell phones and diminishing of data rates as a result of excessive levels of PIM.

Carrier signals and their harmonics mix to generate PIM generation, with distortion levels diminishing as the order of the mixing products increases. While third-, fifth-, and seventh-order intermodulation products from a given transmitter may fall in the operating frequency range of a nearby receiver, usually the third- and fifth-order products are the only ones at power levels sufficient to exceed the sensitivity of a receiver.

Of course, with the growing number of wireless devices and frequency bands commonly in



2. This block diagram provides an example of a reflective test setup for measuring PIM. *(Courtesy of Anritsu Co.)*

use, PIM from the transmitter(s) of one wireless application may also fall within the receive range of another wireless application. Therefore, it can be useful to at least know where several orders of PIM products may fall, so as to determine whether they can cause interference for other wireless receivers in range.

The two main intermodulation products of concern are third- and fifth-order intermodulation, which for two frequencies (f1 and f2) are produced by the mixing of fundamentals and harmonics *(Fig. 1)*:

Third-order intermodulation: 2f1 – f2
Fifth-order intermodulation: 3f1 – 2f2

These mixing products are of concern when they fall within a receiver's passband. For example, for a transmitter broadcasting tones at 870 and 890 MHz, the third-order intermodulation is 2(870) – 890 = 850 MHz, while the fifth-order intermodulation is 3(870) – 2(890) = 830 MHz. Intermodulation is also produced by the sum of the carriers and different harmonics, but this distortion will occur at much higher frequencies—usually out of the range of an applicable receiver.

While using components designed for low-PIM performance is advisable in systems with receivers and transmitters closely spaced in frequency, PIM is not always predictable; its behavior can change over time and operating conditions, such as temperature. Low PIM levels may be validated when commissioning a cell site or base station, but those levels can worsen over time as mechanical junctions in the transmission path deteriorate. Keeping any transmission junctions free of dirt, rust, oxidation, or corrosion is essential to maintaining low long-term PIM performance, and testing for PIM can confirm that suitable performance levels are being maintained.

Even printed-circuit boards (PCBs) are subject to PIM, such as in printed antennas for wireless communications devices and systems, depending on their composition and the types and layouts of transmission lines fabricated on them. Various PCB material manufacturers offer low-PIM grades of their materials, fabricated with materials less likely to give rise to PIM at higher power levels.

Measuring PIM levels has grown easier in recent years due to the growing number of portable battery-powered high-frequency spectrum analyzers that can be used for on-site testing, as well as several dedicated PIM testers from various suppliers. When testing is performed with a spectrum analyzer—rather than an all-in-one tester—two signal generators or an arbitrary waveform generator capable of providing two independent test signals will be needed to simulate two signals, giving rise to intermodulation products. In addition, a pair of amplifiers will likely be needed to boost the test signals to levels comparable to those produced within the transmitter's transmission path.

PIM levels are usually gauged by means of reflective testing. For example, two signals are injected into a device under test (DUT) or into a transmission path, such as one leading to an antenna, and the levels of PIM are analyzed from the reflected signals at the input port of the DUT or transmission path *(Fig. 2)*. Cables are usually part of the test setup, but they can also be part of the PIM problem. Coaxial cables may be the source of PIM in a high-frequency transmitter, but they may also be used to test for PIM in the same transmitter.

Such cables should be manufactured with the appropriate materials and properly tested for low-PIM performance, lest they contribute to the signals under test. A number of suppliers offer low-PIM cables for such test purposes, with some also providing free-of-charge application notes on the use of their cables for PIM measurements.

The electrical length of a test cable can also affect the accuracy of a reflective PIM test, especially when the test is conducted with two fixed-frequency carriers (f1 and f2). Changing the frequencies of the two carriers and repeating the measurements can provide insight into the amount of signal addition and/or cancellation that might be taking place in the test cables to degrade the accuracy of the PIM measurements, and resulting in erroneous detected PIM levels.

For best results in a communications or test system, cable connectors should be connected with torque values as recommended by the cable assembly's manufacturer. This will ensure a reliable transmission path without loose fittings and air gaps that can cause arcing at higher power levels, resulting in high PIM levels. When cleaning connector interfaces, whether for testing or maintaining communications systems performance, isopropyl alcohol has long been shown to be a reliable cleaning agent.

While evaluating components for PIM performance, make sure that fair comparisons are being made. Different datasheets present PIM in units of dBc or dBm. It is typically easier to compare the levels for different components using dBm, which is relative to the power level at 1 mW (0 dBm) compared to dBc, which is in turn relative to the carrier level. The use of dBc is fine when different components are characterized in similar ways, but difficult if comparing components that were tested for PIM at different carrier levels.

JACK BROWNE | Contributing Editor

Power Demands Put the Pressure on Packaging

Higher power densities and frequencies are pushing packages to their limits, while emerging wireless applications such as IoT and 5G seek lower-cost housings.

MICROWAVE PACKAGING COVERS a lot of ground (and relies on a reliable ground plane), and includes many configurations and material compositions. Such packages range from microscopic to cabinet-sized for system assemblies. Whatever the size or type, all are designed to protect the electronic devices, components, and circuits within them. Depending on the materials and construction, they may be rated for different levels of temperature, humidity, vibration, shock, and input power.

Increased integration has been an ongoing goal for RF/microwave-package developers to support the mass adoption of high-frequency technology in products like cellular phones and wireless local-area networks (WLANs). It is safe to say that wireless technology brought high-frequency packaging into a more integrated realm. That should continue as RF, microwave, and even millimeter-wave technologies merge with the internet via the fifth generation (5G) of wireless networks and applications such as wearables and Internet of Things (IoT) devices. These applications should increase the use of system-in-package (SiP) and system-on-chip (SoC) devices in order to integrate radio and control circuitry within one compact housing.

SoC and SiP devices have different package configurations, such as 2D and 3D. In the former, semiconductor devices are placed horizontally while in the latter, to save space, devices are mounted and stacked vertically, typically on the layers of a multilayer printed-circuit board (PCB). Devices within a SiP are usually interconnected by flip-chip or wire-bond approaches.

Multichip modules (MCMs) follow a similar integration approach as SiPs and SoCs, with multiple discrete devices or ICs contained within a single package. One difference between an MCM and SiP, however, is that an MCM provides package pin connections for the different devices contained within, rather than the system-level control of an SiP or SoC. This makes it possible to provide biasing for individual components, such as a discrete power transistor or an active mixer.

These higher levels of packaged integration are driven by requirements for smaller size and less power consumption *(Figs. 1 and 2)*. While SoCs, SiPs, and MCMs support miniaturization, a price is paid for that small size: Integrating multiple active and passive components within a single package tends to reduce production yields, since any one defective component in the module will cause the entire module to fail.

1. High-power packages have traditionally relied on large flanges for thermal dissipation.

TOUGH PACKAGING TASKS

Perhaps one of the more difficult RF/microwave devices to package is the high-power discrete transistor or high-power monolithic-microwave-integrated-circuit (MMIC) amplifier. Though physically small, it is a large source of heat. In addition to providing an effective thermal path from the active device to outside circuitry or a heat sink, the packaging materials must also offer low-loss transmission paths for input and output signals and, in some cases, operate effectively with high voltages.

With the increasingly widespread use of high-power-density devices such as gallium-nitride (GaN) transistors, thermal management in packaging is becoming as great a concern as electrical performance. Ideally, a GaN device would turn all applied electrical energy into electromagnetic (EM) energy, and very little heat would be dissipated. But modern power transistors and MMIC amplifiers are not capable of perfect power-added efficiency (PAE) and a considerably amount of bias energy converts into heat, which must be dissipated efficiently to ensure the long-term reliability of the device and surrounding circuitry.

Power transistor packages usually incorporate ceramic frames with conductive metal grounds and conductors, such as copper (Cu). The main problem in packaging a device that generates lots of heat in a small space is the differences in the coefficient of thermal expansion (CTE) for, say, the ceramic, Cu, and semiconductor die itself. If they don't match closely enough, the materials expand and contract with temperature at different rates, causing stress and cracks in the ceramic or copper conductors.

High-power transistor packages have traditionally provided reliable thermal paths, typically by means of robust flange-mount packages *(Fig. 1, again)*. While thermally efficient, such packages are large and expensive, driving many semiconductor manufacturers to search for more cost-effective ways of packaging high-power RF/microwave transistors and MMICs

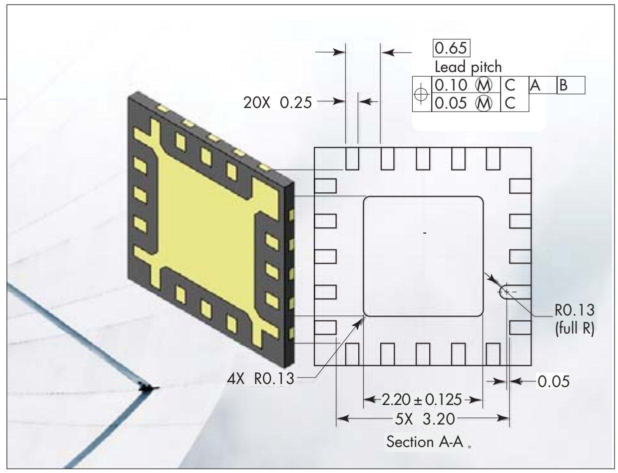
Kyocera (http://global.kyocera.com) has done extensive research on different materials for heat sinks used in high-power packaged transistors, for the purpose of finding a cost-effective material with efficient thermal dissipation. Copper heat sinks are estimated to have 40 to 50% reduction in thermal resistance compared to more exotic (more expensive) copper-tungsten (CuW) materials. Copper, the lowest-cost heat-sink material, is readily available from multiple sources to reduce cost. Any material with enhanced thermal properties compared to copper will be more expensive, such as copper silicon carbide (CuSiC), Cu diamond, and Cu graphite.

The firm found copper laminates could replace the more exotic CuW base and heat-sink materials in high-power packages. As with CuW, the copper laminates supported high-temperature brazing to alumina for fabrication of ceramic packages, with significantly improved thermal resistance and potentially reduced cost. In addition, CuW has a much higher modulus of elasticity (is much stiffer) than copper, allowing for some greater tolerances in the assembly and manufacturing processes.

However, in the Kyocera studies, it was found that copper and CuW differed somewhat in terms of surface defects, which could impact the thermal flow from an active device to the heat sink. CuW is a machined or ground substance with a very even and consistent surface, while rolled copper or copper laminates have very uneven surfaces and are subject to voids underneath a semiconductor die mounted on their surface. Such voids are interruptions in the thermal path and can become hot spots.

SEARCHING BEYOND CERAMICS

But is there some alternative to ceramic materials, such as alumina and low-temperature cofired ceramic (LTCC) for high-power RF/microwave device packages? With the widespread adoption of GaN as the high-power RF/microwave semiconductor substrate of choice, and with higher-power apps (e.g., radar) no longer the exclusive domain of military systems, the need for lower-cost power RF/microwave device packaging is apparent.



2. Surface-mount-technology (SMT) packages such as this air-cavity housing provide thermal dissipation through the mounting interface. *(Courtesy of RJR Technologies)*

Package and semiconductor developers have long considered alternatives to ceramic package frames, including organic laminates and plastic materials. In fact, several firms have introduced high-power devices in packages with plastic frames, both for continuous-wave (CW) and pulsed applications.

More higher-power GaN devices are arriving in low-cost plastic packages as well. Two years ago, at the International Microwave Symposium, Cree/Wolfspeed (www.wolfspeed.com) introduced GaN discrete transistors that operated at frequencies to 3.8 GHz in plastic packages. The +50-V dc transistors operate across multiple cellular communications bands with 65% efficiency at saturated output-power levels. The plastic packages provide effective thermal management plus help lower cost and reduce weight.

Plastic-encased GaN transistors or amplifiers were also made available from MACOM, Qorvo, and NXP. MACOM's (www.macom.com) MAGX family, based on the firm's GaN-on-Si process, is housed in lightweight plastic packages. The packages employ advanced heat-sink and die-attachment techniques to achieve less than +115°C average junction temperature (with an +80°C base plate) for a pulsed output power of 93 W. The input pulses have a 1000-μs pulse width and 10% duty cycle.

Designed for use at +50 V dc, the transistors come in standard 3 × 6 mm dual-flat-no-lead (DFN) packaging. They can be mounted on PCBs via ground/thermal arrays and be reliably operated at temperatures to +200°C or higher. In fact, the plastic-packaged devices were lifetime-tested and projected to have high reliability for 100 years when operating at +218°C.

Just one year ago, NXP/Freescale (www.nxp.com) introduced its RF5011N, a GaN-on-SiC transistor for use at frequencies to 3 GHz. Designed for a +28-V dc supply, it provides 10-W output power with 10-dB gain. The transistor is surrounded by the firm's OM-270-8 plastic packaging and uses advanced die-attach technology to achieve outstanding thermal resistance even without the ceramic materials. The firm's 125-W (from a +50-V dc supply) model RF5015N also comes in the plastic package. mw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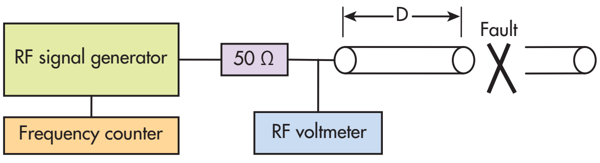
Method Finds Faults In COAXIAL CABLES

This straightforward technique works in the frequency domain without need for exotic test equipment to accurately find the distance to a fault in RF/microwave coaxial cables.

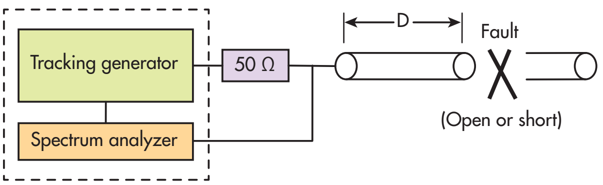
Coaxial cables are essential to many RF/microwave applications, being the external transmission lines that connect high-frequency signals from one point to another. Unfortunately, whether used in a circuit, a system, or in a test setup, coaxial cables can develop unseen faults that may be anywhere in their length. Finding those faults can often be challenging, typically requiring the use of time-domain reflectometry (TDR), which operates much like a radar system; it sends a signal with fast edge into the cable and measuring the time required for the reflected signal edge to return from the fault.

Analysis of the reflected signal gives insight into the location and type of fault. The resolution of a distance measurement depends on the rise-time of the pulsed test signal, which must be in the picosecond range to resolve a cable fault that may be only inches away from the test signal connection. In addition, the accuracy of TDR measurements will suffer when working with transmission lines which cannot support these high frequencies; attenuation is increased as the distance to fault increases.

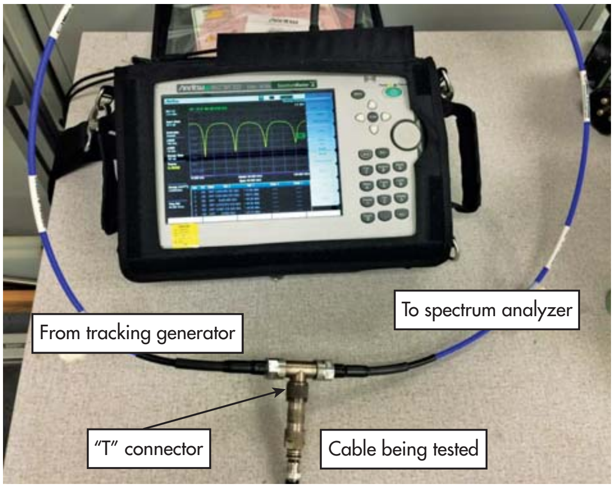
There is, how-



1. When TDR techniques are used for finding faults in cables, a pulse generator is used with an oscilloscope, although with the (FD)^2 method, the pulse generator can be replaced by an RF signal generator and the scope by an RF voltmeter.



