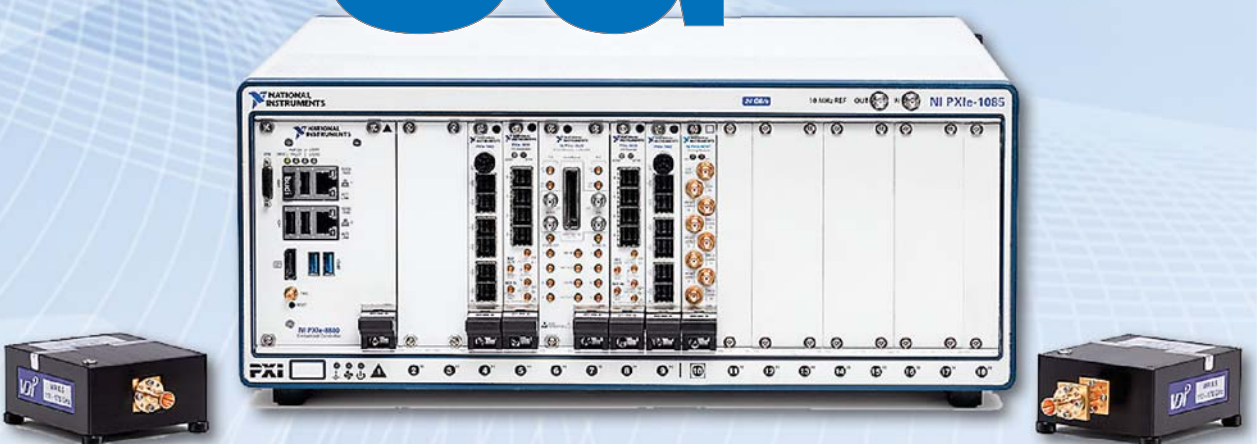
Microwaves & RF®

YOUR TRUSTED ENGINEERING RESOURCE FOR OVER 50 YEARS

NOVEMBER 2019 mwrf.com

# Setting the Stage for 6G

While 5G gears up, the arrival of this sub-THz testbed pushes 6G into the picture p19



# Planar Monolithics Industries, Inc.

## Integrated RF/Microwave Assemblies & Modules

PMI offers the highest quality multi-function modules and integrated microwave assemblies for industrial and military applications in frequency ranges up to 50 GHz. Built to your specifications with functions that include amplification, attenuation, filtering, switching, phase shifting, power detection, modulation, coupling, limiting and digital/analog control. PMI offers many other standard models with various options that are available at:
https://www.pmi-rf.com/categories/integrated-mic-mmic-assemblies

- Amplifiers
- Attenuators
- Bi-Phase Modulators
- Couplers
- Detectors - RF / Microwave
- DLVAs, ERDLVAs & SDLVAs
- Filters & Switched Filter Banks
- Form, Fit, Functional Products & Services
- Frequency Converters
- Frequency Sources
- Frequency Discriminators & IFM
- Frequency Synthesizers
- Gain & Loss Equalizers
- Integrated MIC/MMIC Assemblies
- IQ Vector Modulators
- Limiters - RF / Microwave
- Miscellaneous Products
- Monopulse Comparators
- Multifunction Integrated Assemblies
- Phase Shifters
- Power Dividers
- Rack & Chassis Mount Products
- Receiver Front Ends & Transceivers
- Single Side Band Modulators
- SMT & QFN Products
- Switch Matrices
- Switch Filter Banks
- Switches - Solid-State
- Systems - Radar Sense & Avoid
- Systems - Fly Eye Radar
- USB Style Product

### 3U Open VPX Transceiver

**PTRAN-100M18G-SFB-3UVPX-10HP-MAH**
http://www.pmi-rf.com/model-ptran-100m18g-sfb-3uvpx-10hp-mah

- 100 MHz to 18.0 GHz Transceiver
- Integrated Up and Down Converters
- IF up to 4 GHz
- Time Gated SDLVA for Pulse Blanking
- -80 to -10 dBm Input Dynamic Range
- Customizable Switched Filter Banks
- 0 to +10 dBm Transmit Power
- 100 ns Switching Speed
- Fits into a 3U open VPX form factor utilizing the high speed VITA 67 RF connector.
- CW Immunity

### Amplified RF Downconverter Modules

**LCM-7R7G8R2G-CD-1 & LCM-16G100MBW-CD-1**
https://www.pmi-rf.com/model-no-lcm-7r7g8r2g-cd-1
https://www.pmi-rf.com/model-no-lcm-16g100mbw-cd-1

- Customized Frequency Ranges:
  LCM-7R7G8R2G-CD-1: 7.7 to 8.2 GHz
  LCM-16G100MBW-CD-1: 16.0 GHz ± 50 MHz
- IF range of DC to 10 KHz
- Features a 20 dB voltage programmable attenuator and a 360° phase shifter.
- Designed for low spectral noise and high reverse isolation
- Slim line housing measuring only 2.5" x 1.75" x 0.4"

### Phase and Amplitude Matched Integrated Modules in sets of four

**PCAM-05G18G-INT-S5F**
https://www.pmi-rf.com/product-details/pcam-05g18g-int-s5f

- Operating Frequency Range of 0.5 to 18.0 GHz.
- Built in sets of four, phase and amplitude matched to industry leading levels of ±10° and ±1.5 dB over the frequency range.
- Incorporates limiters, LNAs, switches, and variable digital attenuators.
- These units allow for high and low gain paths, a calibration input, and an auxiliary channel.
- A low noise figure and high output P1dB of +15 dBm are achieved by utilizing system analysis software and in-house hybrid/MIC processes.
- SMA Female connectors and small housing configuration.

### Quad Phase and Amplitude Matched Diplexer Gain Module

**DGM-18G40G-292FF-DS**
https://www.pmi-rf.com/model-dgm-18g40g-292ff-ds

- Operating Frequency Range: 18.0 to 40 GHz.
- Switched output and an integrated power divider feeding the four antenna inputs via a 20 dB coupler for ease of system integration.
- Band select function not only switches bands, but allows the amplified bands not in use to be turned off to reduce power consumption.
- Designed to have better than 60 dB harmonic suppression.

### CW immune EW Detector Modules

**EWDM-2G8G-65-70MV & EWDM-8G18G-65-70MV**
https://www.pmi-rf.com/product-details/ewdm-2g8g-65-70mv
https://www.pmi-rf.com/product-details/ewdm-8g18g-65-70mv

- Customized Frequency Ranges:
  EWDM-2G8G-65-70MV: 2.2 to 8.0 GHz
  EWDM-8G18G-65-70MV: 8.0 to 18 GHz
- Internal switch used to switch between the Bit IN and RF IN with input blanking on both ports.
- RF output port is provided with a gain of 33 dB minimum
- Video output is designed to drive a 150 ft. cable with input dynamic range of 65 dB & TSS of -71 dBm

### Active, Filtered, Frequency Doubler Modules

**PFDM-3R66R65-13-7R5DC-SFF**
https://www.pmi-rf.com/active-filtered-frequency-doubler-module-3-6ghz-to-13-3ghz-

- Frequency Range: Input: 3.6 - 6.65 GHz
  Output: 3.6 - 13.3 GHz
- Dual RF Output - TTL Switchable, Switching Speed: < 20 ns
- RF Output #1 to RF Output #2 Isolation: >35 dB
- Slim line housing measuring only 3.0" x 1.5" x 0.375"
- Other Frequency Ranges and Output Power Levels Available.


**West Coast Operation:**
4921 Robert J. Mathews Pkwy, Suite 1
El Dorado Hills, CA 95762 USA
Tel: 916-542-1401, Fax: 916-265-2597

**East Coast Operation:**
7311-F Grove Road
Frederick, MD 21704 USA
Tel: 301-662-5019, Fax: 301-662-1731

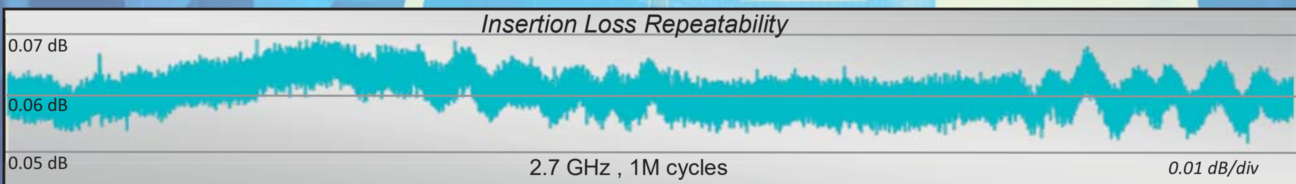
sales@pmi-rf.com . www.pmi-rf.com


ISO9001-2015 REGISTERED

# High Performance Switches

***50*** **years of expertise and the largest selection up to *50* GHz**

| Features | SPDT | TRAN | SPMT |
|---|---|---|---|
| Frequency Coverage | DC to 3, 6, 12, 18, 20, 26.5, 40 or 50 GHz | | |
| Actuator Operation | Failsafe, Latching | Failsafe, Latching | Normally Open, Failsafe, Latching |
| Switch Voltage (Vdc) | 12, 15, 24, 28 (standard) | | |
| Outputs | 2 or 3 | 2 | 3 up to 12 |
| 50Ω Terminations | Option (Int or Ext) | Ext | Option (Int or Ext) |
| Life | Up to 5,000,000 cycles | | |
| RF Connectors - Female | SMA, 2.92mm, 2.4mm, Type-N, SC, SMT | | |
| Control Connection | Solder Terminals, D-Sub, Mini D-Sub, Dip Socket | | |
| Additional Features | Indicators, Self Cut-Off, TTL, Decoders, +COM, Auto Reset, Diodes, Moisture Sealing, Ruggedized, Custom Designs, Obsolete OEM Replacements, LoPIM, High-Power | | |




| Specialty Products | | | | | | |
|---|---|---|---|---|---|---|
| Attribute | Switch Family | SMA | Type-N | SC | 7/16 DIN | 4.3-10 DIN |
| Power Handling (avg) | SPDT, TRAN, SPMT | 110W | 300-450W | 800W-1kW | | |
| Lo-PIM (typ) | SPDT, TRAN, SPMT | -160 dBc | -163 dBc | | -165 dBc | -165 dBc |