2. The (FD)^2 method for finding faults in coaxial cables can be further simplified when performed with a spectrum analyzer and a tracking generator.



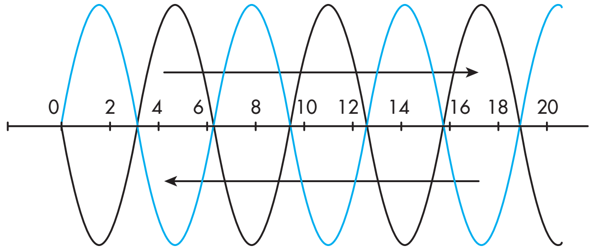
3. This is the test setup that was used for the $(FD)^2$ cable fault detection measurements, consisting of a spectrum analyzer with integral tracking generator.

ever, an alternative approach to finding faults in coaxial cables, by means of a new frequency-domain fault detection $(FD)^2$ method.

Cable fault detection based on TDR techniques is accurate and reliable, although the measurements can be complex and require sophisticated and often expensive test equipment, such as a high-frequency oscilloscope and pulse generator or a single integrated TDR tester. The $(FD)^2$ method does not require specialized test equipment or very high test frequencies to determine the location of a cable fault.

In fact, with the $(FD)^2$ approach, the longer the distance to the fault, the lower the frequency required to find it. The test method was easily capable of resolving the addition of an 0.8-in.-long BNC adapter to the end of a 2-ft.-long coaxial cable. It should be noted, however, that while a TDR measurement determines both the location and nature of a cable fault (open, short, or complex impedance), the $(FD)^2$ approach only provides the location of a simple fault (an open or short). In many cases, this is all that is needed.

For the measurement examples presented in this report, a model MS2720T Spectrum Master spectrum analyzer with integrated tracking generator from Anritsu Co. (www.anritsu.com) was used. The base model in this series of instruments operates from 9 kHz to 9 GHz with resolution bandwidths from 1 Hz to 10 MHz. For the purpose of performing $(FD)^2$ cable fault detection, however, this is quite a suitable frequency range performance in a relatively small, battery-powered package. In fact, to perform $(FD)^2$ cable fault detection, all that is required is a calibrated frequency source (such as a synthesized frequency generator or frequency generator with a frequency counter) and a means of detecting its relative amplitude (such as an oscilloscope or RF power meter).



4. Nulls occur when a reflected wave is delayed by 180 deg. or by ½ wavelength during every 360-deg. cycle of transmission.

PRINCIPLE OF OPERATION

Like fault detection using TDR, the $(FD)^2$ method sends a signal down a cable and measures the reflected versions of that original signal. However, the $(FD)^2$ approach uses a continuous sinewave signal rather than the high-speed pulsed signals of TDR measurements. Like TDR measurements, signal reflections will occur at a cable fault due to the interruption in the transmission line impedance at that point, and the reflected signals will travel back toward the signal source.

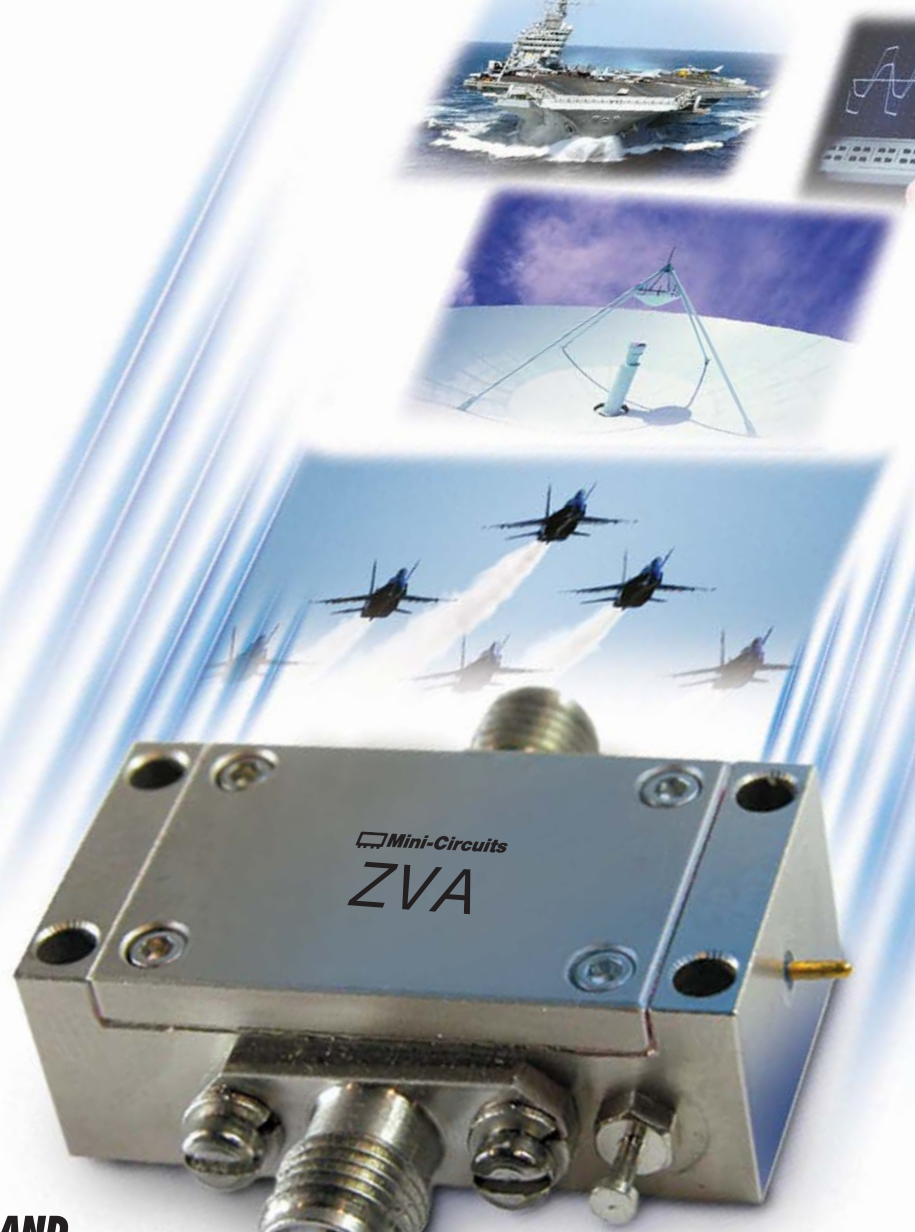
At particular frequencies and line lengths, the reflected signal wave will be completely out of phase with the initial forward-wave signal, resulting in cancellation of the signal wave. By measuring the frequencies at which these cancellations (or nulls) in the signal waves occur, it is possible to determine the distance from the signal source to the cable fault.

The measurement setup for the $(FD)^2$ method is very similar to that used for TDR measurements, except that the pulse generator is replaced by a signal generator and the oscilloscope is replaced by an RF voltmeter *(Fig. 1)*. When a spectrum analyzer with an integral tracking generator is used, the test setup simplifies to the configuration shown in *Fig. 2*. A photograph of the actual measurement setup used for the examples in this article is shown in *Fig. 3*.

As noted, the returning signal waves reflected from the fault

SAMPLE WORKSHEET FOR FINDING FAULTS IN COAXIAL CABLES

Line	Parameter	Equation	Value	Units
1	Calibration cable length			in.
2	"T" connector length		3	in.
3	Net calibration length, l_0	(line 1) + (line 2)		in.
4	Calibration cable, Δf_0			MHz
5	Cable velocity	2(line 3) × (line 4)		MHz-in.
6	Unknown cable, Δf			MHz
7	Distance to fault	0.5(line 5/line 6)		in.
8	Distance to fault in cable	(line 7) – (line 2)		in.



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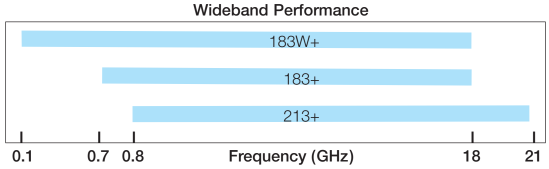
Wideband Performance



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will result in cancellations with the forward wave when the two waves are out of phase with each other; a null will occur whenever the reflected wave is delayed by 180 deg. (or ½ wavelength) and repeated every 360 deg. that the wave travels *(Fig. 4)*. These nulls occur according to the relationship in Eq. 1:

$$2d = \lambda/2,\ 3\lambda/2,\ 5\lambda/2,\ (2n + 1)\lambda/2, \ldots \text{ with } n = 3, 4, 5, \ldots \quad (1)$$

where d is the distance to the fault and λ is the wavelength of the cable at a frequency of interest.

Similarly, peaks occur when the reflected wave is in phase with the forward wave, and delayed by an integral number of wavelengths, as shown in Eq. 2:

$$2d = \lambda,\ 2\lambda,\ 3\lambda,\ n\lambda, \ldots \text{ with } n = 4, 5, 6, \ldots \quad (2)$$

Substituting $\lambda = v/f$, where v is the velocity of propagation of the cable (approximately 0.6c or three-fifths the speed of light) and f is the test frequency, and performing some algebraic manipulation, it is possible to find that nulls and peaks will occur in an open-circuited cable for the conditions shown in Eqs. 3a and b:

Nulls occur at

$$f = (1/4)(v/d),\ (3/4)(v/d),\ (5/4)(v/d),\ [(2n+1)/4](v/d), \ldots \text{ with } n = 3, 4, \ldots \quad (3a)$$

Peaks occur at

$$f = (1/2)(v/d),\ (2/2)(v/d),\ (3/2)(v/d),\ (n/2)(v/d), \text{ with } n = 4, 5, 6, \ldots \quad (3b)$$

The difference in frequency between two successive nulls or peaks can be found by Eq. 4:

$$\Delta f = (1/2)(v/d) \quad (4)$$

or by solving for the distance to the fault in the cable, d, by means of Eq. 5:

$$d = (1/2)(v/\Delta f) \quad (5)$$

By knowing the values of v and Δf, it is possible to find the value of d.

A similar analysis can be performed for a shorted cable, where Eqs. 4 and 5 still apply, although it should be noted that the $(FD)^2$ method cannot differentiate between open-circuit and short-circuit cable faults.


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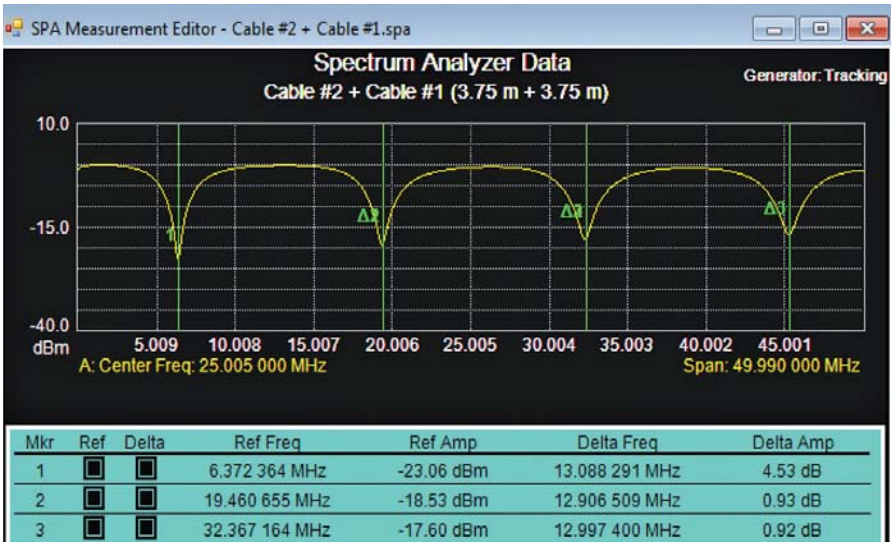


5. This spectrum analyzer screenshot shows the successive nulls for two lengths of 3.75-m coaxial cables linked with a T-connector. Using the three markers shown, it is possible to calculate $\Delta f_{average}$ = 12.9974 MHz.

EXPLORE AN EXAMPLE

To demonstrate an example of using this fault-finding technique, first calibrate the test system using a known length of cable of the same type to be tested. Simulate a break in the known cable length and then find the distance to the fault. Calibration can be performed by connecting an unterminated 7.5-m length of cable to the test system (two 3.75-m-long cables coupled together). Equation 6 can be applied with an added 3-in. length for the arm of the T-connector in the test setup of Fig. 3 to find (as shown in *Fig. 5*):

$$v = 2(3.75\text{ m} + 3\text{ in.})12.9974\text{ MHz}$$
$$v = 1.969 \times 10^8\text{ m/s}$$

Prior to performing cable fault detection with the $(FD)^2$ method, it is necessary to calibrate cable velocity, v, for the particular cable using a known length of the same kind of cable as the transmission line that is being tested. For this purpose, Eq. 4 is solved for v as shown in Eq. 6:

$$v = (2d)(\Delta f) \quad (6)$$

Finding the distance to the fault is then simply a matter of measuring the frequency difference between successive nulls and applying Eq. 5.

Although either peaks or nulls could be measured for this purpose, it is easier to measure nulls on account of their being sharper.

The fault in the cable can be simulated by breaking the coupling between the two 3.75-m cables, so that the correction answer, 3.75 m, is already known.

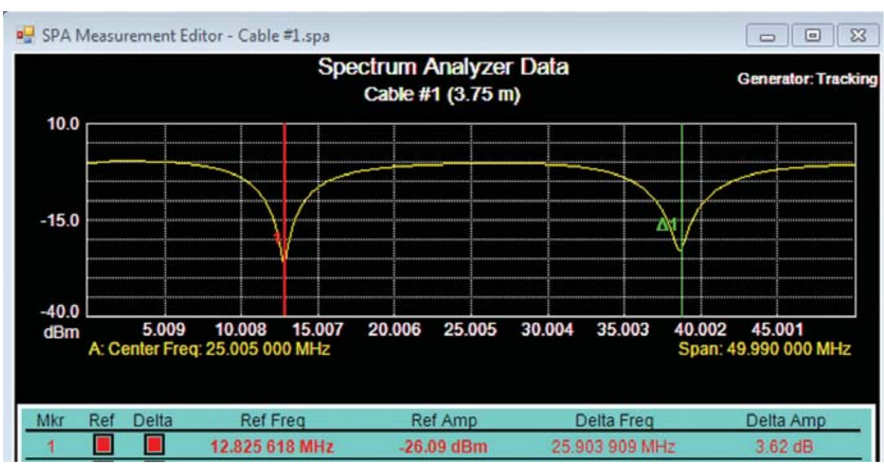
Using Eq. 5 and then subtracting out the 3-in. length of the T-connector in the test setup (Fig. 3), it is possible to calculate the additional cable length (as shown in *Fig. 6*):

$$d = (1/2)[(1.969 \times 10^8\text{ m/s})/(25.904\text{ MHz})] - 3\text{ in.}$$

$$d = 3.725\text{ m}$$

An error of 25 mm (about 0.67%) from the actual known 3.75-m distance is due in large part to the (lack of) frequency resolution of the spectrum analyzer. Higher analyzer resolution can be achieved by reducing the frequency span so that just a single null is shown on the analyzer's display screen.

In short, the $(FD)^2$ method provides a simple means to find the distance to a gross fault, such as an open or short, in a transmission line using only a relatively low-frequency signal generator and some form of amplitude measuring instrument, such as a general-purpose spectrum analyzer. The new method eliminates the need for complex TDR techniques and more expensive test equipment for finding faults in coaxial cables. mw



6. The spectrum analyzer screen provides a measurement of one 3.75-m length of cable across an approximate frequency span of 50 MHz with Δf = 25.904 MHz.

PAUL DAVIDSSON | President
Microwave Distributors Company, 9020 Kimberly Blvd., Boca Raton, FL 33434; (561) 948-2164, (800) MD-SHELF (800-637-4353), www.microwavedistributors.com

Design and Test Tips to Help Extend Product Lifetimes

Understanding the impact of selecting different materials and manufacturing processes can separate standard high-power resistive components from those designed and tested for true high-reliability applications.

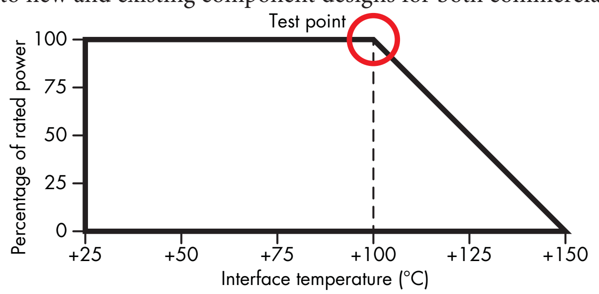
High reliability and long lifetimes, two product attributes that tend to go together, can be enhanced through the thoughtful selection of materials for designing and fabricating a high-frequency component. A 250-W termination will serve as an example on how following proper design guidelines and how standardization of high-power testing methods aid in material selection for reliable high-power components.

Accelerated life testing, where a component is subjected to operating conditions that may cause it to fail, can provide insight into how to make its next design iteration more robust and reliable. To better understand design and process issues that limit product reliability, particularly for high-power, flange-mounted attenuators, resistors, and terminations, a 1000-h cyclic burn-in methodology was developed to address catastrophic failures.

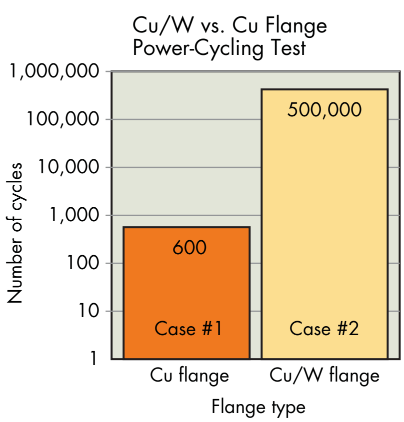
ACCELERATED LIFE-TEST SPECIFICS

The test procedure was developed to evaluate components for high-reliability (hi-rel) applications, but has merit when applied to new and existing component designs for both commercial and military use. The lifespan of these components depends solely on the end use of the product; e.g., it is known that steady-state operation will ultimately yield the highest reliability when a component is operated according to recommended limits *(Fig. 1)*. In contrast, reliability will be compromised when components are subjected to operation that involves on/off power conditions and temperature cycling *(Fig. 2)*.

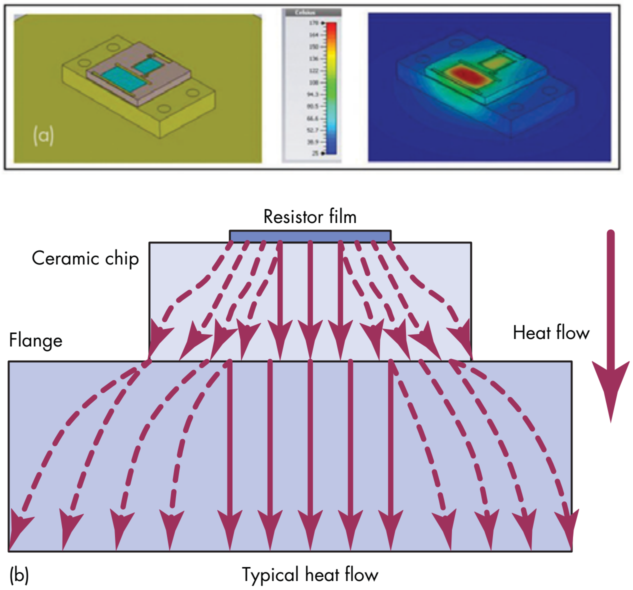
Performing accelerated power testing on 250-W flange-mount terminations required the selection of several groups of components: Group A with no failures, Group B with one test plan, and Group C with a somewhat different test plan. Group B testing involved mounting the terminations on a burn-in plate, maintaining the device base temperature at +100°C, and burning-in the terminations at 250-W continuous-wave (CW) input power. Group C testing included a cyclic 1000-h burn-in period that involved mounting the terminations on a burn-in plate, maintaining the base at a temperature not exceeding +100°C, and applying 250-W input power in cycles of 1.5 h on and 0.5 h off for a total duration of 1000 h. The devices were



1. The plot shows that high component reliability can be achieved with normal steady-state operation.



2. Reliability suffers when a component must endure power and temperature changes in cycles.



3. Creating a thermal model of a passive resistive component involves studying thermal patterns (a) and understanding differences in thermal flow (b) through different materials in the component.

allowed to stabilize at room temperature for not less than 1 h and not more than 2 h.

The testing resulted in two catastrophic failures, which were identified as fractured beryllium-oxide (BeO) ceramic chips. Such failures can then be correlated to a “root cause” analysis and included in a report that summarizes the cause of the failures. This study helps address materials and processes that could have an impact on failures occurring with present and future component designs. The results have also identified the need for possible design modifications to increase reliability and lifespan.

DIGGING INTO DESIGN

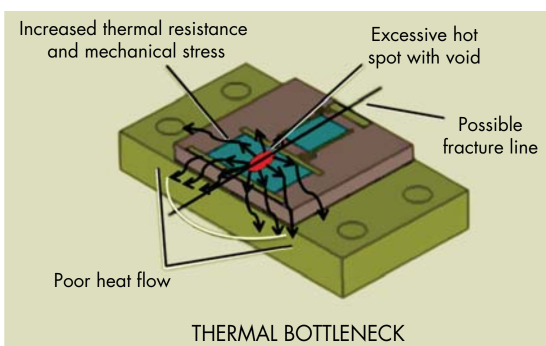
During the design phase, the following recommendations apply to high-power resistive devices: reviewing and understanding a customer’s specifications; knowing the maximum operating frequency, the maximum VSWR, and the minimum and maximum operating temperatures at full rated power; knowing pulsed-signal requirements (e.g., pulse width and duty cycle); knowing the power derating specifications; and knowing the power and temperature-cycling requirements.

Selection of materials is critical when designing and developing a high-power resistive component for specific customer requirements. One starting point is deciding which ceramic material can serve as the building-block material to meet a customer’s electrical and thermal design requirements, and whether the design should be fabricated as a thick- or thin-film device. If thin film, should it be based on tantalum-nitrate (TaN) or nickel-chromium (NiCr) films, typically deposited on an alumina, aluminum-nitride, or beryllium-oxide substrate? In addition, if NiCr material is chosen, does the application (such as a high-power pulsed circuit) require any sort of metal reinforcement, such as nickel?

Materials selection also extends to the device flange—it should meet various thermal requirements, such as a coefficient of thermal expansion (CTE) that is well matched to the other materials selected for a hi-rel component. In addition, decisions must be made on the flange plating material, such as intermetallic materials, and solder or brazing material used to attach a chip component to a flange-mount package. Other materials selection requirements involve whether chip plating will be needed (depending on the solder or brazing requirements) to meet the requirements of a particular application.

Developing a high-power passive component will involve the calculation of an optimum film topology for handling the required power levels while still meeting the RF/microwave performance specifications. It will also necessitate thermal analysis and simulation of the material stack-up per customer requirements using modern computer-aided-engineering (CAE) software simulation tools, as well as simulation of the electrical performance, such as insertion loss, return, loss, and VSWR.

Along with proper materials selection, the choice of manufacturing process should be based on meeting the design goals and customer requirements for a particular component. In addition, test procedures should be formulated in support of characterizing a component for the performance goals set during the design and materials selection stages of a product’s development. It’s crucial that test fixtures be designed for accurate testing of the manufactured component. Also, the fixtures should be able to deliver accurate data consistently throughout the validation process, since this data will determine the success or failure of achieving the design goals. All test data should be recorded, compiled, and incorporated in a validation report that is available for future use.

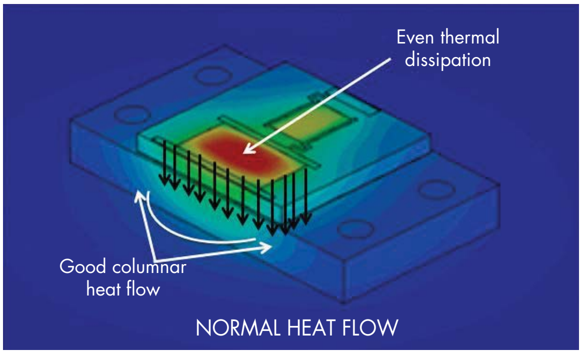


4. Voids in component material stack-ups can lead to hot spots and reliability issues when operating at high power levels.

VALIDATING A DESIGN

For a high-power resistor or termination, two main design considerations can impact the hoped-for long-term reliability of the component: the component being subjected to high temperatures that exceed the limits of its materials, causing reliability issues; and excessively high temperatures being sustained for a long-enough duration that results in damage to the component, or complete failure.

For such a passive component, when power is dissipated, the temperature gradient through the ceramic, solder, flange, and thermal compounds used to construct the component, along with the CTE mismatches among these materials, creates mechanical stresses whenever CTEs are significantly different. The solder attachment of the chip to the flange is subject to fatigue cracking with repeated exposure to stress. A robust design can withstand any fatigue caused by cycling on and off and will not degrade and fail over time.



5. Ideally, good columnar heat flow through a passive component provides effective dissipation of heat at high operating power levels and temperatures.

Material selection is critical for hi-rel components so as to avoid thermally induced stresses that can cause failures. For steady-state operation, a standard material stack-up is normally sufficient. However, when a component must handle power and temperature cycling, solder and flange material selection is critical for high reliability *(Fig. 2, again)*.

Two cases were used to explore the effects of material selection. In the first case, the material stack-up thermal resistance is 0.1580°C/W with a Δt gradient of +39.5°C at 250 W, resulting in an approximate film temperature of +139°C. This is well below the industry-standard limit of +150° to +180°C. Although the junction temperature (θ_{jc}) is very good, the CTEs of the materials differ significantly, resulting in mechanical stresses that will eventually lead to component failures. In the second case, the thermal resistance is 0.2036°C/W, which is higher than the first case, with an approximate film temperature of +150.9°C. This is still within the preferred limit, but the CTE of the material stack-up is almost identical to the first case. Nonetheless, the second case's material stack-up has the advantage of sustaining higher reliability and a longer life span.

The material stack-up of the first case *(Table 1)* is widely used throughout the industry, consisting of a BeO chip, copper flange (with Ni plating), and Sn-96 solder; components with this material stack-up show failures

TABLE 1: DETAILING MATERIAL PARAMETERS FOR THE FIRST CASE

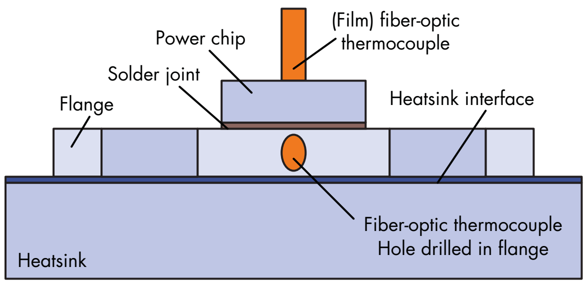
Material	CTE (ppm/°C)	K (W/cm°C)	Theta (°C/W)
BeO chip (0.375 × 0.375 in.)	9.0	2.61	0.0930
Sn-96 solder	30.0	0.33	0.0240
Ni-plated Cu flange	17.0	3.94	0.0330
Thermal grease	N/A	0.09	0.0080

Note: (θ_{jc}) = 0.1580°C/W × 250 W = Δt of 29.5°C. The film temperature at +100°C mounting-plate temperature is approximately +139.5°C.

TABLE 2: DETAILING MATERIAL PARAMETERS FOR THE SECOND CASE

Material	CTE (ppm/°C)	K (W/cm°C)	Theta(°C/W)
BeO chip (0.375 × 0.375 in.)	9.0	2.61	0.0930
Au/Ge solder (88%/12%)	10.0	0.44	0.0126
Au-plated Cu/W flange	10.0	1.85	0.0900
Thermal grease	N/A	0.09	0.0080

Note: (θ_{jc}) = 0.2036°C/W × 250 W = Δt of 50.9°C. The film temperature at +100°C mounting-plate temperature is approximately +150.9°C.



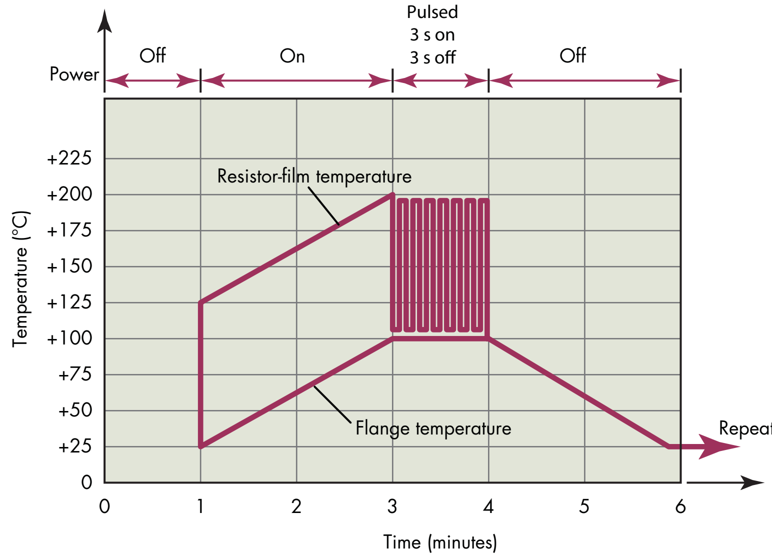
6. The junctions between different materials comprising a passive component are subject to mechanical stresses at high power levels and temperatures due to differences in CTE values.

beginning at 400 on/off cycles *(Fig. 2, again)*. The material stack-up of the second case *(Table 2)* employs exotic materials, including a BeO chip, tungsten/copper (Ti/W) flange with gold (Au) plating, and gold/germanium (Au/Ge) or gold-tin (Au/Sn) brazing material. Components using the material stack-up in the second case show failures beginning at 500,000 on/off cycles—a factor of 1250× higher than the industry standard *(Fig. 2, again)*.

Solder voids must be considered during the processing phase when assembling high-power devices. This has been addressed by the semiconductor industry over many years of research and testing. Myriad papers have been written that pertain to the reliability impact of thermal rise within the junction of the semiconductors. A simple rule of thumb: For every 10°C rise in junction temperature, the reliability drops by 50%. Although this rule of thumb is meant for semiconductors, the same design approach and process methods should be practiced for high-power resistors and terminations designed for long lifetimes.