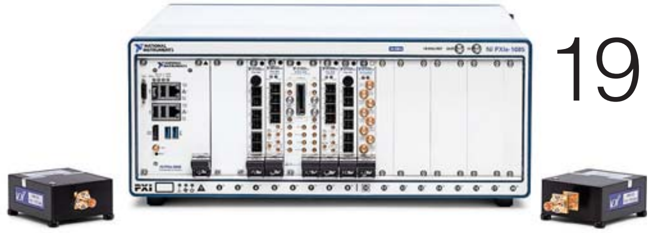
**Our ISO-9001 certified manufacturing capability exceeds 10,000 units/month. We offer a full line of switches and relays on based 50 years of innovative design expertise. Contact us today for all of your switch and relay needs.**

**e360microwave**

***www.e360microwave.com***

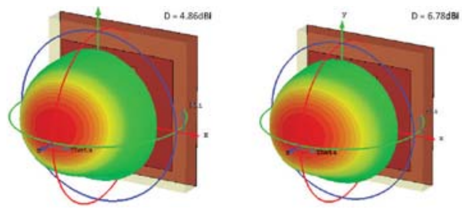
*Santa Clara, California USA / 1-408-650-8360 (O)*

# IN THIS ISSUE

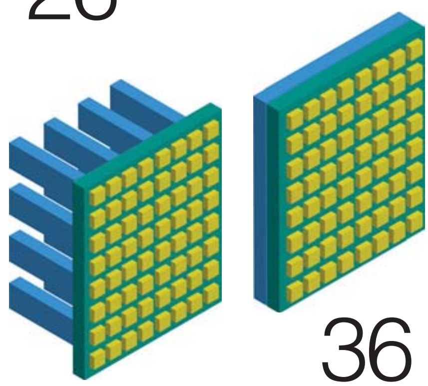

19

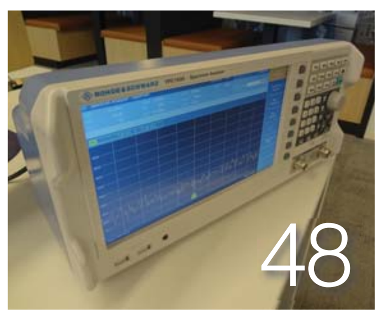
## FEATURES





26


36




## NEWS & COLUMNS



## PRODUCTS & TECHNOLOGY



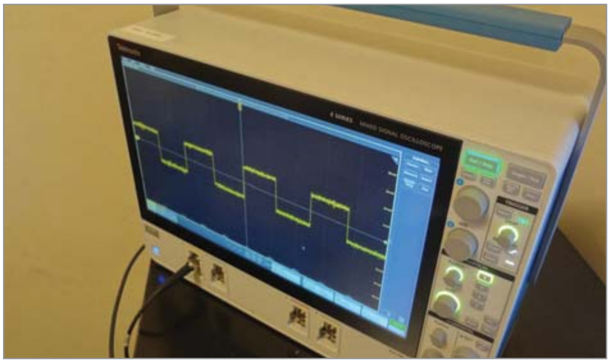
JOIN US ONLINE

follow us @MicrowavesRF

become a fan at facebook.com/microwavesRF


52

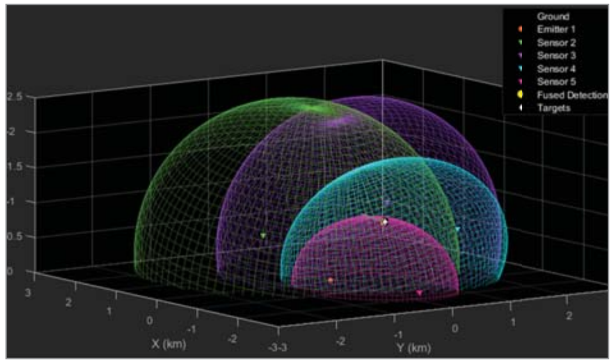
# ON MICROWAVES&RF.COM



## Analyze Multiple Domains with Just One Oscilloscope

Equipped with new mixed-domain analysis capability, this scope goes above and beyond traditional measurements.

*https://www.mwrf.com/test-measurement/analyze-multiple-domains-just-one-oscilloscope*




## Modeling Multistatic Radar Systems

In this Algorithms to Antenna blog, the authors review an example of how polarization can be used in a multistatic radar to localize and track multiple targets.

*https://www.mwrf.com/systems/algorithms-antenna-modeling-multistatic-radar-systems*

## 60-GHz Wireless Data Interconnect Targets Slip-Ring Applications

To handle the demands of Industry 4.0, high speed, ultra-low latency, and maintenance-free operation are important parameters. Here's a mmWave-based solution for slip-ring assemblies that meets those needs.

*https://www.mwrf.com/systems/60-ghz-wireless-data-interconnect-targets-slip-ring-applications*

## SCADA: Alive and Well in the Age of IoT

Despite the onslaught of the Internet of Things within the industrial world, SCADA will continue to evolve to meet today's demands.

*https://www.mwrf.com/systems/scada-alive-and-well-age-iot*

join us online

twitter.com/MicrowavesRF facebook.com/microwavesrf

Editorial

CHRIS DeMARTINO | Editor
chris.demartino@informa.com

# Where Will Tomorrow's Technology Take Us?

**Wireless technology has become a dominant force in our everyday lives, yet some are looking way ahead with the hope of pushing the envelope further to create tomorrow's communications.**

It comes as no surprise to anyone that wireless technology has become a central aspect of our lives today. Of course, it's hard to imagine a world without smartphones—simply look around and everyone seemingly has one in hand. But years ago, did people think that such technology would be as entrenched in our lives as it is today? After all, it wasn't that long ago when cell phones weren't even part of the culture.

Furthermore, services like Uber and Lyft, which are now a major part of our everyday lives, didn't exist a mere 15 years ago. Back then, could we really predict that we would one day have such ridesharing companies? They represent only two of many examples that illustrate how technology has made such an impact on our lives. But this discussion does help lead to the next question: What will tomorrow's technology bring us?

We're constantly hearing about 5G communications and the great promise it holds. Of course, we'll have to wait and see how 5G ultimately plays out. But what's really eye-opening is that while we're only at the dawn of the 5G era, some are already investigating 6G technology. That's right, 6G technology! For proof of this, check out the article, "Looking Way Ahead to 6G" *(see p. 19)*, which examines a new sub-terahertz (sub-THz) testbed intended for 6G research. The testbed was built through a collaboration between National Instruments (NI) *(www.ni.com)* and Virginia Diodes (VDI) *(www.vadiodes.com)*.

In the article, NI's Sarah Yost states she "thinks that this testbed for THz and sub-THz research definitely does fall into something that can truly be considered 6G technology." She also noted that she's "really looking forward to seeing where the research goes as we get into 6G and some of these 'far-out' applications and ideas for communications."

We don't know for certain what the technology of the future will look like. But what we do know is that while the world takes advantage of today's technology, some people are busy researching what they hope will be the transformative technology in the future. What will the communications technology of tomorrow be like? Only time will tell. mw

Microwaves&RF **NOVEMBER 2019**

## EDITORIAL

GROUP CONTENT DIRECTOR: **KAREN FIELD** karen.field@informa.com
SENIOR CONTENT DIRECTOR: **BILL WONG** bill.wong@informa.com
EDITOR: **CHRIS DeMARTINO** chris.demartino@informa.com
SENIOR STAFF WRITER: **JAMES MORRA** james.morra@informa.com
TECHNICAL EDITOR: **JACK BROWNE** jack.browne@informa.com
ASSOCIATE EDITOR/COMMUNITY MANAGER: **ROGER ENGELKE** roger.engelke@informa.com

## ART DEPARTMENT

GROUP DESIGN DIRECTOR: **ANTHONY VITOLO** tony.vitolo@informa.com
CONTENT DESIGN SPECIALIST: **JOCELYN HARTZOG** jocelyn.hartzog@informa.com
CONTENT & DESIGN PRODUCTION MANAGER: **JULIE JANTZER-WARD** julie.jantzer-ward@informa.com

## PRODUCTION

GROUP PRODUCTION MANAGER: **GREG ARAUJO** greg.araujo@informa.com
PRODUCTION MANAGER: **VICKI McCARTY** vicki.mccarty@informa.com

## AUDIENCE MARKETING

USER MARKETING MANAGER: **DEBBIE BRADY** debbie.brady@informa.com

**FREE SUBSCRIPTION / STATUS OF SUBSCRIPTION / ADDRESS CHANGE/ MISSING BACK ISSUES:**
OMEDA **T** | 847.513.6022 **TOLL FREE** | 866.505.7173

## SALES & MARKETING

MANAGING DIRECTOR: **TRACY SMITH** **T** | 913.967.1324 **F** | 913.514.6881 tracy.smith@informa.com
REGIONAL SALES REPRESENTATIVES:
AZ, NM, TX: **GREGORY MONTGOMERY** **T** | 480.254.5540 gregory.montgomery@informa.com
AK, NORTHERN CA, OR, WA, WESTERN CANADA: **STUART BOWEN** **T** | 425.681.4395 stuart.bowen@informa.com
AL, AR, SOUTHERN CA, CO, FL, GA, HI, IA, ID, IL, IN, KS, KY, LA, MI, MN, MO, MS, MT, NC, ND, NE, NV, OH, OK, SC, SD, TN, UT, VA, WI, WV, WY, CENTRAL CANADA: **JAMIE ALLEN** **T** | 415.608.1959 **F** | 913.514.3667 jamie.allen@informa.com
CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT, EASTERN CANADA:
**ELIZABETH ELDRIDGE** **T** | 917.789.3012 elizabeth.eldridge@informa.com

INTERNATIONAL SALES:
GERMANY, AUSTRIA, SWITZERLAND: **CHRISTIAN HOELSCHER** **T** | 011.49.89.95002778
christian.hoelscher@husonmedia.com
BELGIUM, NETHERLANDS, LUXEMBURG, UNITED KINGDOM, SCANDINAVIA, FRANCE, SPAIN, PORTUGAL:
**JAMES RHOADES-BROWN** **T** | +011 44 1932 564999 **M** | +011 44 1932 564998 james.rhoadesbrown@husonmedia.co.uk
ITALY: **DIEGO CASIRAGHI** diego@casiraghi-adv.com
PAN-ASIA: **HELEN LAI** **T** | 886 2-2727 7799 helen@twoway-com.com
PAN-ASIA: **CHARLES LIU** **T** | 886 2-2727 7799 liu@twoway-com.com