New designs and validation of current designs should be subjected to thermal-analysis modeling *(Figs. 3a and b)* and become part of the engineering design practice. Although thermal modeling may not account for some mechanical variances, it can provide a model that is relatively close to the real application. Solder voids are the "invisible killer" for high-power components. Solder voids can create a "thermal bottleneck" or an interruption in the normal thermal conductivity of the resistive film, leading to potentially catastrophic hot spots at high power levels.

A significant size void directly under a thin film can considerably increase film temperature. The resultant heat flow depends on lateral heat flow through the ceramic to an area where no voids are present in order to dissipate the additional heat. This creates higher thermal resistance and mechanical stress. The



7. This diagram is a test profile for power/thermal cycling when evaluating a passive component.

mechanical stress and higher temperature could in fact induce a fracture in the ceramic material, causing a catastrophic failure shown in *Fig. 4* as opposed to a normal heat flow shown in *Fig. 5*.

POWER TEST

Power testing involves two phases. The first phase verifies the film topology of the termination and its power-handling capability for the intended maximum power levels of 250 W. During this test, a component is subjected to full (dc) input power while maintaining a flange temperature at +100°C *(Table 1, again)*. The test runs for 30 min. The temperature of the resistive film is monitored *(Fig. 6)* to verify that the maximum operating-temperature boundary limits are not exceeded. If the resistive film stays within the boundary range, and no damage is evident to the film, power testing can proceed to the second phase.

During the second phase of power testing, the termination is subjected to cyclic thermal and power levels to determine if it can withstand the stresses resulting from material CTE mismatches. *Figure 7* shows a typical profile for this testing. The resistive-film temperature is monitored for the duration of the test *(Fig. 1, again)*. At the conclusion of the test, the entire termination assembly is analyzed to ensure that no failures have occurred.

Power-test cycling begins with a device under test (DUT) at room temperature (+25°C). Full input power is then applied to the DUT and the flange temperature is raised to +100°C and maintained at that temperature. Once the flange temperature stabilizes at +100°C, the DUT is pulsed with 10 cycles of power-on, power-off operation. This pulsing consists of full power on for 3 s and then zero power for 3 s. After 10 cycles of pulsing, the power to the DUT is turned off and the DUT is cooled down to +25°C. This process is repeated 300 times *(Fig. 7, again)*.

Subsequently, each DUT is examined for any permanent change in resistance or damage to the part. A permanent change in resistance indicates the part is at risk in terms of reliability over its design lifetime. Such power testing is conducted on multiple samples to achieve reasonable confidence in the accuracy of the test data; the data establishes the reliability of a tested part.

Editor's Note: The author has been involved in the development of new product lines of attenuators, resistors, and terminations based on the design methodologies presented here, with enhanced reliability for all commercial and hi-rel applications. The new product lines will be available in the June 2016 timeframe. mw

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CHRIS DeMARTINO | Technology Editor

Part 2: What are the Differences Between COAXIAL CONNECTORS?

A wide array of coaxial connectors is available from a large number of suppliers to satisfy high-frequency requirements.

This two-part series examines the coaxial connector, which is an often overlooked—but nonetheless vital—aspect of an RF/microwave application. Part 1, which provided a general overview of connectors, discussed important parameters and terminology. In Part 2, we'll continue by describing various types of coaxial connectors that are commonly used for RF/microwave applications.

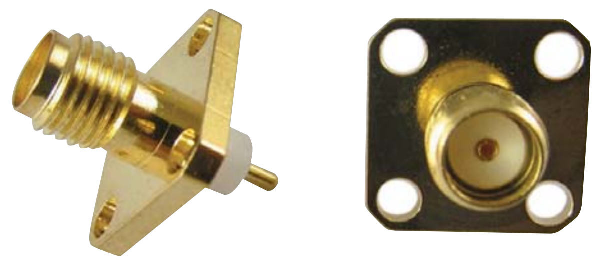
TYPE-N AND 7/16 DIN CONNECTORS

As stated in Part 1, the Type-N connector was introduced in 1942. Still commonly used today, this connector, which employs threaded coupling, is known for its durability. Standard Type-N connectors perform to 11 GHz, while versions that perform to 18 GHz are offered by some connector suppliers. Furthermore, both 50- and 75-Ω versions are available. Type-N connectors are covered by the MIL-C-39012 specification.

The 7/16 DIN connector derives its name from its dimensions; the diameter of its inner conductor contact is 7 mm and the internal diameter of its outer conductor is 16 mm. These connectors are known for their superior return loss and intermodulation-distortion (IMD) characteristics. The 7/16 DIN connector can cover a frequency range of dc to 7.5 GHz.

THE SMA CONNECTOR AND ITS MATES: 3.5- AND 2.92-mm CONNECTORS

The SMA connector is widely used throughout the RF/microwave industry (*Fig.1*). It originated in the late 1950s when James Cheal of Bendix Research Laboratories designed the Bendix real miniature (BRM) connector. The development of the BRM connector continued, leading to its incorporation into MIL-C-39012 in 1968. The connector was then designated the Sub-Miniature A, or SMA, connector.



1. The SMA connector is one of the most common connector types used for RF/microwave applications.

Like the Type-N connector, the SMA connector—which has an impedance of 50 Ω—employs threaded coupling. Originally intended to be used with 0.141-in.-diameter semi-rigid coaxial cables, the SMA connector's usage was later extended to flexible cables as well. As mentioned in Part 1, SMA connectors employ a solid dielectric.

Furthermore, while standard SMA connectors operate from dc to 18 GHz, some suppliers provide versions that can perform to 26.5 GHz. Although they are common and inexpensive, SMA connectors have their limitations—they are rated for a very limited number of connection cycles.

The SMA connector is mechanically compatible with two other connector types: 3.5- and 2.92-mm connectors. Both employ an air dielectric and can perform at higher frequencies than their SMA counterpart. They are named in accordance with the inside diameter of their respective outer conductors.

The 3.5-mm connector, which can achieve mode-free performance to 34 GHz, first appeared in the 1970s. The connector was primarily developed at Hewlett-Packard (HP) and later manufactured by Amphenol. These connectors are known for their durability, as they were designed to allow thousands of repeatable connections.

2. The 2.92-mm connectors can be used at frequencies as high as 40 GHz.

Introduced by Wiltron (now Anritsu) as the Type-K connector in 1983, the 2.92-mm connector is available today from a wide range of suppliers (*Fig. 2*). These connectors can be used at higher frequencies than 3.5-mm connectors, as they offer performance to 40 GHz. Measurement systems and high-performance components, for example, sometimes implement 2.92-mm connectors.

HIGHER-FREQUENCY CONNECTORS: 2.4-, 1.85-, AND 1.0-mm

Even higher-frequency performance can be achieved by 2.4-, 1.85-, and 1.0-mm connectors. Like 3.5- and 2.92-mm connectors, they employ an air dielectric. They also derive their names from the inside diameter of their respective outer conductors.

> "Even higher-frequency performance can be achieved by 2.4-, 1.85-, and 1.0-mm connectors. Like 3.5- and 2.92-mm connectors, they employ an air dielectric."

The 2.4-mm connector, which was developed in the mid-1980s, can achieve performance to 50 GHz. These connectors have a thick outer wall, thus making them less frail than SMA and 2.92-mm connectors. At first glance, it may be difficult to distinguish a 2.4-mm connector from a 2.92-mm connector. However, should one attempt to connect a 2.4-mm connector to an SMA connector, the difference will be very clear—the two connector types will not mate. Therefore, an appropriate adapter is needed to connect a 2.4-mm connector to either an SMA, 3.5-mm, or 2.92-mm connector.

In addition, the 1.85-mm connector can achieve mode-free performance to 65 GHz. HP initially developed the connector in the mid-1980s. The company then offered its design as public domain in 1988 for the purpose of standardizing connector types. The 1.85-mm connectors can be mated with 2.4-mm connectors, but not with SMA, 3.5-mm, and 2.92-mm connectors.

Furthermore, millimeter-wave applications can take advantage of the 1.0-mm connector. This connector, which was also developed by HP, can achieve performance to 110 GHz. Probe stations are an example of an application that utilizes 1.0-mm connectors.

NOT FORGOTTEN—BNC AND TNC CONNECTORS

The widely used BNC connector has a typical frequency range of dc to 4 GHz (*Fig. 3*). Commonly used for test-and-measurement equipment, the BNC connector, which employs the bayonet-coupling technique, is offered with an impedance of either 50 or 75 Ω. Female connectors have two bayonet lugs and can be connected to male connectors with just a ¼-turn of the coupling nut. Unfortunately, BNC connectors are not usable above 4 GHz because they are prone to radiation at those frequencies. BNC connectors are covered by MIL-C-39012.

The TNC connector is a threaded version of the BNC connector, offering higher-frequency performance than its BNC counterpart. These connectors are typically rated to 11 GHz. Like the BNC connector, the TNC connector is covered by MIL-C-39012.

3. The BNC connector is often found in test instruments.

To summarize, a wide range of coaxial connectors are available to satisfy the demands of today's high-frequency applications. This series discussed some of the commonly used connectors, but additional types exist that were not mentioned. Although connectors may seem mundane, they are crucial for any application. Thus, it is important to understand the basics of coaxial connectors and the many options that are available today. mw

VECTOR NETWORK ANALYZERS
ARM THEMSELVES FOR NEW CHALLENGES

FIFTH-GENERATION (5G) NETWORKS are expected to require wider bandwidths and higher frequencies. As a result, characterizing power amplifiers (PAs) and other components will become even more complicated. To measure these devices, a wide-bandwidth vector network analyzer (VNA) measurement approach can be utilized. In the white paper, "Millimeter-wave VNA characterization using modulated signals," Anritsu discusses how a VNA-based measurement platform can benefit higher-frequency PA measurements for 5G and related applications.

Anritsu Corp., 490 Jarvis Dr., Morgan Hill, CA 95037-2809; (408) 778-2000; www.anritsu.com

Characterizing PAs for future 5G applications will be extremely vital. However, accomplishing this will be more challenging for a number of reasons. For example, measurement stability and repeatability can be more difficult as a result of higher carrier frequencies. And wider bandwidths and higher frequencies tend to mean lower return losses, which can affect measurement accuracy. The white paper discusses other challenges, as well as PA parameters that play an important role when it comes to wider bandwidths. A wide-intermediate-frequency (wide-IF) VNA platform is one approach to solving these challenges, as it has intrinsic match characterization and correction capabilities. Its inherent capability to ratio helps with stability and accurate power delivery. In addition, the VNA's normal low-level sweep capabilities can help with measurement speed.

The white paper discusses a measurement setup based on the MS464XB VNA equipped with several options. Modulated signals can be generated by using an external modulated source alongside the VNA. By using either the internal VNA source or an external synthesizer as a local-oscillator (LO), the output of the external source is then upconverted to the desired frequency. The document also discusses calibration, which can significantly impact measurement accuracy.

Several example measurements and scenarios are demonstrated. The first example presents output power measurements of an amplifier supplied with a 60-MHz bandwidth signal. Measurements were performed with both a VNA match correction and a normalization calibration. Another example demonstrated phase-deviation measurements for a 60-GHz amplifier with both VNA and normalization calibration. AM/AM and AM/PM measurements of an amplifier at 40-GHz are also presented for both continuous-wave (CW) and modulated waveforms.

DISCERN BETWEEN WIRELESS MODULES FOR IoT APPLICATIONS

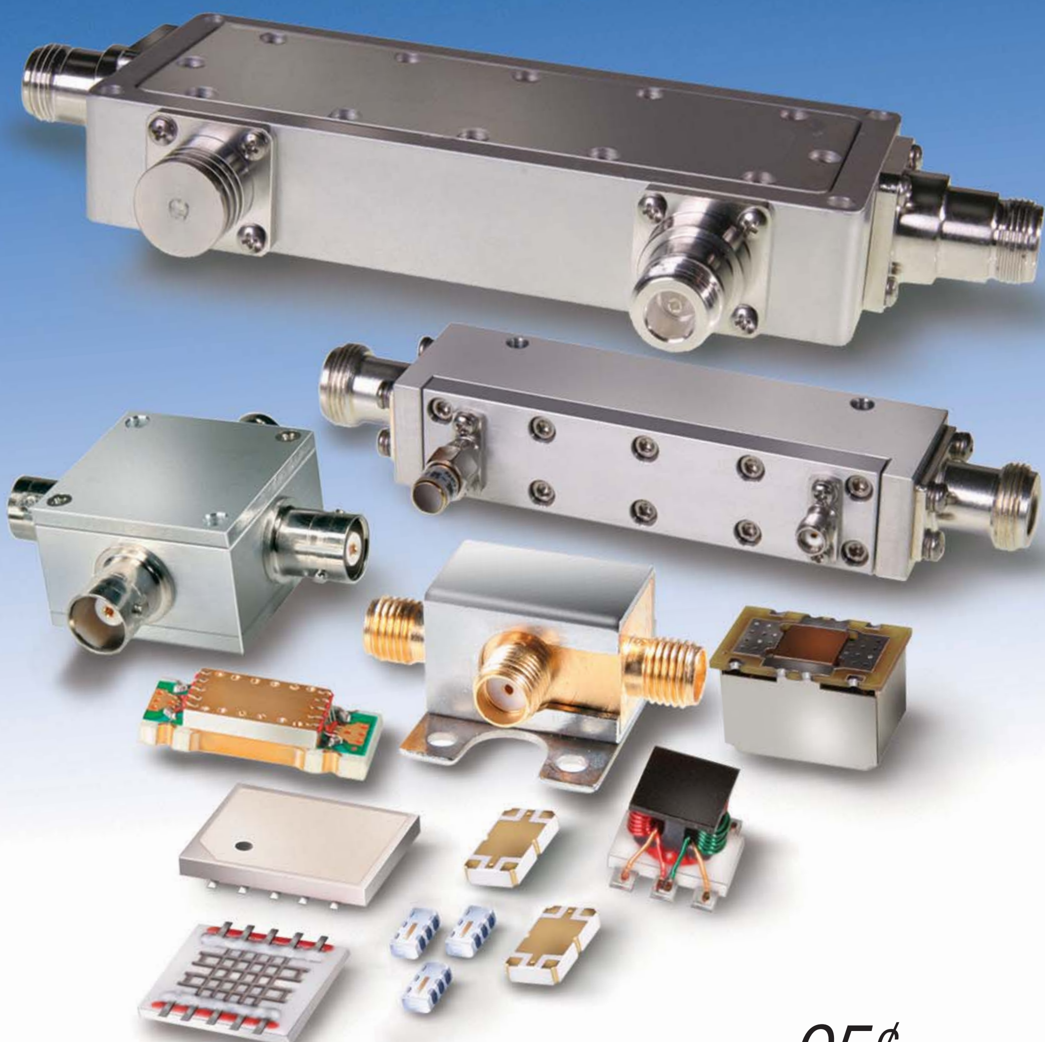
MANY FACTORS MUST be taken into account when developing an Internet of Things (IoT) hardware solution. Wireless embedded modules have simplified the development of IoT hardware. However, one still must consider many factors when selecting such a module for an IoT development project. In the tutorial, "Selecting the Right Wireless Module," Tektronix discusses some of the important aspects that are associated with selecting a wireless module for an IoT application.

The tutorial discusses several different approaches to IoT hardware development. One option is to utilize a chip-design solution, which is a development approach that begins with components like wireless transceiver and microcontroller unit (MCU) chips. A system-on-a-chip (SoC) design solution is another option, as this approach allows development teams to utilize SoCs that can integrate wireless transceivers and MCUs. Yet another approach is to take advantage of an embedded module solution, which is closer to the final product. Embedded modules are ready-to-use solutions that drastically reduce the amount of hardware development work.

Tektronix Inc., 14150 SW Karl Braun Dr., Beaverton, OR 97077; (800) 833-9200; www.tek.com

Choosing an embedded wireless module also means choosing a wireless standard. These modules are generally developed to follow standardized wireless protocols. IoT communications can be enabled by a number of wireless protocols, which include cellular and wireless-local-area-networking (WLAN) standards. Bluetooth technology is another connectivity option, as well as the IEEE 802.15.4 standard. Additional standards for the IoT include SIGFOX, LoRa, and more. Furthermore, the document discusses compliance requirements, which must be considered when selecting a wireless module. A list of some of the current embedded module vendors is also provided. When selecting a module vendor, it is important to consider additional factors like quality and long-term availability, among others.

The document concludes by explaining design and pre-production test considerations. To bring a high-performance electronic device to market, it must be tested in all development phases from design to production. Integrating a complete device without performing the required testing can lead to project delays. It is therefore important to use an appropriate set of hardware and software testing tools for IoT devices.



JACK BROWNE | Technical Contributor

Radio IC Paves Way

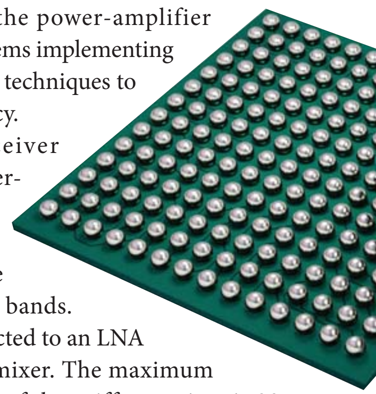
This single integrated circuit contains most of the analog, digital, and mixed-signal components needed for direct-conversion FDD and TDD communications from 300 to 6000 MHz.

WIDEBAND COMMUNICATIONS TECHNOLOGY is no longer a luxury—it's become a necessity. Because communications has moved beyond voice to include video and massive amounts of data on a regular basis, wireless communications technologies have evolved from "primitive" first-generation analog cellular networks and telephones to the current third-generation (3G) and fourth-generation (4G) systems and beyond. Now these technologies are homing in on wideband fifth-generation (5G) wireless networks and a plethora of supported wireless devices.

Of course, wideband transmitters and receivers are needed to support such networks, with performance levels that can literally cut through the noise of earlier systems. As integrated-circuit (IC) technology would have it, one solution lies in having multiple wideband transmitters and receivers on a single chip, the highly integrated RadioVerse AD9371 transceiver from Analog Devices. Packed with performance, this impressive device provides a frequency range from 300 MHz to 6 GHz and wide bandwidths of 100 MHz to enable the next generation of wireless communications.

The AD9371 direct-conversion transceiver IC *(Fig. 1)* integrates almost all of the components needed for a high-performance radio solution, with two independent transmitter paths and two independent receiver paths *(Fig. 2)*. The differential transmitters and receivers are programmable and support frequency-division-duplex (FDD) and time-division-duplex (TDD) operation in 3G, 4G, and one day, 5G wireless systems.

In addition, the AD9371 includes a two-input observation receiver and a three-input sniffer receiver. The observation receiver operates much like the main receivers, with two differential inputs. The inputs share a common RF front-end analog-to-digital converter (ADC) and baseband circuitry, so that only one observation receiver can be active at one time. The observation receiver observes the power-amplifier (PA) output for systems implementing digital predistortion techniques to improve PA efficiency.



The sniffer receiver provides three differential input ports that can be used to monitor three different frequency bands. Each input is connected to an LNA that feeds a single mixer. The maximum channel bandwidth of the sniffer receiver is 20 MHz. All of the receivers tune across a 300- to 6000-MHz frequency range.

The IC doesn't require an external local oscillator (LO), since it contains multiple voltage-controlled oscillators (VCOs), loop filters, and three fractional-N phase-locked loops (PLLs). It does require a stable, external low-phase-noise differential clock operating between 10 and 320 MHz to generate the RF LO signals and all internal converters, digital clocks, and interface clocks. It also requires at least one external bypass capacitor, but very little else.

This is not just an analog transceiver, however. It includes multiple ADCs and digital-to-analog converters (DACs) in support of the analog receiver and transmitter circuits, respectively. The IC provides self-calibration for dc offset, wideband dynamic quadrature error correction (QEC), transmit LO leakage, and digital-signal-processing functions like programmable FIR, decimation, and interpolation filters. The IC is backed by comprehensive software support and robust algorithms to ensure outstanding linearity

for Emerging Wireless Designs

across the wide bandwidths and the AD9371's total frequency range.

The transceiver uses API or Linux drivers to communicate with a baseband processor via an SPI port. It supports JESD204B for transferring data at 6 Gb/s and, in spite of the massive functionality of its multiple transmitters, receivers, and digital hardware, consumes only about 5-W power. That breaks down to about 2 W for the two receivers, 2 W for the transmitters, and about 0.8 W for the observation receiver.

1. The RadioVerse AD9371 transceiver provides multiple receivers and transmitters in support of direct-conversion communications systems with differential I and Q signals from 300 MHz to 6 GHz.

Of course, commercial communications is just one possible application area for this device. With its bandwidth and flexibility, it is a candidate for military manpack and vehicular tactical radios, in signal-intelligence and electronic-warfare systems, and for a host of different test instruments, such as network and spectrum analyzers.

TRACING THE EVOLUTION

The two-receiver, two-transmitter concept is not new. The AD9371 is actually an evolution of the firm's earlier model AD9361 transceiver IC *(see Microwaves & RF, May 2016, p. 45)*. The new chip has a much higher level of integration and a serious upgrade in performance in an attempt to eliminate external components, simplify the radio system, and ultimately deliver lower cost, size, power, and development-time benefits.

Both transceivers employ direct-conversion architectures, also known as homodyne radios. In this approach, input RF signals to the receiver are mixed with LO signals at the same frequency to produce a signal at baseband or dc, also known as a zero-IF receiver. By translating input signals so low in frequency, filtering is simplified (by means of lowpass filters in the AD9371) and the baseband signals can then be efficiently converted by on-chip ADCs *(Fig. 2, again)*.

The many challenges with classic direct-conversion approaches, such as LO leakage and I/Q imbalance, have been overcome in the AD9371 through careful design and circuit layout, in addition to leveraging breakthrough error-correction algorithms. Furthermore, very close attention was paid to the placement of the RF ports, chip layout, and laminate design to achieve isolation between the two transmitters, and between either transmitter or either receiver, of better than 60 dB when tested with LOs at 2.6 and 3.5 GHz.

PROBING THE PERFORMANCE

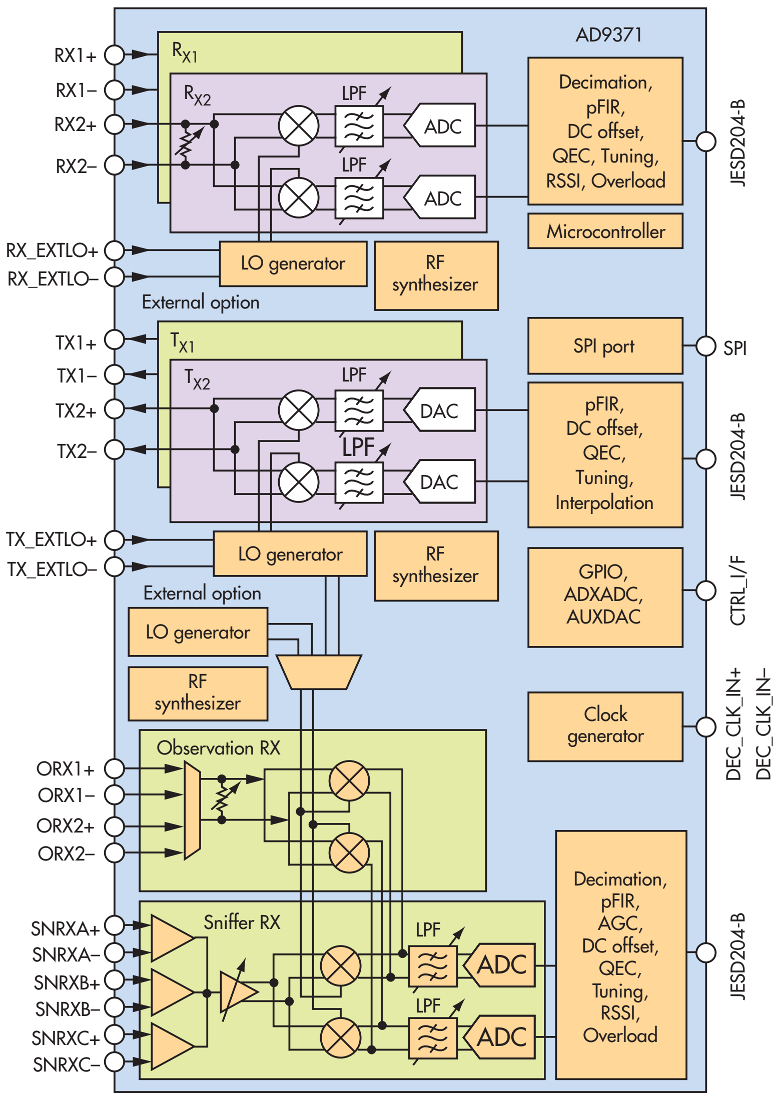
Taking a closer look at the AD9371's various sections, the two transmitters operate with signal bandwidths as wide as 100 MHz over a total bandwidth of 300 to 6000 MHz. They are supported by a transmit synthesis bandwidth of 250 MHz and amplitude flatness of ±0.5 dB across that bandwidth when compensated by a programmable finite-impulse-response (FIR) filter. For any 20-MHz bandwidth, the amplitude flatness can be improved to ±0.15 dB with the same programmable FIR filter. The deviation from linear phase is 10 deg. across the transmit-synthesis full 250-MHz bandwidth.

The transmitters deliver a maximum output of +7 dBm at 2.6-GHz LO and as much as +6 dBm for a 3.5-GHz LO. Transmit power can be controlled over a range of 0 to 42 dB with 0.05-dB resolution. The two transmitters are well isolated, with 65 dB or more isolation between transmitters when measured for LOs at 2.6 and 3.5 GHz.

When tested using four UMTS carriers, the adjacent-channel leakage ratio (ACLR) is –64 dBc for a 2.6-GHz LO and –63 dBc for a 3.5-GHz LO. The in-band transmitter noise is –155 dB full scale (FS)/Hz. Image rejection is 65 dB for either of the two LOs, while carrier leakage measures –81 dBFS for either LO. The third-order output intermodulation intercept point (IIP3) is +27 dBm for the 2.6-GHz LO and +25 dBm for the 3.5-GHz LO.

The two main receivers operate at center frequencies from 300 to 6000 MHz with tunable instantaneous signal bandwidths from 5 to 100 MHz. They include a gain adjustment range of 0 to 30 dB, which can be set in 0.5-dB steps. The maximum recommended input power is –14 dBm. The amplitude ripple for any 100-MHz bandwidth is ±0.5 dB, which reduces to ±0.2 dB for any 20-MHz bandwidth. Receive and image rejection is 75 dB or better.

As with the transmitters, the receivers were characterized with LOs of 2.6 and 3.5 GHz, and were found to have noise figures of 14 and 15 dB, respectively, when operating with those two LOs. The IIP3 is –22 dBm for the lower-frequency LO. The second-order input intermodulation intercept point (IIP2) is –65 dBm for either LO.



2. This block diagram shows the different analog, digital, and mixed-signal components that equip the RadioVerse AD9371 transceiver for direct-conversion communications from 300 to 6000 MHz.

As noted earlier, one of the chief challenges in highly integrated RF designs involves achieving good port-to-port isolation, but the separate function blocks of the AD9371 are well isolated. The isolation between receiver 1 and transmitter 1 and receiver 2 and transmitter 2 is 68 dB for the 2.6-GHz LO and 62 dB for the 3.5-GHz LO. The isolation between receiver 2 and transmitter 1 and receiver 1 and transmitter 2 is 70 dB for the 2.6-GHz LO and 62 dB for the 3.5-GHz LO. The isolation between the receivers themselves is 60 dB. The LO leakage is well controlled, with receiver LO leakage of –65 dBm for the 2.6-GHz LO and –62 dBm for the 3.5-GHz LO, both at maximum input gain. The in-band spurious content referenced to the RF input is –95 dBm, also at maximum gain.

Performance levels of the observation and sniffer receivers are similar. They cover the same total bandwidth, with 250-MHz bandwidth for the observation receiver and 20-MHz bandwidth for the sniffer receiver.

The AD9371 transceiver IC is an evolution of the company's highly regarded AD9361 transceiver, but in many ways, it also represents a revolution for wideband radio designers. It is a single chip, supplied in a 196-ball ball-grid-array (BGA) chip-scale package (CSP) measuring 12 × 12 mm, that can handle all of the radio functions over a bandwidth wide enough to serve many of today's wireless applications in the commercial, industrial, and military sectors. If ever there was a case of "one chip fits all," it is the RadioVerse AD9371 transceiver IC. mw

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New	CMA-81+	DC-6	10	19.5	38	7.5	5	6.45
New	CMA-82+	DC-7	15	20	42	6.8	5	6.45
New	CMA-84+	DC-7	24	21	38	5.5	5	6.45
	CMA-62+	0.01-6	15	19	33	5	5	4.95
	CMA-63+	0.01-6	20	18	32	4	5	4.95
	CMA-545+	0.05-6	15	20	37	1	3	4.95
	CMA-5043+	0.05-4	18	20	33	0.8	5	4.95
	CMA-545G1+	0.4-2.2	32	23	36	0.9	5	5.45
	CMA-162LN+	0.7-1.6	23	19	30	0.5	4	4.95
	CMA-252LN+	1.5-2.5	17	18	30	1	4	4.95

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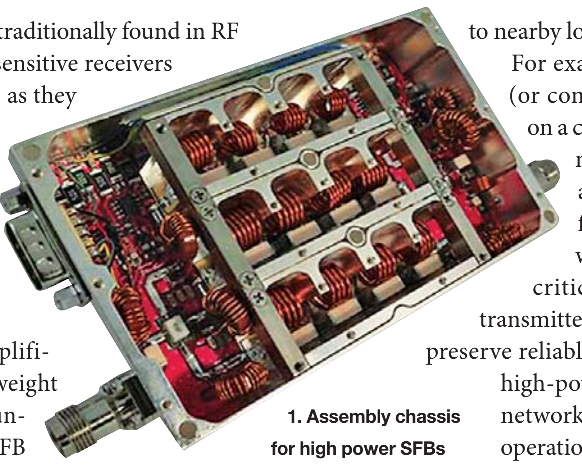
High-Power Switched Filter Banks Pose Design Challenges

For high-power switched filter banks, the power and voltage stresses of rapidly switching at high power—along with achieving low insertion loss and high out-of-band rejection—require novel strategies to support these emerging needs.

SWITCHED FILTER BANKS (SFBs) are traditionally found in RF front ends or intermediate stages of sensitive receivers for military and defense applications, as they help reduce harmonic and spurious content which is critical to communications systems. Until recently, high-power SFBs (*Fig. 1*) have been limited to fixed locations or on larger mobile platforms due to their inherent large size.