PLEASE SEND INSERTION ORDERS TO: orders@informa.com
INFORMA REPRINTS: **WRIGHT'S MEDIA** **T** | 877.652.5295
LIST RENTALS/ SMARTREACH CLIENT SERVICES MANAGER: **MARY RALICKI** **T** | 212.204.4284
mary.ralicki@informa.com

## DIGITAL

GROUP DIGITAL DIRECTOR: **RYAN MALEC** ryan.malec@informa.com

## DESIGN ENGINEERING & SOURCING GROUP

GROUP CONTENT DIRECTOR: **KAREN FIELD** karen.field@informa.com
VP OF MARKETING: **JACQUIE NIEMIEC** jacquie.niemiec@informa.com

## INFORMA MEDIA INC.

605 THIRD AVENUE
NEW YORK, NY 10158 USA **T** | 212.204.4200

informa

Electronic Design | Machine Design | Microwaves & RF | Source ESB | Hydraulics & Pneumatics |
Global Purchasing | Distribution Resource | Power Electronics | Defense Electronics

# News

# BRING UNITY TO Electrical and Thermal Analysis

Earlier this year, Cadence *(www.cadence.com)* introduced the Clarity 3D Solver, a 3D electromagnetic (EM) field solver for printed-circuit-board (PCB) and integrated-circuit (IC) package design. Following up on that, Cadence recently unveiled the Celsius Thermal Solver, which the company says is the first complete electrical-thermal co-simulation solution for electronic systems *(see figure)*. Continuing what the Clarity 3D Solver began, the Celsius Thermal Solver is the second product in what Cadence calls its new system analysis initiative.

Cadence maintains that next-generation designs require a new electrical-thermal co-simulation solution. CT Kao, product management director at Cadence, provides some background information concerning this topic. "Electrical performance and thermal profiles are interwoven together," he says. "A system's electrical performance will depend on the thermal response. Electrical resistance and power dissipation will be affected by temperature. The temperature profile will impact the electronic system's functionality. Sometimes it will even cause failure if there are unwanted hotspots."

Kao continues, "The thermal profile will be affected by electrical behavior because currents traveling through resistance will introduce an additional heat source. In some cases, high-current surges can arise that can cause local hotspots and result in damage. So, electrical and thermal analysis must be performed together. That's why we want to address these challenges and provide a unified tool."

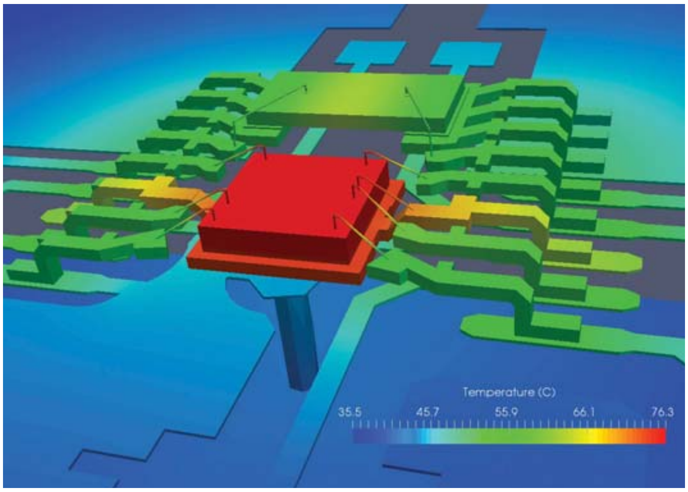
On top of that, Kao points out that transient simulation is critical in electronic design, with a main reason being multiple operational modes. "Take a smartphone, for example," he says. "You're watching videos, listening to audio, and browsing the web—but not at the same time. All of the power has to be turned on and off to satisfy the user needs. The power scheme and the power profile have to be time-varying. That introduces difficulties in the analysis and simulation."

### THE ANSWER: CELSIUS THERMAL SOLVER

Cadence believes that the solution to today's thermal analysis challenges lies in its new Celsius Thermal Solver tool, which enables iterative electrical-thermal co-simulation at the IC, package/PCB, and system levels.

At the IC level, the Celsius Thermal Solver tool allows for analysis within the chip. It addresses 3D-ICs, die-to-die bonding, and through-silicon vias (TSVs). At the package/PCB level, the tool features finite-element-analysis (FEA) and computational-fluid-dynamics (CFD) techniques for both transient and steady-state simulation. Furthermore, the capabilities of Celsius Thermal Solver extend beyond packages/PCBs—the tool also delivers a system-centric approach by including objects like heat sinks, enclosures, etc.

The Celsius Thermal Solver is based on a massively parallel architecture that delivers significantly faster performance than legacy solutions, according to Cadence. It also integrates with various Cadence design platforms, such as Virtuoso and Allegro. ■




**With both transient and steady-state analysis, Cadence maintains that Celsius Thermal Solver delivers accurate electrical-thermal co-simulation.**

## Low Noise

# BYPASS AMPLIFIERS

## 1 MHz to 43.5 GHz

- *Built-in bypass and shutdown*
- *Noise figure as low as 1.1 dB*
- *Ultra-wide bandwidths with flat gain*

Mini-Circuits®

**www.minicircuits.com** P.O. Box 350166, Brooklyn, NY 11235-0003 (718) 934-4500 sales@minicircuits.com

584 Rev B_P

# X-MICROWAVE DROP-IN FORMAT
## Supports 800-Plus Mini-Circuits Components

**THE X-MICROWAVE** *(www.xmicrowave.com)* portfolio of Mini-Circuits *(www.minicircuits.com)* products now includes over 800 Mini-Circuits models on over 1,000 X-MWblock drop-in modules. It more than doubles the number of offerings that were first available when the partnership between the two companies began in 2017. The expanded selection features models in 12 categories, which include:

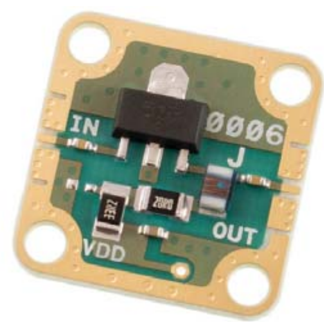
- Amplifiers
- Attenuators
- Couplers
- Equalizers
- Filters
- Limiters
- Mixers
- Multipliers
- Splitters
- Switches
- Transformers and baluns
- VCOs

In addition to the growing variety of drop-in blocks, X-Microwave introduced over 700 part numbers for Mini-Circuits components in connectorized housings for evaluation and integration into subassemblies.

X-Microwave's X-MWsystem is a modular, solderless evaluation system that incorporates thousands of physically compatible drop-in building blocks from multiple manufacturers for prototyping microwave assemblies. System blocks come fully characterized and modeled with X-parameters, S-parameters, and Sys-parameters. As a result, simulation and physical configuration through X-Microwave's free online tools for nonlinear simulation and mechanical layout becomes an easier task. This modular approach, which eliminates the need for custom evaluation board layouts, has turned into a popular solution within the industry to shorten design cycles and accelerate time to market.

"Our partnership with X-Microwave has allowed us to offer a valuable and truly innovative resource to customers using Mini-Circuits components in their designs," says Steven Scheinkopf, VP of technical marketing at Mini-Circuits. "We're very pleased to continue expanding the partnership to support our customers' design efforts with even more options."

John Richardson, president of X-Microwave adds, "We are very excited about the number of Mini-Circuits parts that are now available on our drop-in format. Mini-Circuits' broad range of parts and our modular system make it easy for designers to quickly transition from prototype to production hardware. For maximum flexibility, we are aggressively designing in the full portfolio of Mini-Circuits SMT and die parts."




"Our partnership with X-Microwave has allowed us to offer a valuable and truly innovative resource to customers using Mini-Circuits components in their designs."

Browse the full selection of X-MWblock drop-in modules for Mini-Circuits parts at the online directory of Mini-Circuits models referenced to X-Microwave part numbers, or on the X-Microwave website. ■

## *Now up to 40 GHz!*

# TEST

MODULAR TEST SYSTEMS

PROGRAMMABLE ATTENUATORS


NxM SWITCH MATRICES

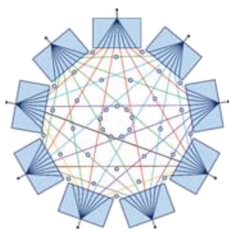

PATCH PANELS

# SOLUTIONS

***Flexible, Reliable, Affordable & Fast***

MECHANICAL SWITCH MATRICES

SOLID STATE SWITCH MATRICES



MESH NETWORK TEST SYSTEMS

INSTRUMENTATION AMPLIFIERS

SIGNAL GENERATION, MEASUREMENT & CONTROL

HIGH POWER TEST SYSTEMS

SIGNAL DISTRIBUTION

CUSTOM SYSTEMS

Mini-Circuits®

**www.minicircuits.com** P.O. Box 350166, Brooklyn, NY 11235-0003 (718) 934-4500 sales@minicircuits.com

616 Rev_Orig M&RF

# NEW BOOK IS an Antenna Resource for All

**THE NEW BOOK, TITLED** "Practical Microstrip and Printed Antenna Design," is intended to serve as a practical antenna design guide that covers real-world applications. The author, Anil Pandey from Keysight Technologies *(www.keysight.com),* geared the book more toward practical antenna design rather than theoretical analysis. Pandey also states that it includes the most useful recent work available from research in the printed and microstrip antenna fields. The guide targets both new antenna engineers and experienced designers alike, as well as those in the academic world.

The new book, titled "Practical Microstrip and Printed Antenna Design," is intended to serve as a practical antenna design guide that covers real-world applications.

Chapter 1 introduces various types of printed antennas, such as microstrip, slot, inverted-F, planar inverted-F, and monopole antennas, among others. A table compares 13 different antennas types, describing each one's radiation pattern, directivity, and bandwidth. Furthermore, the chapter discusses the important specifications associated with antenna design, such as operating frequency, impedance, return loss, radiation pattern, gain, efficiency, and bandwidth.

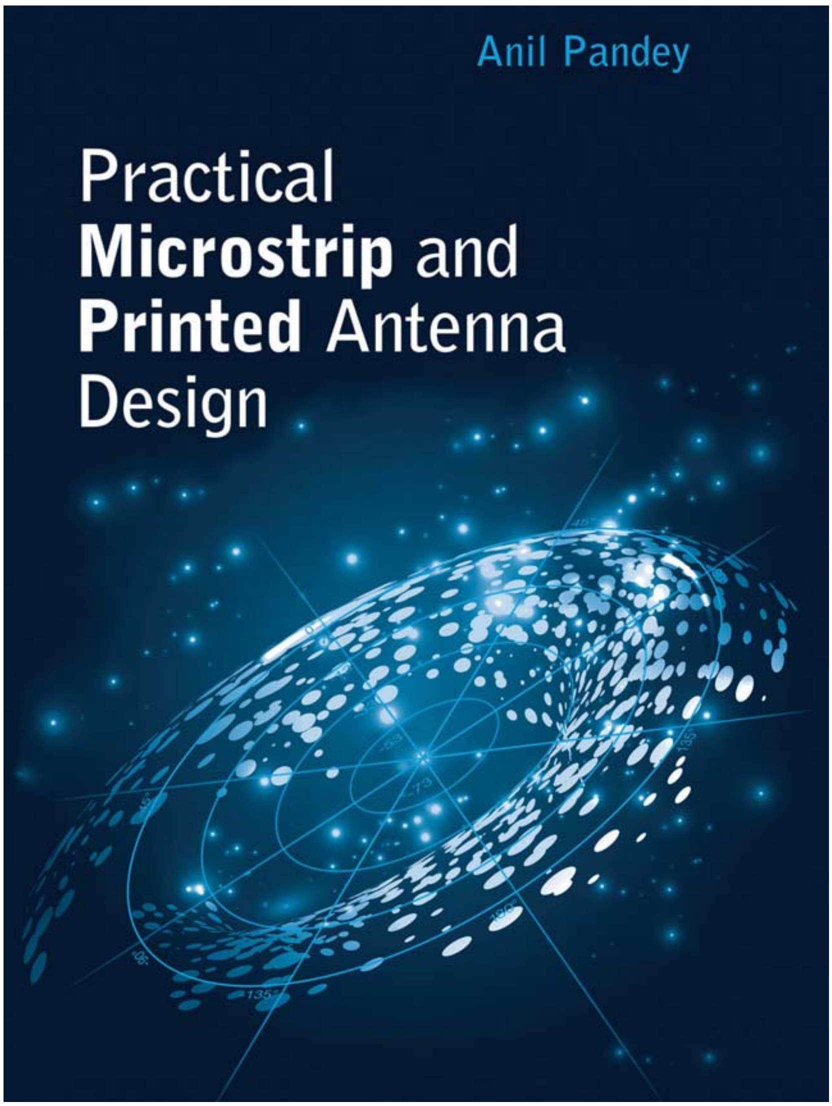
Also included in the first chapter is a section on analysis and simulation software for antenna design. The book states that transmission-line, cavity, and full-wave models are the most popular models used to analyze printed antennas.

Microstrip antenna design is the focus of Chapter 2. Topics covered include a microstrip antenna design process, with the corresponding steps visually depicted. The chapter also touches on substrate selection and losses in microstrip antennas, plus other key areas of interest.

In addition, Chapter 2 discusses feed techniques, explaining that microstrip patch-antenna elements can be fed by a variety of methods. Specifically, these methods can be grouped into two categories: direct or indirect contact. The author points out that the four most popular feed techniques used are microstrip lines, coaxial probes, proximity coupling, and aperture coupling.

On top of that, Chapter 2 covers the design and electromagnetic (EM) simulation of microstrip antennas. Shown is a design example of a 2.4-GHz microstrip patch antenna.

Among the many topics covered in subsequent chapters are antenna design for wireless communication and mobile phones, smartphone antenna design compliances and measurement, and printed antenna arrays. The book also has a chapter on automotive antennas, as well as one on phased arrays and beamforming networks for 5G communication systems. ■



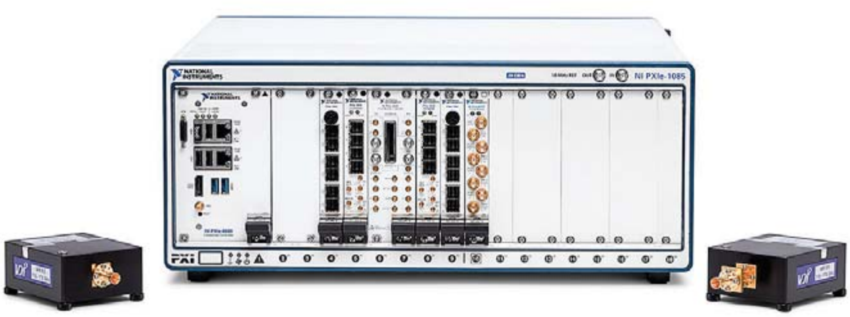
CHRIS DeMARTINO | Editor

# Looking Way Ahead TO 6G

**While 5G represents the next generation of wireless communications, a new sub-terahertz testbed is already setting the stage for 6G research.**

With the 5G era just barely upon us, it may seem preposterous to already be thinking about 6G communications. However, some are indeed looking ahead to 6G technology, evidenced by National Instruments' (NI) *(www.ni.com)* recent announcement of a sub-terahertz (sub-THz) testbed for 6G research *(Fig. 1)*. Built through a collaboration between NI and Virginia Diodes (VDI) *(www.vadiodes.com),* the testbed features NI's millimeter-wave (mmWave) transceiver system along with radio heads from VDI.

Of course, some might question the legitimacy of any kind of talk surrounding 6G communications—something that NI is keenly aware of. First of all, will we even see 6G anytime soon? And is this new testbed even pertinent to 6G technology? According to Sarah Yost, senior solutions marketing manager, SDR, at NI, "I think 6G is quite far away, but I do think the testbed that we put together for THz and sub-THz research definitely does fall into something that can truly be considered 6G technology."



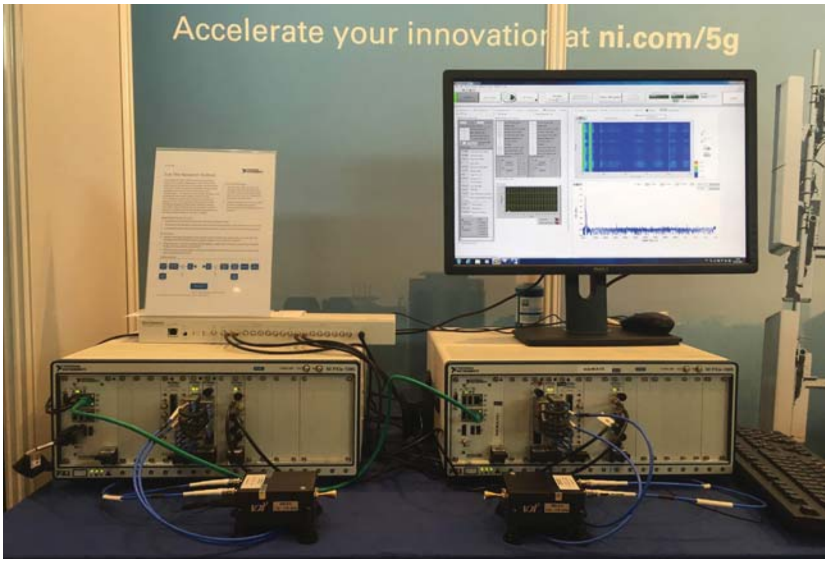

**1. This sub-THz testbed for 6G research combines NI's mmWave transceiver system with Virginia Diodes' radio heads.**

With 6G clearly linked to the THz spectrum, it makes sense for VDI to be playing a key role in 6G research—the company is at the forefront of mmWave and THz technology. Yost explains the history between NI and VDI, as well as what prompted NI to investigate the THz realm in the first place. "We've worked with VDI for a number of years, and we were looking for an opportunity to collaborate on a larger scale for quite a while.

"Back in 2015, we released our mmWave transceiver system, which has a baseband component, intermediate-frequency (IF) component, and mmWave radio heads. In late 2015, we actually connected some VDI radios to this system for basically a one-off opportunity. But what I noticed is that I started to receive a lot of inquiries concerning what we were doing in terms of THz technology and the 100- to 300-GHz frequency range. With that, we reached out to VDI and were able to get some of the appropriate radios in house."

After obtaining the VDI radios, NI was able to extend its mmWave technology to even higher frequencies. Yost adds, "We connected VDI's radios to our mmWave system. So, we were able to reuse the baseband and IF—and I think most importantly, we were able to reuse all of our software IP and use VDI's radios as the up/downconverters. So, we were able to take a lot of the research that we'd already done in regard to mmWave channel sounding and communication and extend that up in frequency to allow people to start looking at THz and sub-THz and all of the new applications that come with that."

NI recently demonstrated a 155-GHz channel sounder—the company's first sub-THz demo—at the recent 5G World Forum *(Fig. 2)*. "It was pretty cool to see that we were able to get all of that set up," says Yost. "I'm really looking forward to exploring this partnership between NI and VDI and seeing where the research




2. NI demonstrated this 155-GHz channel sounder at the 5G World Forum in Dresden, Germany.

goes as we get into 6G and some of these 'far-out' applications and ideas for communications."

As mentioned, the sub-THz testbed features NI's mmWave transceiver system. Inside the PXI chassis are digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) that connect to field-programmable gate arrays (FPGAs), which is where all of the real-time processing takes place. The local-oscillator (LO) and IF signals are created by a module that connects to the VDI radio heads. The demo at the 5G World Forum featured VDI's 110- to 170-GHz radio, which was tuned to 155 GHz.

"There are some really cool things that THz technology is going to allow. At the base of all of it is still the idea of communications. If you look at what we're doing with mmWaves, one application area involves increasing the total throughput possible. THz frequencies actually allow for even wider bandwidths."

### 6G APPLICATIONS?

Yost mentioned the "far-out" applications and ideas associated with 6G. But what exactly are they? She explains, "There are some really cool things that THz technology is going to allow. At the base of all of it is still the idea of communications. If you look at what we're doing with mmWaves, one application area involves increasing the total throughput possible. THz frequencies actually allow for even wider bandwidths.