Gallium-nitride (GaN) power amplifiers (PAs) have reduced the size and weight of high-power transmitters in the hundreds of watts range. The demand for SFB assemblies has thus followed suit. However, the leap from traditional SFBs to high-power equivalents is not straightforward, and many tradeoffs and design considerations must be made in order to develop a suitable high-power SFB.

One application that has driven the early development of high-power SFBs is communications band signal jamming at VHF and UHF frequencies. These devices have predominantly been used to prevent communications band signals to remotely triggered explosives and to deny cellular service near secure governmental and military facilities. Ironically, technology that has initially been leveraged to mitigate communications may be a solution that enhances communications in modern and future trending applications.



1. Assembly chassis for high power SFBs must be designed to incorporate design elements to optimize electrical, RF, and thermal performance.

PRACTICAL JUSTIFICATIONS FOR HIGH-POWER SFBs

As communications band usage increases with the explosion of the Internet of Things (IoT) and machine-to-machine (M2M) devices, there may be greater commercial and industrial sector demand for high-power amplification and switching technology that limits the spurious content in these bands. A reason for this is that any additional harmonics or spurious content could dramatically increase the interference and noise to nearby low-power IoT/M2M systems.

For example, the latest autonomous (or connected) car may heavily rely on a constant communication channel to a common base station and between other vehicles for safe operation. In a world with a densely packed web of critical systems, cranking up the transmitter power won't be an option to preserve reliable communications. Thus, the high-power systems in heterogeneous networks may require more stringent operational specifications.

Another future application of high-power SFBs could be enabling high-speed communications channels for commercial and industrial drones. The adoption of unmanned aerial systems (UAS) technology is accelerating and may play a larger role in commercial and industrial applications. The reliable control and communication with these systems will require more agile and small payload radio technology, possibly served by high-power SFBs coupled with the latest high-power amplifiers (HPAs).

At API Technologies (www.apitech.com), high-power filter bank solutions have been developed to filter the high-power signals generated by PAs. There are several constraints that must be considered when developing high-power SFB solutions, which include the pass-band, applied power, reflected power, switching speed, and the stop-band region (*Fig. 2*).

THE DIFFERENCES BETWEEN HIGH-POWER AND LOW-POWER SFBs

High-power SFBs are generally judged by the same performance parameters as lower-power SFBs: among them, size, weight, and cost. Electrical considerations, such as passband, roll-off, insertion loss, and out-of-band rejection are also just as significant in high-power SFBs. Achieving a lower insertion loss and higher out-of-band rejection may require more design effort for high-power SFBs, as heat dissipation from a high insertion loss and attenuating high power harmonics are often key considerations.

The main differentiations between low-power and high-power SFB requirements include high-power SFBs' heat dissipation characteristics and the high voltage handling needs. These two factors of high-power operation induce greater voltage and thermal stresses on the switch elements and components directly in the signal chain. Additionally, higher voltages and power increase the impact of nonlinearities in system components. These factors demand a detailed analysis of each component's performance over a wide range of operational parameters.

HIGH-POWER SFB DESIGN CHALLENGES

The SFB is often considered a less-critical component than an HPA system. However, an assembly that wasn't designed upfront with the considerations of the SFB may lead to an underutilization of the amplifier module's capability or significant amounts of costly redesign. It is therefore important to consider the high-power SFB as a critical item in the assembly.

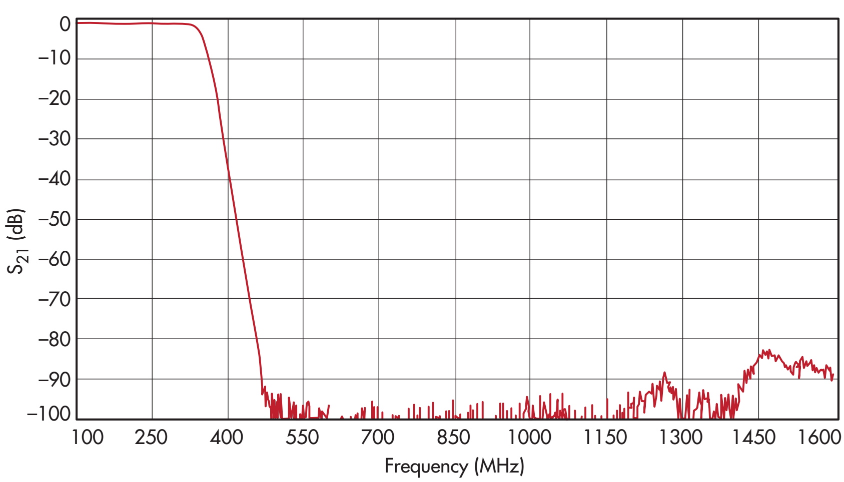
The physical demands by the latest applications also encourage much lower size and weight and reduced cost structure, without sacrificing functionality. This is hard to achieve without optimizing the physical and electrical design of the SFB section in an integrated assembly. The power and thermal factors also form a trade-off with frequency and bandwidth, as high-frequency RF signals tend to generate greater thermal dissipation in signal chain components in much smaller dimensions.

Additionally, high power, voltage, current, and thermal stresses can exceed the maximum operating specifications for many components not designed specifically for high-power operation. A complete understanding of the signal characteristics presented to the assembly establishes design requirements so that each component can be optimized to withstand the various stresses associated with the applied power. For example, various continuous and pulsed power conditions can dramatically influence the thermal consideration and transient voltage/current handling parameters of many signal chain components.

Another electrical consideration is the increased harmonics from nonlinear components whose harmonic products scale with input power. The active switching elements—such as PIN diode and FET switches—fall under this category, as does any nonlinear driver and bias circuitry. Higher RF power also leads to increased reverse bias voltages that can affect diodes, drivers, resistors, and interconnect components. This in turn increases the thermal stresses experienced by those components. The switching speed is also limited by the power and thermal stresses experienced during switching.

COMPONENT/DEVICE LIMITATIONS AND CONSIDERATIONS

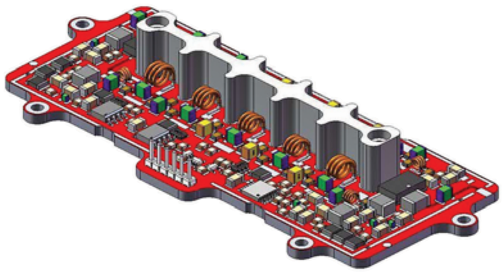
Every component and device in the signal chain of a high-power SFB also brings limiting factors, parasitics, and design challenges. For example, switches and inductors are critical to design performance. For inductors, the ability to carry high RF power requires an increase in wire thickness to minimize thermal concerns from resistive losses. An increase in wire diameter also increases the parasitic capacitances—interwinding capacitance and shunt capacitance to nearby grounds—and overall inductor size and inductance, which ultimately limits the diversity of filter topologies and quality factor of the filter stage.



2. Both a flat passband with low insertion loss and steep drop off on high power SFB filters is critical to enable the hundreds of watts of RF power that are passed and filtered by these devices.

The switches in a high-power SFB are burdened with the twin tasks of allowing and blocking hundreds of watts of RF power without exceeding power, voltage, current, and thermal operating parameters. For these reasons, it is generally infeasible to achieve the necessary device performance while enabling hot-switching capability. Hot switching would induce potentially significant transients that could easily exceed the switch device ratings, or even the PA and downstream components.

Specifically for PIN diode switches in a high-power SFB, hot switching poses a hazard to itself and other



3. The latest 3D CAD tools enable more optimal component placement and more compact designs in a rapid design cycle.

components and devices. During a PIN diode on-state, the insertion loss through the switch is very low; in the off-state, the PIN diode has a very high resistance and low leakage current. However, while a PIN diode is switching, the impedance during the transitional state can cause the switch to dissipate the bulk of the applied power, resulting in failure of the diode (*Fig. 3*). Thermal energy induced during hot-switching could also exceed the switch materials' operating parameters, leading to accelerated aging or device failure.

THE BIG THERMAL CHALLENGE

Though understanding the magnitude of RF energy converted to thermal energy in a high-power signal chain is relatively straightforward physics, managing the thermal energy in such a way that prevents device/component failure and undesired operation is a far greater challenge. As sustained high temperatures can influence performance, accelerate aging, and even destroy components/devices, appropriately designing and testing a high-power SFB assembly can ensure longevity and proper operation, even under environmental extremes. In many cases, an assembly is tested under extreme temperature conditions to determine whole assembly survivability.

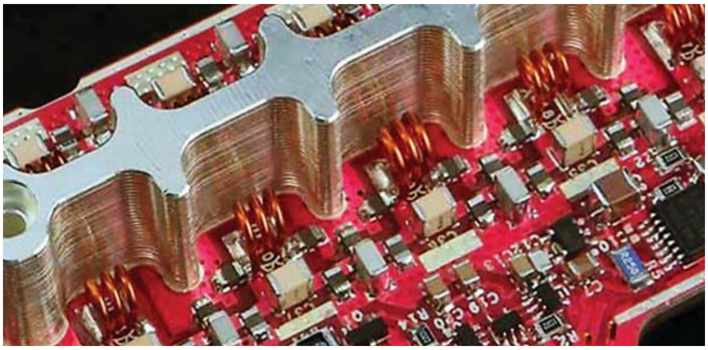
However, extreme temperatures may not occur or affect each component in an assembly in the same way. These factors may require rigorous and individual device and component testing while thermal cycling to discover failure modes and limitations. Understandably, this level of consideration applies to applications where failure of the assembly in the field is worth the added upfront expense of such rigorous performance analysis.

At API Technologies, to avoid failures from thermal breakdown, every high-power design is examined with an infrared camera while under worst-case operational conditions to determine which, if any, components are exceeding their maximum operational tem-

peratures. Typically, if a component is within 15-20% of the maximum operational temperature, they are examined more closely and mitigation actions are taken. In some cases, the company requires the part be tested 100% while being examined with the camera to ensure that those parts do not exceed the operational temperature.

Other methods of optimizing a design with thermal considerations include using 3D CAD models in both electromagnetic (EM) simulators and thermal simulators to predict areas of thermal concern early in the design phase. With some details known about the high thermal stress areas in the design, changes to the thermal management system of the assembly can be successfully made in early stages of the design cycle—where costs for modifications tend to be less expensive.

Computer modeling and simulations have advanced significantly in the past few years (*Fig. 4*). Nevertheless, these design tools cannot replace an engineer's design experience and understanding of the complex interactions between system components. Additionally, a trained eye is extremely valuable in interpreting the modeling and simulation data, then converting that information into design solutions.



4. The placement and design parameters of each component in a high-power SFB are critical for proper device behavior.

The complex design challenges associated with providing reliable and high-performance filtering for the latest high-power applications has brought about many creative and unconventional solutions when compared to a traditional SFB. Producing drop-in SFB modules that leverage standard high volume assembly methods is one approach to reducing the size, cost, and manufacturing time of previous sophisticated custom-made hardware. Future communications technology trends—along with increased commercial, industrial, and military demand for high-power SFB technology—will continue to require design and system engineers to push the boundaries of filter assembly design. mw

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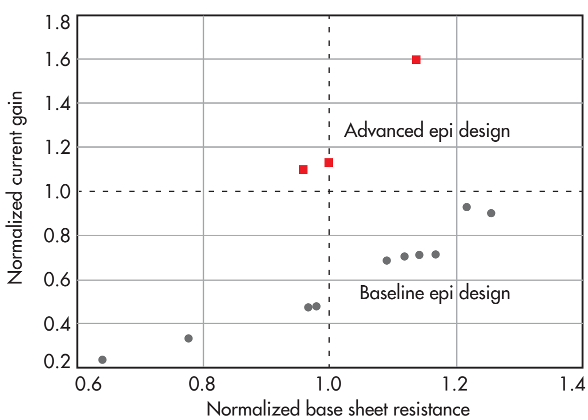
NEXT-GENERATION HIGH-SPEED DIGITAL INTERFACES are quickly and dramatically changing the requirements for millimeter-wave test-and-measurement instruments. For the first time, millimeter-wave components and systems have the potential to reach the masses, in such applications as fifth-generation (5G) cellular communications systems, terabit-rate coherent optical modulation communications, and systems based on the upcoming IEEE P802.3bs 400G standard. All of these applications will require test equipment at millimeter-wave frequencies once considered more experimental than practical, but requirements for bandwidth as faster data rates are creating real needs for those higher frequencies.

Engineers working in these areas will need to test equipment that supports operating frequencies above 60 GHz, data rates faster than 32 Gbaud, and the capability to transmit and receive multi-level coherent modulation formats in multiple-input/multiple-output (MIMO) signaling technologies. The performance of these test instruments is primarily set by the characteristics of the analog front end, which encompasses integrated circuits (ICs) that process analog signals between an instrument's RF input connectors and its data converters.

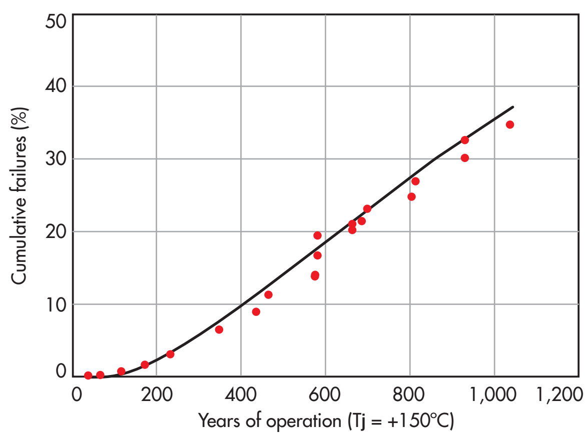
Several years ago, Keysight Technologies took a fresh approach to instrument front-ends by applying indium phosphide (InP) semiconductor technology.[1] ICs fabricated with Keysight's first-generation InP process now power many instrument front-ends, including several of the company's real-time oscilloscopes.[2] Now, with the recent announcement of next-generation real-time and equivalent-time oscilloscopes,[3] ICs fabricated in Keysight's second-generation InP process are paving the way for high-performance instruments that reach beyond 100 GHz.

EXPLORING InP TECHNOLOGY

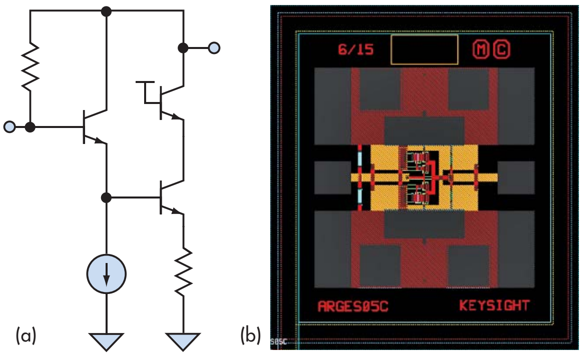
Heterojunction bipolar transistors (HBTs) inherently achieve high RF power levels and high gain per unit area, excellent current gain and turn-on voltage uniformity, large transconductance, and low 1/f noise. The superior material properties of InP



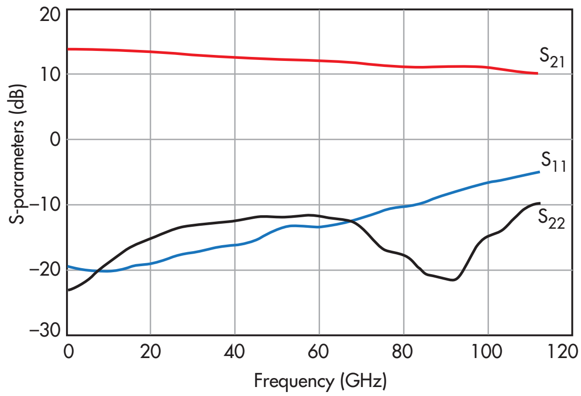
1. The data points show beta versus normalized base sheet resistance values for conventional and advanced base epitaxial design processes.



2. Cumulative failure percentage is shown versus extrapolated lifetime for normal use conditions for about 1,300 HBTs. Stress conditions included junction current, J_c = 4 mA/µm^2, and junction temperature, T_j = +275°C. The results indicate less than 0.4% cumulative failures in over 60 years of normal instrument life.



3. This schematic diagram (left) and circuit artwork (right) show the feedback amplifier.



4. Measurements were made of the feedback amplifier's S-parameter performance.

yield HBT devices with very high speeds, low resistances, high breakdown voltages, and semi-insulating substrates.

These beneficial properties enable the design of ICs for measurement instruments with low noise and high dynamic range beyond 100 GHz. For example, device and process engineers at Keysight's High Frequency Technology Center have successfully scaled the existing InP process[1] by shrinking lateral dimensions, applying advanced epitaxial design, and optimizing dielectric materials and metallization. The second-generation process achieves delay times on the order of 2 ps and maximum frequency of oscillation (f_{max}) approaching 600 GHz while maintaining breakdown voltages above 7 V for high output voltage swings and current gain greater than 50 for robust IC design.

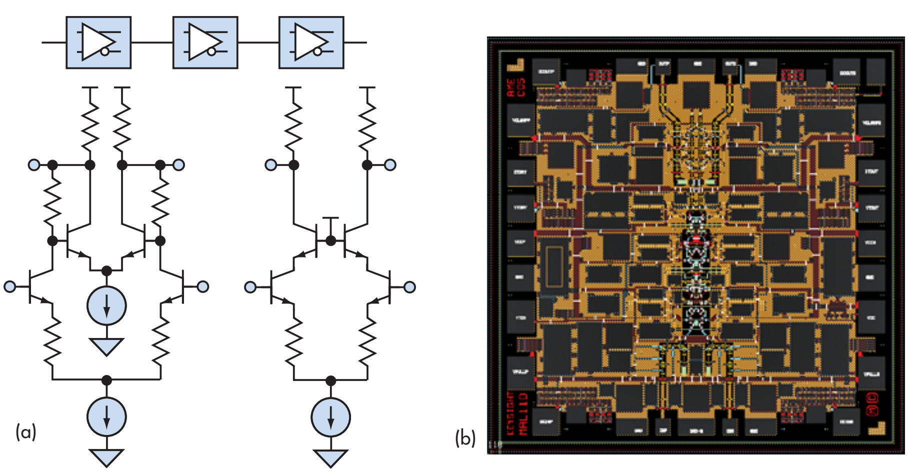
Flexible layout options are available for designs that include any combination of high-speed, low-noise, and low-power attributes. This includes active- and passive-circuit elements (such as HBTs, diodes, thin-film resistors, and capacitors), enabling creation of digital, mixed-signal, and precision analog ICs for next-generation test instruments. The 3-in.-wafer, semiconductor fabrication process is well-suited for low development costs and economical fabrication of very-high-mix ICs in low-to-moderate quantities.

HBT performance has been optimized for instrument-specific requirements. HBT epitaxial design is a key element in determining high device performance, and several major tradeoffs must be optimized to realize performance goals. Two-dimensional physical modeling was used to understand process and circuit tradeoffs to develop the best devices for test-and-measurement instrument purposes.

The three major components of the HBT—emitter, base, and collector—were all optimized. For the emitter and collector, doping and thicknesses were selected for the best balance of device speed, series resistances, and high-voltage operation. For the base, the key tradeoff is between base resistance (lower resistance enables higher speed) and current gain or beta. A minimum value of beta is required for robust circuit performance over the lifetime of the transistor. For Keysight instrument device technology, the base epitaxial structure was designed to accelerate electron flow through the base. This approach allows higher beta for a given base sheet resistance compared to more conventional base epitaxial designs *(Fig. 1)*.

Excellent process control and reliability are essential for an instrument-grade technology that will be used to support a large number of IC and instrument designs. From the beginning of development, the design team emphasized yield, manufacturability, and reliability. To optimize process control, relatively large numbers of lots and wafers were processed, and extensive yield analysis was performed.

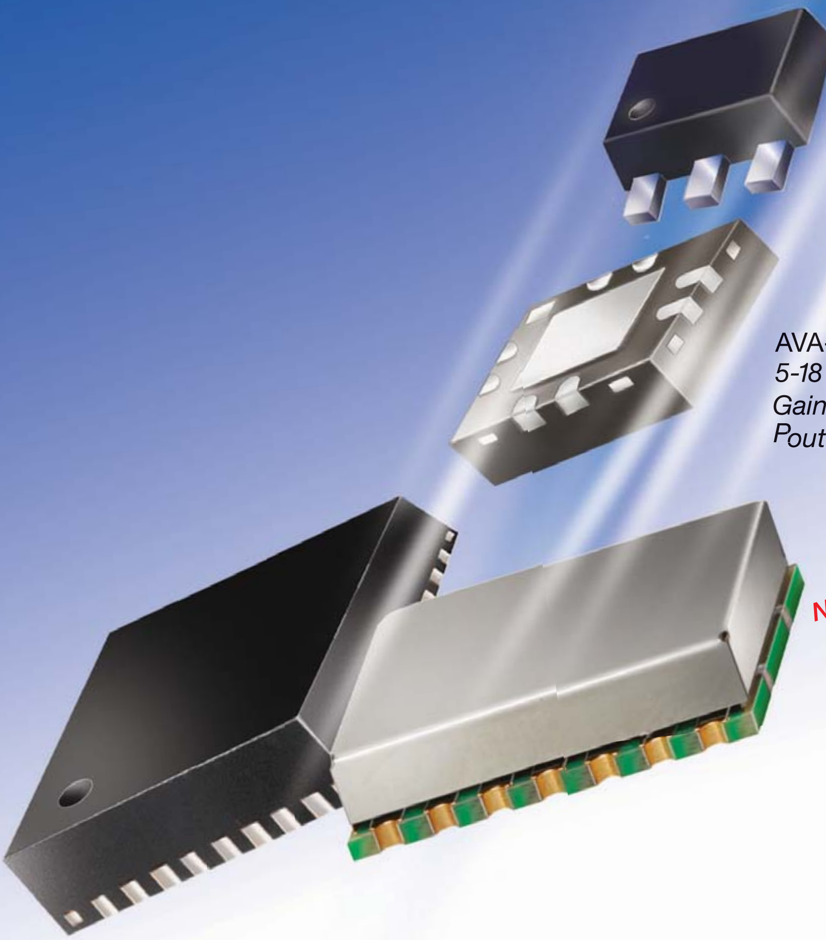
Processes were also optimized for achieving the best conditions of wear-out, infant mortality, and interconnect electro-



5. This schematic diagram (left) and circuit artwork (right) show the differential limiting amplifier.

50 MHz to 26.5 GHz

MICROWAVE MMIC AMPLIFIERS



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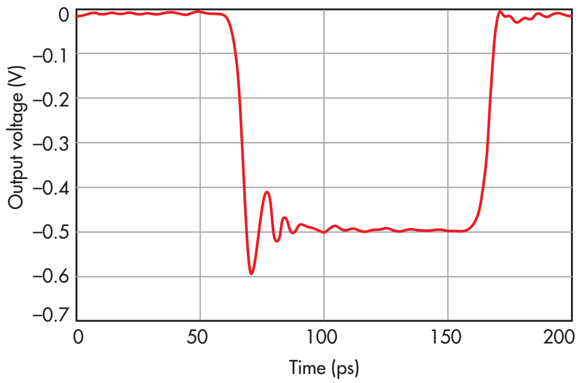
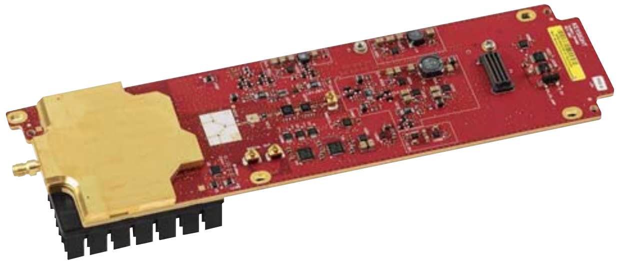


6. Measurements were made of the differential limiting amplifier's rise and fall times.

migration reliability. The result has yielded devices with excellent instrument-grade reliability of less than 0.4% cumulative failures in 60 years of instrument life *(Fig. 2)*. In addition, specialized devices provide built-in electrostatic-discharge (ESD) protection of more than 2 kV.

InP is a workhorse semiconductor process technology that is ideally suited for a wide range of IC types and topologies, ranging from simple passive multipliers and mixers to complex differential pulse amplifiers and multimodulus prescalers. InP diodes and transistors enable creation of ICs with extremely wide bandwidths, large signal swings, low noise, and low dissipated power—all of which are key attributes of time-domain and millimeter-wave-frequency test-and-measurement instruments.

Two general-purpose ICs can be used as examples to highlight the performance capabilities of this second-generation InP HBT semiconductor process: a single-ended feedback amplifier and a differential limiting amplifier. Both ICs have



7. This single-channel front end covers a frequency range of more than dc to 100 GHz.

been designed in a full front-to-back design flow using the Keysight EEsof Advanced Design System (ADS) electronic-design-automation (EDA) software, with Keysight HBT transistor models validated to 110 GHz.

A feedback amplifier provides a simple but effective demonstration of the useful frequency range of a semiconductor process. The device consists of one or more interconnected transistors that comprise a single gain stage surrounded by two feedback resistors that set the amplifier gain and return loss. At high frequencies, capacitances that are inside the transistor reduce the transistor gain and ultimately define the amplifier bandwidth.

Figure 3 shows a schematic diagram and artwork for a recently fabricated feedback amplifier design. In this example, the gain stage is implemented in a cascode Darlington configuration that exhibits low input and output capacitances to maximize bandwidth. *Figure 4* shows the measured small-signal S-parameters for this feedback amplifier. It delivers more than 10 dB gain and 10 dB return loss across a 90-GHz 3-dB bandwidth, making it a generic-but-versatile gain block for millimeter-wave instruments.

(continued on p. 86)

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JACK BROWNE | Technical Contributor

Clocks Attenuate Jitter in Coherent Optical Systems

Using a combination of frequency-generation technologies, this pair of low-jitter clocks provides the clean outputs needed to drive data converters in coherent optical transceivers.

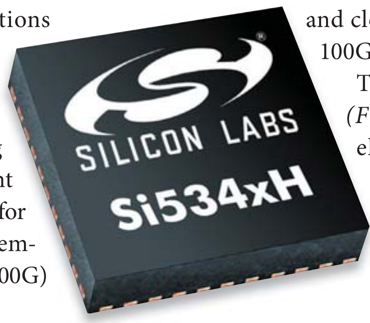
BANDWIDTH IS ESSENTIAL to any communications network, with the need for bandwidth growing as more users communicate on worldwide networks. With voice, video, and data being moved from place to place, the need for speed is driving network operators to pursue faster, more efficient networks. In fact, once standards were established for 100-Gb/s (100G) Ethernet networks, the debate seemingly began about requirements for a 400-Gb/s (400G) Ethernet standard.

Such high data rates typically call for optical communications systems, and those systems require precise clocks for timing and synchronization. To meet the needs of present 100G and future 400G Ethernet in wireless infrastructure, data-center-interconnect (DCI), metro, and long-haul networking equipment, Silicon Labs developed its Si534xH coherent optical clock family.

Boasting output frequencies as high as 2.75 GHz, these devices provide near jitter-free operation in support of coherent optical-fiber communications networks. With unparalleled frequency flexibility and multiple outputs, these clocks are candidates to replace much larger clock trees based on high-frequency voltage-controlled surface-acoustic-wave (SAW) oscillators (VCSOs) for such applications as data-converter clocking in coherent optical transceivers.

Coherent optical communications has made a comeback, in large part, due to advances in digital signal processing (DSP) and field-programmable gate arrays (FPGAs), which provide the digital processing capabilities for implementing advanced modulation schemes such as quadrature phase shift keying (QPSK) in broadband optical cables. Digital techniques can also overcome the limitations of fiber chromatic dispersion and polarization-mode dispersion that haunted earlier versions of chromatical optical communications systems.

For any broadband optical communications network, timing and synchronization are important functions, and the Si534xH series of high-speed clocks minimizes phase noise and clock jitter to levels that permit reliable 100G network performance.



1. The Si534xH series of coherent optical clocks accept inputs from 8 kHz to 750 MHz and provide outputs to 2.75 GHz in high-frequency mode.

The Si534xH series of high-speed clocks (*Fig. 1*) currently consists of two models: the two-input, two-output model Si5342H and the two-input, four-output model Si5344H. Both accept inputs from 8 kHz to 750 MHz and provide outputs to 2.75 GHz. Suitable for transmit- or receive-side timing, they achieve impressively low root-mean-square (RMS) phase jitter of 50 fs for offsets from 1 to 40 MHz when operated in high-frequency mode.

Both models are based on the firm's fourth-generation DSPLL technology, which replaces discrete fixed-frequency PLLs with an innovative, frequency-flexible mixed-signal approach that combines a low-phase-noise analog VCO with a digital phase detector and DSP-intensive, all-digital loop filter. This architecture also leverages SiLabs' proven MultiSynth fractional-N frequency-synthesis technology to generate a wide combination of output frequencies with 0 ppm errors.

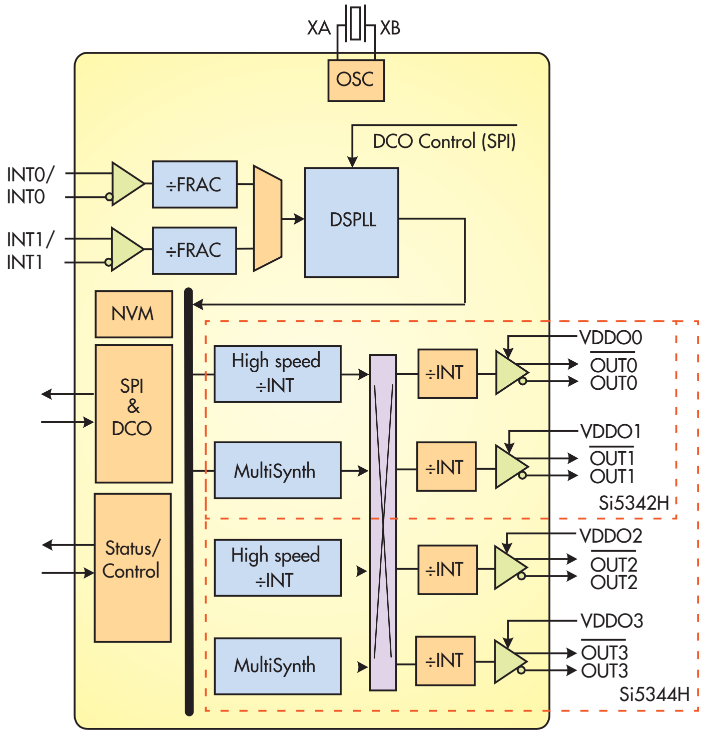
In addition to the high-frequency signals provided by the DSPLL architecture (*Fig. 2*), both devices support lower-frequency clock synthesis based on the firm's MultiSynth technology, capable of generating any frequency to 712.5 MHz. The typical phase jitter for these outputs is less than 150 fs for offsets from 12 kHz to 20 MHz. Output ports for the two devices can be configured for either of the operating modes.