"One application area that I've seen is very short-range, high-throughput scenarios. The end-use application might be a data center in which you get rid of all of the wires. You're not necessarily doing long-range communications, but you can have these ultra-high-throughput applications without needing all of the wires. So, that's maybe one of the more traditional ways that you can think of in regard to how this technology can be used."

THz technology is also associated with other use cases, such as sensing. Yost adds, "I think one of the more interesting ways people are using THz technology involves incorporating some aspects of sensing into the communications protocol. Airport scanners are one good example. Today, we have these airport scanners, which can very reliably provide detailed information like the different types of fabric we're wearing, whether we're carrying any sort of metal, etc. You can actually get a lot of that same information using THz frequencies.

"One example I heard is a company with THz short-range sensing capability that's using the technology to see the cut position of the plywood. The company can make sure the plywood meets its quality standards and that there's enough wood versus glue components. You can even extend that and use the technology in food—one of the big applications I've heard—in which you can test for allergens as well as contaminants."

Positioning is another application that could potentially be tied to THz frequencies. Yost explains, "There's currently an ongoing work item in the standards to make our positioning less reliant on GPS satellites. The goal is to take more advantage of the cellular standards and improve the accuracy. There's a field of research that's already looking at extending these frequencies into the THz spectrum to try to achieve positioning with cm-level accuracy."

To conclude, while we're not likely to see THz 6G for a long time, companies like NI and VDI are setting out to prove that it's more than just a pipe dream. Yost sums it up, "I think we're going to see an uptick in this type of work. I'm excited to see how it goes. THz technology has been pretty unobtainable for a long time. We're hoping to bring more people into the research community." mw

# 86 GHz


*A New Generation of Products for Next Generation Wireless Applications*

- Coaxial Adapters
- Amplifiers
- Attenuators
- Couplers
- Filters
- Splitters
- Terminations
- Test Cables

Mini-Circuits®

(718) 934-4500 sales@minicircuits.com **www.minicircuits.com** 566 Rev G_P

MATT STERGIOU | Senior Product Manager, IoT, Laird Connectivity
www.lairdconnect.com

# 6 KEYS to Success for Cellular IoT

**What should engineers consider when designing with LTE CAT M1 and NB-IoT? This article presents a checklist to help guide the process.**

Integrating wireless capabilities into products can be challenging for engineers who are not specialists in RF design, even when working with familiar technologies like Wi-Fi and Bluetooth. But those challenges become even bigger when the design project involves the new low-power cellular Internet of Things (IoT) protocols: LTE CAT M1 (CAT M1) and narrowband-IoT (NB-IoT). That complexity is driven by several interconnected factors:

- The complexity of cellular chipsets, which make them very difficult to work with for engineers other than true cellular experts.
- The need for a long list of niche expertise—including specific areas of embedded systems programming, expertise in time series-based architectures, and more—to build each segment of the connectivity pathways.
- The rigorous security and performance standards for the devices' applications, including industrial and healthcare IoT use-case implementations.
- The hurdles involved in cellular certification, which are more rigorous than typically involved in products using other protocols.
- The sheer newness of the cellular IoT protocols, which means fewer resources and knowledgeable colleagues available for assistance.

Even a highly skilled engineer who has experience working with other wireless technologies may be intimidated by the degree of difficulty of cellular IoT projects. However, because the advantages of CAT M1 and NB-IoT make them very attractive technologies for IoT deployments, product engineers must have a solid strategy to successfully navigate the world of cellular IoT. This article provides six key tips to help engineers get off to a successful start with CAT M1 and NB-IoT projects, while also avoiding missteps that might cause major setbacks.

Before we get to those, let's talk about why CAT M1 and NB-IoT are poised to be a major focus of development pipelines over the next two years. Given how much cellular infrastructure currently exists around the world, cellular networks may seem like an ideal platform for IoT deployments. But the always-on architecture of cellular technology causes it to drain batteries at an impractical rate for IoT deployments. And even if energy usage is not an issue, the high cost of hardware and connectivity would be just as much of an impediment.

Those hurdles are removed with the aforementioned new low-power versions of LTE technology—CAT M1 and NB-IoT. They have battery lives of up to 10 years and a cost structure that's ideal for IoT deployments. One emphasizes extending battery life and minimizing cost, while the other provides more flexibility and performance when engineers want to prioritize those at the expense of a bit of battery life and cost efficiency (interested readers can get a deeper dive into the attributes of CAT M1 and NB-IoT in a recent white paper written by Laird Connectivity).

The bottom line for an engineering team is that the remarkable battery life, ubiquitous network infrastructure, and low total cost of ownership (TCO) mean that these two protocols will soon likely be the centerpiece of IoT design projects. Here are a series of tips to help you navigate your first cellular IoT projects:

**1. It's not either/or with cellular IoT:** One of the questions often asked regarding CAT M1 and NB-IoT surrounds which protocol a team should choose at the beginning of a given project. That binary choice is common with other wireless protocols in which one must choose a path early in the development process and stick to it. But it's not an either/or choice with cellular IoT. The choice will likely be both.

CAT M1 and NB-IoT are designed to coexist in IoT deployments, allowing engineers to make a choice at the device level (to suit that device's job) rather than to make a one-size-fits-all choice for the entire implementation. This gives engineers a great deal of flexibility and does not mean that a high-stakes decision must be made early in the planning process.

**2. One of your most important decisions involves the cloud:** While you don't have to make an either/or choice about CAT M1 and NB-IoT early in the planning process, you do have some important early decisions to make regarding cloud connectivity. How you use the cloud significantly impacts operational costs for your deployment.

Yes, NB-IoT and LTE-M are designed to make data costs manageable for IoT deployments, but there are still data costs, and those costs can be high if you choose to deliver large amounts of data from your device back to the cloud. This is because data-transfer rates from these two protocols are purposefully designed to not be robust. That means sending a large amount of data to the cloud may require long transfer sessions that rack up lots of data costs. To avoid that, engineering teams should carefully plan what data the device reports, how much of it truly needs to be fed back to the cloud, and how data processing and storage are handled by the device versus the cloud.

**3. Your carrier matters:** One of the misconceptions raised by engineers considering cellular IoT is that the carrier decision comes later in the process. It matters earlier on because carriers have networks with differing coverage areas, technical specifications, performance, and customer offerings for IoT deployments. Evaluating carriers to pinpoint the one that best fits your needs is critical because that decision drives many engineering choices made during the rest of the design process. And the right fit is dictated by the specifics of your deployment, including geographic location, proximity to nearby towers, IoT data plans offered by competing carriers, and other criteria.

**4. The earlier the better regarding discussions about certifications:** Cellular certifications are notoriously difficult, not only because of their rigor, but because so many organizations are involved, including the carriers, telecommunications industry organizations, and national/international governmental agencies. Unexpected hurdles with these certifications can cause significant delays that could easily derail a cellular IoT project. Thus, engineering teams should pay close attention to the pre-certification of components, modules, and antennas that later expedites the certification process. Having partners with experience in cellular testing and certification also can be invaluable in keeping projects on time and on budget.

**5. Think carefully about antennas:** Literally thousands of antennas are available to choose from for RF design projects, which means there are thousands of potentially ill-suited antennas for a given project. Selecting the right antenna is always hard, but it's particularly hard for cellular projects.

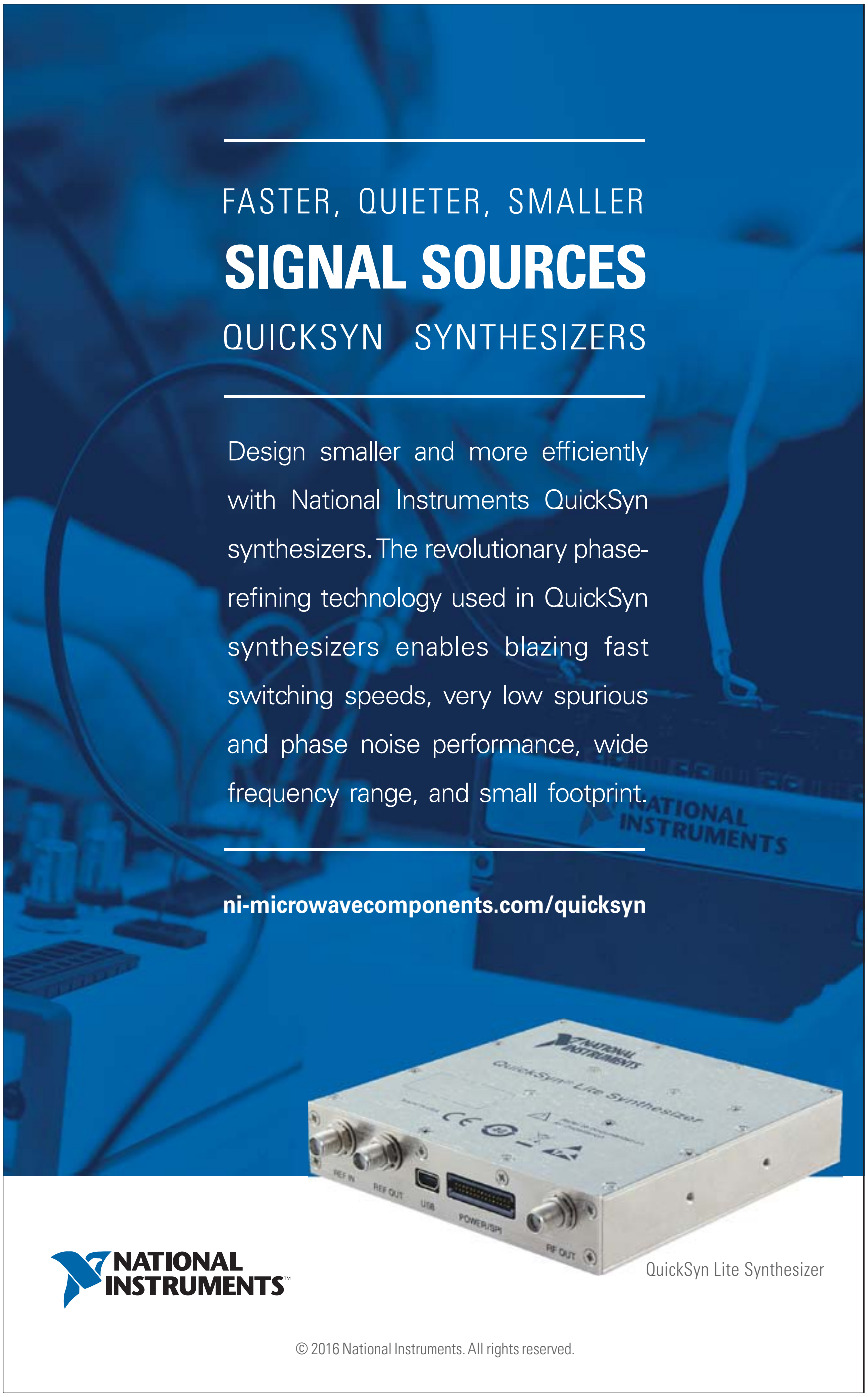
One reason for the complexity is that frequency range must match the carrier you work with, while also meeting the performance needs your team mapped out. You may also want to deploy other wireless technologies like Bluetooth as a complement to CAT M1 and NB-IoT, which means you also must look at antennas that have multiple bands with performance characteristics that meet your needs. As with all antennas, pretesting is a key step to ensure that the antenna performs as desired before you make a major commitment.