These coherent optical clocks employ frequency multiplication, fractional input dividers, and the internal DSPLL circuitry to produce low-phase-noise outputs from the provided input signals. They can even switch between input clocks without suffering hits, with input switching performed manually or automatically with an internal state machine. The DSPLL circuitry can execute hitless switching between input clocks, even for two input clocks that are as much as ±500 ppm apart in frequency.

The amount of input clock jitter attenuation is controlled by the DSPLL loop bandwidth, with programmable loop bandwidths ranging from 0.1 Hz to 4 kHz. Since narrowband PLLs typically trade off longer lock acquisition times for greater jitter filtering at lower loop bandwidths, the Si534xH clocks offer a fast-lock mode that enables the devices to quickly acquire lock at a higher loop bandwidth and dynamically switch to a lower loop bandwidth once PLL lock is achieved.

In addition to the DSPLL circuit, both coherent optical clocks include MultiSynth dividers, capable of generating output signals that are integers or fractionally related multiples of the input signals for further signal-generation flexibility.

The Si5344H and Si5342H clocks include a digitally controlled oscillator (DCO) mode in which fast update rates can be achieved, and where all outputs are controlled simultaneously. This mode disables the outer loop of the dual-loop DSPLL circuitry to achieve updates that are essentially limited by the speed of the serial bus interface.



2. This block diagram shows the basic components within each of the two coherent optical clocks, and how different operating modes are achieved.

Both devices offer clock outputs that are highly configurable and can be programmed with specific voltage swings and for compatibility with a wide range of digital waveform standards. These include low-voltage positive emitter coupled logic (LVPECL), low-voltage complementary metal oxide semiconductor (LVCMOS), low-voltage differential signaling (LVDS), current mode logic (CML), and high-speed current-steering logic, although only LVPECL is available in the high-frequency mode.

The two clocks feature fast warmup time, with typical startup of 30 ms from power on to providing free-running output signals with stability based on an external reference oscillator. Both the Si5342H and the Si5344H devices are designed to provide precise frequency multiplication of supplied input signals and work with a simple, low-cost fundamental mode crystal. Due to the PLL design of these clocks, the best jitter performance is obtained with a crystal reference source from 48 to 52 MHz. A frequency-adjustment feature provides an adjustment range of ±200 ppm to correct for frequency offsets.

The devices offer multiple operating modes, including free-run, lock-acquisition, locked, and holdover modes. In free-run mode, the frequency accuracy of the output clock signals depends on the frequency accuracy of the external crystal or reference clock. The frequency accuracy of the output signals will match the accuracy of the reference. When high accuracy is needed in this operating mode, a high-stability oscillator, such as a temperature-controlled crystal oscillator (TCXO), may be used.

In lock-acquisition mode, input signals are monitored for a valid clock signal. After a selected input clock is validated, the DSPLL will automatically start the lock-acquisition process. In locked mode, the DSPLL generates output signals that are frequency- and phase-locked to the selected input clock. Once this is achieved, any input crystal-oscillator frequency drift will not affect the accuracy of the output frequency.

These devices will enter holdover mode when the selected input clock becomes invalid and a valid clock is not available on the other input. At that point, the DSPLL uses an averaged input-clock frequency as its holdover frequency to minimize degradation of the output-clock phase and frequency. The holdover circuitry stores as much as 120 s of historical frequency data while locked to a valid clock input, for use in holdover mode.

Both devices are programmed by means of a serial interface—either a serial peripheral interface (SPI) or I^2C interface. The ICs contain on-board nonvolatile memory that is read upon power-up, allowing the clocks to power up with a preprogrammed frequency configuration, simplifying device startup. They operate on core voltages of +1.8 and +3.3 V dc and include independent output supply pins for voltages of +3.3 V dc, +2.5 V dc, and +1.8 V dc.

Users can work with the firm's ClockBuilderPro software to program either device or choose factory-preprogrammed devices for known applications. Both clocks are built with lead-free and RoHS-compliant manufacturing processes and are designed for operating temperatures from −40 to +85°C. They are both supplied in 7- × 7-mm, 44-lead QFN packages. MW

DAVID LEWICKI | Military Products Manager, RF Power
NXP Semiconductors

Broadband GaN Transistors Power EW, Tactical Radios

These half-dozen new RF power transistors are extremely rugged and reliable, with generous output-power levels over broad bandwidths—ideal for demanding battlefield requirements.

ELECTRONIC WARFARE (EW) systems have commonly been broadband, with operating frequencies extending well into the millimeter-wave region and requiring components capable of handling broad bandwidths—often under hostile operating conditions. In contrast, improvised explosive devices (IEDs) make it necessary for jammers to operate at much lower frequencies, down to the high-frequency (HF) range.

Military communication systems are also operating over wider frequency ranges for effective operation in diverse environments. To meet so many different requirements, NXP has expanded its portfolio of broadband gallium nitride (GaN) RF power transistors with six new driver and output-stage devices for use at frequencies from 1 to 3,000 MHz.

The new transistors are designed using GaN-on-SiC technology that provides high power density, along with ruggedness and very flat frequency response over wide bandwidths. All six models are input-matched to optimize operating frequency range, and can withstand VSWRs greater than 20:1 with 3-dB overdrive without degradation. All but one operate from a +50-V dc supply, with the other requiring +28 V dc. NXP's proprietary low-thermal-resistance, over-molded plastic packaging houses five of the transistors. To help designers, application circuits are available in support of continuous-wave (CW) circuits from 200 to 2,500 MHz.

Models MMRF5011NR5 and MMRF5013NR5 operate between 1 and 3,000 MHz, delivering broadband RF output power of 10 W CW and narrowband RF output power of 12 W CW. The MMRF5011NR5 is a +28-V dc device with high 60% efficiency, while the MMRF5013NR5 operates from a +50-V dc supply with 60% efficiency. The MMRF5013N is designed to drive the MMRF5015NR5, an output-stage device that delivers 100 W CW broadband output power and 125 W CW narrowband output power across a total frequency range of 1 to 2,700 MHz with 64% efficiency.

The model MMRF5021HR5 GaN-on-SiC RF power transistor delivers as much as 250 W CW output power with 58% efficiency from 1 to 2,700 MHz.

The MMRF5019NR5 operates between 1 and 3,000 MHz with RF output power of 20 W CW broadband and 25 W CW narrowband output power and 66% efficiency. It is designed to drive the MMRF5021HR5 output-stage device, which operates between 1 and 2,700 MHz and is tailored for wideband applications, delivering 250 W CW with 58% efficiency *(see figure)*. Finally, model MMRF-5023NR5 also operates between 1 and 2,700 MHz, producing 50 W CW broadband and 63 W CW narrowband output power with 60% efficiency.

All of the devices have a broad frequency range from HF to S-band, making it possible to reduce the number of RF power transistors required for broadband amplifiers in EW systems and battlefield radios. The result is a reduction in design complexity, as well as in the bill of materials (BOM) for those systems.

Since the company increased its support of defense applications in 2013, it has expanded its range of RF power transistors for EW and communications applications—as well as for HF, VHF, UHF, and L-band radar; identify-friend-or-foe (IFF) transponders; and avionics systems. In addition to GaN devices, the firm offers more than 40 LDMOS transistors between 1 to 3,000 MHz, from low power levels to 1,500 W CW—currently the highest RF output power available from a single device over its operating frequency range of 1,030 to 1,090 MHz. The six new GaN transistors are either sampling or in production. mw

NXP SEMICONDUCTORS, 1300 North Alma School Road., Chandler, AZ 85224; *www.nxp.com/RF*

Low-Noise Amplifier Gains 1 to 2 GHz

AMPLIFIERS WITH LOW NOISE figure enable a receiver with sufficient sensitivity to capture low-level signals within their frequency range. As a candidate for broadband receivers in the 1-to-2-GHz frequency range, model PEC-53-12-10-15-SFF is a low-noise amplifier (LNA) that combines low noise figure of 0.7 dB with high minimum gain of 53 dB to help capture faint signals across that frequency range. The amplifier features gain flatness of ±0.75 dB across the 1-GHz bandwidth. The unit provides minimum of +16 dBm output power at 1-dB compression. It exhibits input/output of 1.50:1 and draws 450 mA current from a voltage supply of +12 to +15 V dc. The amplifier measures 2.405 × 0.66 × 0.20 in. and is supplied with female SMA connectors. It is designed for operating temperatures from –55 to +85°C.

PLANAR MONOLITHICS INDUSTRIES INC., 7311-F Grove Rd., Frederick, MD 21704; (301) 662-5019, *www.pmi-rf.com*

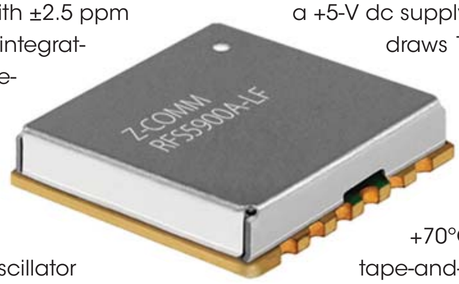
Fixed Attenuators Cover DC to 6 GHz

THE N5405-XX SERIES OF FIXED ATTENUATORS operate from DC to 6 GHz and can be specified with attenuation values of 1 to 60 dB. They handle 5 W continuous input power and as much as 250 W peak input power over the full frequency range. Insertion loss is only 0.5 dB for attenuation values to 20 dB and no more than 1.5 dB for attenuation values to 60 dB. The maximum VSWR is 1.15:1 from DC to 4 GHz and 1.20:1 from 4 to 6 GHz. The rugged attenuators are available with stainless-steel Type-N or SMA male or female coaxial connectors.

ARRA INC., 15 Harold Court, Bay Shore, NY 11706-2296; (516) 231-8400, *www. arra.com*

Synthesizer Locks to C-Band Frequency

MODEL RFS5900A-LF is a phase-locked frequency synthesizer operating at 5.9 GHz with ±2.5 ppm stability. It is fully integrated with a voltage-controlled oscillator (VCO), phase-locked loop (PLL), and 10-MHz reference oscillator in a package measuring 0.6 × 0.6 × 0.13 in. The synthesizer features typical phase noise of –80 dBc/Hz offset 1 kHz from the carrier, –85 dBc/Hz offset 10 kHz from the carrier and –103 dBc/Hz offset 100 kHz from the carrier. It provides +3 dBm output power with ±2-dB flatness. Spectral purity includes second harmonics of –25 dBc and spurious suppression of –65 dBc. The VCO draws 35 mA from a +5-V dc supply while the PLL draws 15 mA from a +3-V dc supply. The synthesizer, which has an operating temperature range of –30 to +70°C, is available in tape-and-reel packaging for automated assembly manufacturing methods.



Z-COMMUNICATIONS INC., 14118 Stowe Dr., Ste. B, Poway, CA 92064; (858) 621-2700, *www.zcomm.com*

VCO Tunes 2 to 4 GHz

MODEL RFVC6405 is a voltage-controlled oscillator (VCO) from Qorvo which is now available from stocking distributor RFMW, Ltd. The oscillator tunes across the full octave band from 2 to 4 GHz with second harmonics of –15 dBc or better and phase noise of –90 dBc/Hz offset 10 kHz from the carrier. The VCO, which draws 25 mA current from a +5-V dc supply, delivers 0 dBm output power across the full tuning range, using tuning voltages from 0 to 16 V dc. The source is supplied in a castellated package measuring 0.5 × 0.5 in. and usable over operating temperatures from –40 to +85°C.

RFMW LTD., Qorvo Stocking Distributor, 188 Martinvale Ln., San Jose, CA 95119; (408) 414-1450, *www.rfmw.com*

Amp Module Boosts Signals to 18 GHz

DESIGNED FOR HIGH EFFICIENCY (better than 14% dc-to-RF efficiency), model BME69188-50 is a broadband power-amplifier (PA) module capable of 50-W output power from 6 to 18 GHz. Based on gallium-nitride (GaN) active device technology, the Class-AB linear PA module delivers 47-dB gain with ±4-dB gain flatness across the full frequency range. The input overdrive level is +10 dBm. The maximum input/output VSWR is 2.0:1. Spectral purity is excellent, with second harmonics of –15 dBc, third harmonics of –25 dBc, and spurious levels of –60 dBc. Suitable for boosting signals in communications, electronic-warfare (EW), and radar systems, the PA module features built-in test functions, including overtemperature, overcurrent, and composite test capabilities. It runs on a +28-V dc supply and has a TTL-controlled enable/disable function with 1-μs switching speed. The amplifier measures 6.56 × 3.50 × 0.84 in. and weighs 1.5 lb. with field-replaceable female SMA RF input and output connectors. It handles operating temperatures from –40 to +55°C.

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

InP Technology

(continued from p. 78)

A differential limiting amplifier offers an alternate demonstration of the second-generation InP semiconductor process—one that is particularly useful for time-domain instruments that measure digital waveforms. In this amplifier, multiple cascaded gain stages amplify an input signal, saturating the output stage and producing a waveform with two well-defined voltage levels and very fast transitions between those levels.

The example shown in *Fig. 5* contains three gain stages implemented as Cherry-Hooper and cascode differential amplifiers. *Figure 6* shows a measured 500-mV output waveform for a 5-GHz input signal. With less than 4-ps rise and fall times, this amplifier will find use in millimeter-wave instruments requiring ultralow jitter.

At millimeter-wave frequencies, a critical element of subsystem design is the monolithic-microwave-integrated-circuit (MMIC) package co-design. Maintaining MMIC performance to the front panel or subsystem connector requires thorough three-dimensional (3D) electromagnetic (EM) modeling. In addition, thermal modeling and validation helps ensure proper thermal management and reliable operation of components and circuits within a test instrument.

Finally, the large level of integration on a subsystem—such as millimeter-wave, RF, analog, and digital circuitry and their components—drives the need for a variety of packaging technologies to address each requirement at the optimal performance/cost point. *Figure 7* shows an example of a complete front-end assembly that combines proprietary hybrid-on-printed-circuit-board (PCB) technology, with precision thin- and thick-film components and surface-mount-technology (SMT) components assembled in a compact 3- × 10-in. footprint.

Design validation and characterization are crucial and challenging to do at millimeter-wave frequencies. The ability to extract and match more data to models often translates into faster convergence on the desired performance in the next MMIC design turn. For the complex circuits required in high-speed-digital and millimeter-wave test equipment, the tests range from frequency-domain S-parameter measurements to measurements of differential S-parameters/compression/harmonics combined with time-domain characterization.

Performance demands of next-generation high-speed digital interfaces are dramatically changing the requirements for millimeter-wave test-and-measurement instruments. Engineers working on technologies such as 400-Gb Ethernet, terabit optical, and 5G communications will need test equipment that meets next-generation requirements for higher speeds, lower noise, lower power dissipation, and higher dynamic range. ICs fabricated in Keysight's second-generation InP process are paving the way for high-performance instruments that reach beyond 100 GHz. mw

KEYSIGHT TECHNOLOGIES INC., 1400 Fountaingrove Pkwy., Santa Rosa, CA 95403; (707) 577-2663, *www.keysight.com*

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