**6. PSM and eDRX are the keys to ultra-long battery life:** For cellular IoT devices to achieve the decade-long battery life that makes CAT M1 and NB-IoT so attractive, engineering teams must effectively manage sleep/wake cycles to optimize performance versus battery life. This includes effectively using deep-sleep modes that conserve the most energy.

Engineers should understand how to utilize the PSM and eDRX power-saving capabilities during the design process, including when to use deep-sleep modes, how to orchestrate devices that have varying sleep settings, and how to coordinate that with complementary technologies like Wi-Fi and Bluetooth, which have different sleep/wake cycles as part of their battery-management capabilities (those interested in a deeper discussion of PSM and eDRX can read the previously mentioned white paper).

Cellular IoT holds exciting possibilities for ultra-low-power wireless device networks that can take advantage of the readily available cellular connectivity. It's a complicated logistical process with timetables and lots of moving parts, but the payoff is significant if you address the items in the checklist as part of your planning process. I hope this set of best practices and caveats proves to be a helpful tool for your first few design projects with these exciting technologies. mw

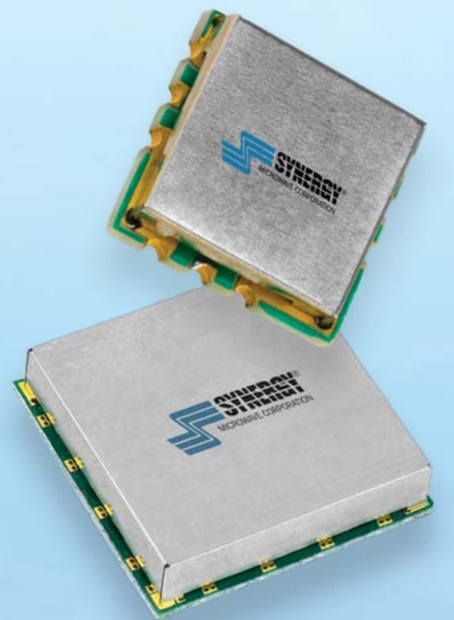
MATT STERGIOU is the senior product manager for IoT at Laird Connectivity Solutions, which provides a full range of embedded wireless modules and other solutions that simplify the process of using wireless technology. In his role, Stergiou oversees development of a range of IoT solutions that support wireless deployments in a range of vertical industries. Prior to Laird, he held positions at Bell and BEworks. Matt earned his degrees from the University of Toronto.

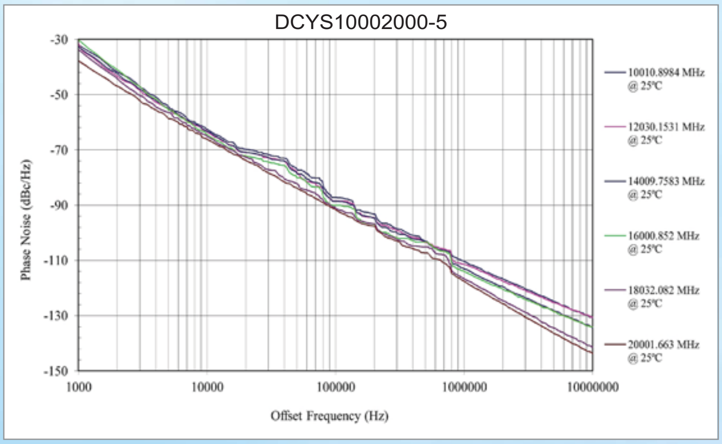


# L to K Band Ultra-Wideband

## Voltage Controlled Oscillators

| Model Number | Frequency | Phase Noise @ 10 kHz offset | Phase Noise @ 100 kHz offset | Tuning Voltage | Output Power |
|---|---|---|---|---|---|
| | ( GHz ) | ( dBc/Hz ) | ( dBc/Hz ) | ( V ) | ( dBm ) |
| **DCO100200-5** | 1 - 2 | -95 | -117 | 0 - 24 | +1 |
| **DCYS100200-12** | 1 - 2 | -105 | -125 | 0 - 28 | +4 |
| **DCO200400-5** | 2 - 4 | -90 | -110 | 0 - 18 | -2 |
| **DCYS200400P-5** | 2 - 4 | -93 | -115 | 0 - 18 | 0 |
| **DCO300600-5** | 3 - 6 | -75 | -104 | 0 - 16 | -3 |
| **DCYS300600P-5** | 3 - 6 | -78 | -109 | 0 - 16 | +2 |
| **DCO400800-5** | 4 - 8 | -75 | -98 | 0 - 15 | -4 |
| **DCO5001000-5** | 5 - 10 | -80 | -106 | 0 - 18 | -2 |
| **DCYS6001200-5** | 6 -12 | -70 | -94 | 0 - 15 | > +10 |
| **DCYS8001600-5** | 8 - 16 | -68 | -93 | 0 - 15 | > +10 |
| **DCYS10002000-5** | 10 - 20 | -65 | -91 | 0 - 18 | > +10 |




***Features:***

- *Superior Phase Noise*
- *High Output Power*
- *Small Size Surface Mount Package*
- *Vcc: 5 volts*
- *Future models up to 30 GHz*

## Talk To Us About Your Custom Requirements.

SYNERGY® MICROWAVE CORPORATION

**Phone: (973) 881-8800 | Fax: (973) 881-8361**
**E-mail: sales@synergymwave.com | Web: www.synergymwave.com**
**Mail: 201 McLean Boulevard, Paterson, NJ 07504**

VLADIMIR VOLMAN | Ph.D., Fellow and PMS of Lockheed Martin (retired), Consultant

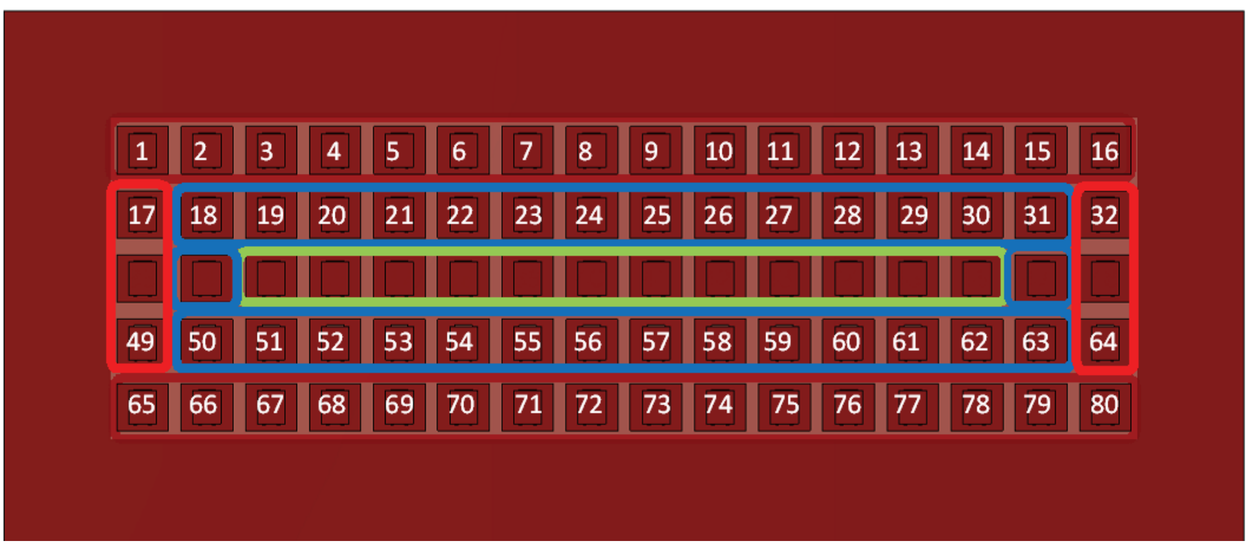
# Analysis of a 24- to 30-GHz Phased Array for 5G Applications (Part 1)

**This series examines 5G phased-array platform/wizard development and offers some recommendations to obtain consistent results. Part 1 focuses on the design and evaluation of the broadband stacked U-slot patch radiator optimized for 24 to 30 GHz.**

In 5G communication systems, the phased-array antenna is one of the lead front-end components that defines massive multiple-input, multiple-output (MIMO) performance. The trend outlined in recent years involves providing a robust and complete platform/wizard for RF/microwave engineers to develop more capable antennas and other RF front-end components in less time than before.[1] In addition, systems that operate at millimeter-wave (mmWave) frequencies offer benefits that include small antenna sizes and more available bandwidth.[2]

However, a challenge arises due to the wide variety of application-driven requirements, which encompasses everything from both city and rural environments to realized gain, scan, and polarization performance attributes to impedance matching and more. Such an extensive number of requirements cannot be met by a single and one-time designed element. This means that any practically convenient modeling platform must contain an extensive library of predesigned antenna elements.

Unfortunately, 5G antennas belong to a class of relatively small and densely populated phased arrays in which the total number of radiators typically does not exceed several hundred. If it does, the consistency of results obtained through such system-level platforms




**1. This 5- × 16-array panel contains rim elements (red), next-to-rim elements (blue rectangles), and center elements, all of which are influenced by neighboring elements.**

ultimately depends on the accuracy of the phased-array element models, which should include the relatively strong mutual coupling with other elements in the array (this mutual coupling can be –15 dB or 0.18 V relative to 1-V element excitation and sometimes even higher).

We will demonstrate that the presence of mutual coupling in such arrays noticeably modifies the input impedance of the elements. This coupling also distorts the shape of the element patterns, resulting in wider and asymmetrical patterns, a splitting of the main beam, a shift in the direction of peak radiation, etc. It's most alarming that such distortions depend on the radiator position in the array.

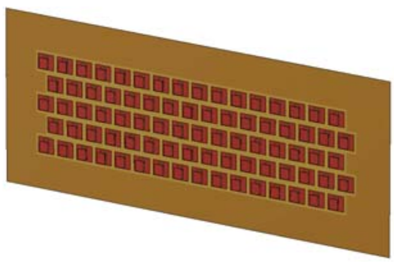
*Figure 1* shows a 5 × 16 array in which each of the *rim* elements marked in red lacks neighboring elements on one side. Each of the *next-to-rim* elements enclosed in blue rectangles is under the influence of the neighboring rim elements on one side, along with multiple inner elements. Finally, each of the *center* elements has two layers of neighbors in a symmetrical fashion.

Therefore, each of the 38 rim elements plus the 30 next-to-rim elements (85%!) should display unique performance relative to the center elements. Note that even in an array of 32 × 32 = 1024 radiators, the number of such elements is 240, or 23.4%. Therefore, we can expect that an array like the one shown in *Figure 1* could be divided into groups of several elements. The individual performance of each element can be determined by its corresponding group.

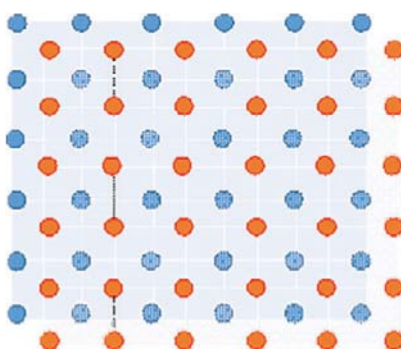
This analysis demonstrates that arrays of 4 × 4 and higher may be designed based on just three elements. In this case, rows 1 and 5 represent the rim elements along with the outer elements of rows 2, 3, and 4. The inner elements of rows 2 and 4 represent the next-to-rim elements. Lastly, the 12 central elements of row 3 represent the center elements.

Therefore, the embedded library database could be truncated without sacrificing the accuracy of the final results.

According to Ref. 3, the power consumption of a 5G station is three times that of its 4G LTE predecessor. In that case, each dBi error in the assessment of array gain can be quite costly.



**2. In creating this triangular lattice, each even row in Figure 1 was moved to the right by a distance equal to half of the array period.**



**3. The triangular lattice is the superposition of two rectangular shapes.**

To date, the antenna-array block of numerous platforms avoids the associated challenges by using data from either a single radiator simulation/test in free space (meaning all elements are identical and mutual coupling is ignored) or a low-complexity and memory-consuming Floquet-Bloch technique. The latter assumes that all radiators are set in an *infinite* array and are thus identical, since each element is mutually coupled with the same *infinite* number of driven neighbors. We will demonstrate why both approaches have limited accuracy and how to overcome them.

This two-part article series focuses on several topics. First, mutual coupling and grating lobes are discussed, as they are critical in terms of beamsteering phased arrays. Presented next is the schematic of the broadband patch element appropriate for practical applications.

Afterward, CST Microwave Studio (MWS) (CST MWS is a product of Dassault Systèmes) and MATLAB simulation results *(see footnote 1 at the end of the article)* are demonstrated—the broadband patch element is placed into the environment of an infinite periodic array. Subsequently, full-wave CST simulation results of a 5- × 16-array based on the same element are presented. The final section discloses the CST analysis results of the same array, but with a triangular lattice.

## MUTUAL COUPLING AND GRATING LOBE IN BEAMSTEERING PHASED ARRAYS

Before starting the analysis, note that the total interaction between elements can be loosely divided into three categories: spatial proximity, aperture coupling, and surface-wave interaction. For the most part, the proximity interaction is defined by nearby quasi-static E- and H-fields. For a single microstrip patch radiator, these fields can be seen in Ref. 4 *(Figures 3 and 4)*.

The presence of aperture coupling means that some portion of each element's radiated power is distributed between all other elements in the array behaving as receiving antennas. Hopefully, both types of mutual coupling diminish as the normalized to wavelength inter-spacing between elements increases.

Furthermore, proximity coupling is typically reactive by nature. A substantial amount of this total coupling drops much faster with distance compared to an aperture coupling. The rule of thumb tells us that the array radiators might be considered independent provided that the separation is above a wavelength and the antenna-array structure does not generate and support surface waves. These waves, if they exist, propagate inside the dielectric substrates and mainly stay confined within them, causing undesired coupling that diminishes relatively slowly from element to element. One of the most effective ways to illuminate these waves is to use a thin dielectric substrate of ultra-low permittivity, as we will demonstrate.

The term *grating lobes* refers to the in-phase addition of a radiated field in more than one direction. Unlike side lobes, the magnitude of the grating lobes might reach the level of the main beam in some unwanted directions.[7] In a periodic array, i.e., an array with uniformly spaced and identically excited elements, a single grating lobe appearance is unavoidable when the element spacing exceeds one-half wavelength but is less than one full wavelength.

For example, the pattern of the linear array is free of grating lobes at the shortest designated wavelength, $\lambda_{min}$, until:[4]

$$\sin\theta < 1/\left(\frac{d}{\lambda_{min}}\right) - 1$$

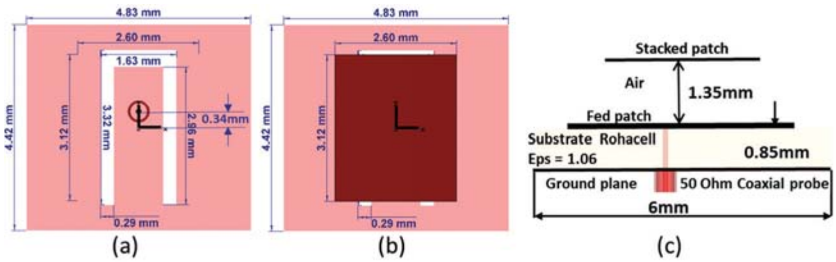
where $\theta$ is the scan angle and $d$ is the separation between adjacent radiators.

Note that deviations from uniform spacing or the introduction of uncorrelated magnitude/phase error destroy the periodicity of an array and may help to suppress the grating lobe level.[9] However, both topics are outside the scope of this article.

One of the most practical and effective ways to extend the scanning sectors or reduce the level of grating lobes is to change the array schematics. For example, we could move each even row in *Figure 1* to the right by a distance equal to half of the array period *(Fig. 2)*. Loosely speaking, in such a so-called triangular lattice, the elements in the odd rows partially fill up the gaps between elements in the even rows and vice versa. The effective separation between array elements then reduces by as much as 16%.[9]

Since the triangular lattice is the superposition of two rectangular shapes *(Fig. 3)*, the grating lobes are not eliminated entirely. Instead, they are diminished in magnitude and shift to higher frequencies or a higher scan angle.

One of the most practical and effective ways to extend the scanning sectors or reduce the level of grating lobes is to change the array schematics.




**4. Shown are the element schematics: top view of the fed patch with U-slot (a); top view of the fed and stacked patch (b); and the side view (c).**

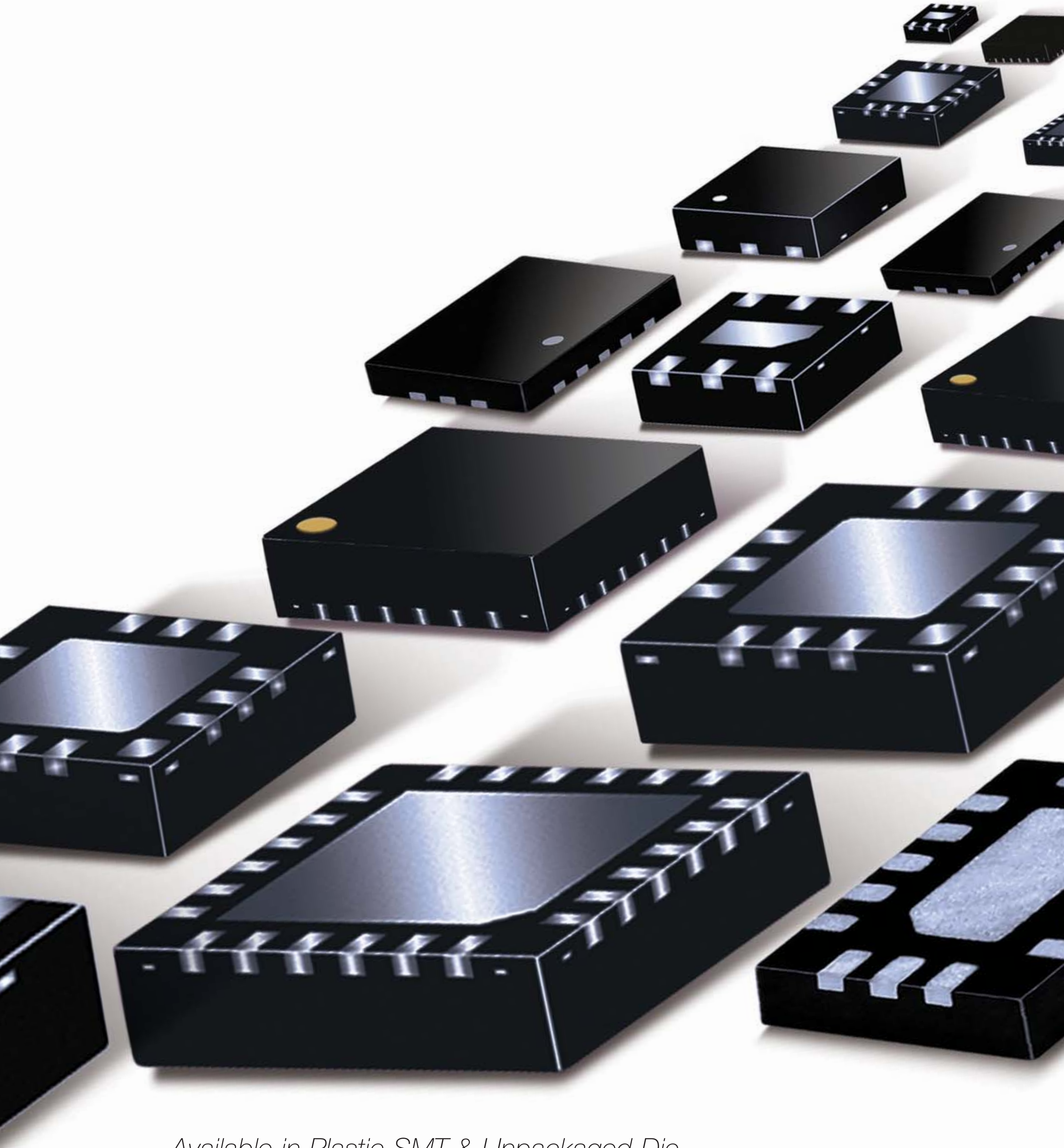
### ARRAY RADIATOR

To make the outcome of the following comparative analysis relevant for practical applications, a linear polarized (LP), back-fed, stacked U-slot patch radiator optimized for a frequency range of 24 to 30 GHz was chosen *(Fig. 4)*. It's compact, low profile, easy-to-integrate, lightweight, low cost, and quite simple in terms of providing fast numerical simulations. The combination of two resonant components—a fed patch with a stacked element and a U-slot—results in dual-broadband characteristics[5] that are required for 5G systems that must meet the demands for high data rates and low latency.

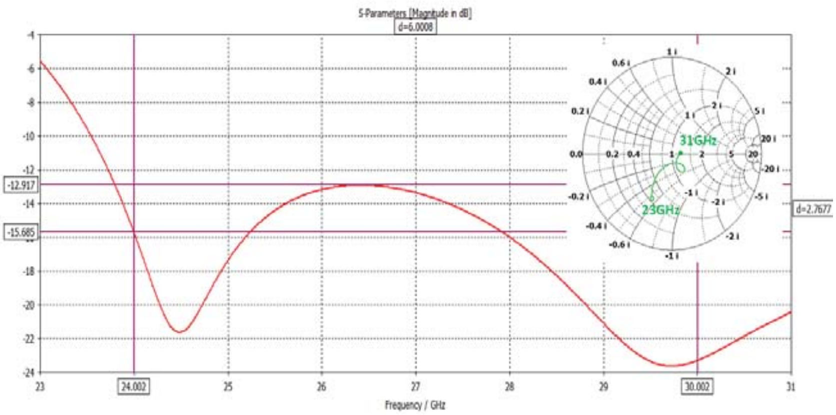
The side arms of the U-slot are symmetrically positioned with respect to the coax feed point shifted 0.34 mm relative to the origin. The thin dielectric substrate with an ultra-low permittivity of 1.07 *(see footnote 2 at the end of the article)* ensures the lowest possibility of surface waves. The stacked patch could be supported by a dielectric rod with a small diameter (not shown in the drawing) or an additional layer of the same dielectric. The original cross-section sizes of the radiator substrate and ground plane are 6 × 6 mm, or 0.48λ × 0.48λ at 24 GHz, meaning no grating lobes at any scan angle. However, grating lobes are expected at 30 GHz, as the element inter-spacing grows to 0.6λ × 0.6λ (as will be seen later).

The radiator model was developed using the 3D full-wave CST MWS software and simulated in the time domain to get wideband data over just one simulation run. Afterward, the frequency response is obtained through a fast Fourier transform (FFT). Since the time-domain simulation is performed on a port-by-port basis, it requires less memory and is faster in comparison to a frequency-domain simulation.

A 31- × 31-mm ground plane was added to alleviate the back radiation as well as the ground-edge diffraction.



*Available in Plastic SMT & Unpackaged Die*




**5. The return loss and input impedance versus frequency plot reveals excellent wideband performance.**

*Figure 5* reveals the return loss plot (i.e., 20 × log10(|$S_{11}$|) over frequency. Excellent wideband performance is demonstrated, as the return loss is below −12 dB at all desired frequencies.

*Figure 5* reveals the return loss plot (i.e., 20 × log10(|$S_{11}$|) over frequency. Excellent wideband performance is demonstrated, as the return loss is below −12 dB at all desired frequencies. *Figure 5* also shows a Smith chart, which depicts the corresponding input impedance. As expected, both the return loss plot and the Smith chart indicate the presence of two overlapping resonances—the first at 24.47 GHz and the second one at 29.62 GHz. Thus, the radiator's performance resembles that of a second-order Chebyshev filter.

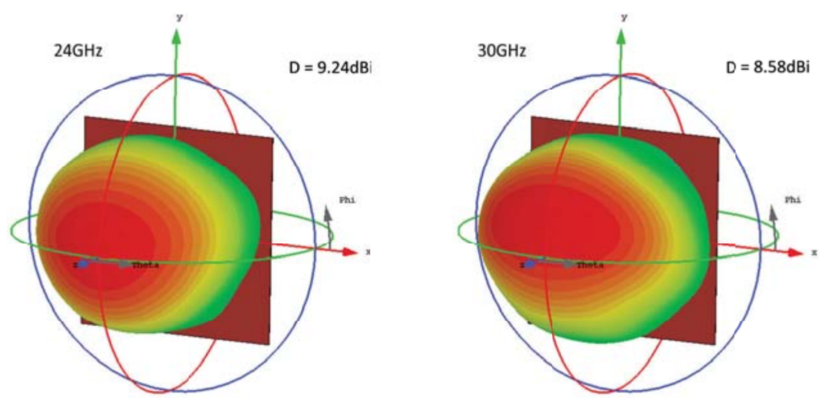
Since the reactive energy stored in E- and H-fields typically reaches extreme levels around resonances,[6] this element is expected to have a spike of spatial proximity coupling around these frequencies. *Figure 6* depicts 3D element patterns and the associated directivity (dBi) at 24 and 30 GHz.

Note that the directivity at both frequencies is not directly related to the element's geometrical size of 6 × 6 mm. Thus, the effective radiation area[6] is much broader than the physical area, since the nearby far-field radiation EM fields extend well beyond 6 × 6 mm.

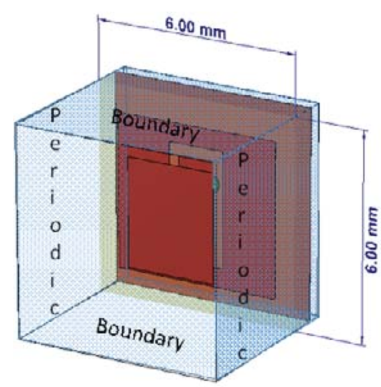
## INFINITE PERIODIC ARRAY ENVIRONMENT

The Floquet-Bloch theory allows one to deduce the property of the whole array with mutual coupling included from a simulation of just a single unit cell *(Fig. 7)* once certain periodic boundary conditions are established *(see blue surface in Figure 7).* Behind this approach lies the assumption that all array elements are uniformly excited, identical in behavior, and are placed into the nodes of a planar and uniform grid of infinite extent (i.e., they form an ideal infinite 2D periodic structure).

While such an approach typically works perfectly well for large arrays of a thousand or more elements, it's worthwhile to check its applicability for arrays of smaller sizes. The main disadvantage of this approach is that one loses information regarding the element's active impedance, as well as the level of mutual coupling. The term "active impedance" is defined as the input impedance of some element when only this element in the array is driven, while all others are terminated with matched loads. The remarkable




**6. These are the patterns with the extended ground.**




**7. Shown is the element schematic in an infinite-array environment.**

**The term "active impedance" is defined as the input impedance of some element when only this element in the array is driven, while all others are terminated with matched loads.**

fact is that knowledge of the active impedance is precious, as it allows one to reconstruct the patterns of the driven element and the whole array.[8]

*Figure 8* reveals the return loss for two beam positions: boresight (red trace) and $\theta_{scan}$ = 45° (green trace). Both curves reflect the parameters of every element in the array provided that all elements are driven and demonstrate adequate broadband performance. The comparison of plots in *Figures 5 and 6* clearly shows the impact and importance of mutual coupling.

The patterns in *Figure 9* are reasonably similar in shape to the ones shown in *Figure 6*, but the directivities are different. The element directivity is defined by the magnitude and phase distribution of the E-and H-fields not only over the element aperture, but also its vicinity, and could be characterized as so-called effective aperture.[6, 7]

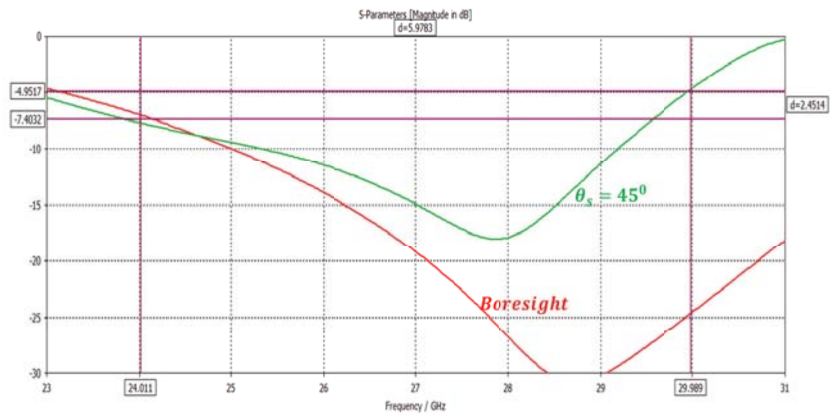
In the case of a solitary element in free space (*Fig. 4, again)*, the effective aperture exceeds the physical size because the fields cover a larger area than the physical sizes (see Ref. 4, *Figures 3 and 4*). In the case of the element in the infinite array, the effective aperture of the element in *Figure 7* is almost equal to its cell, i.e., physical element sizes. mw

FOOTNOTES

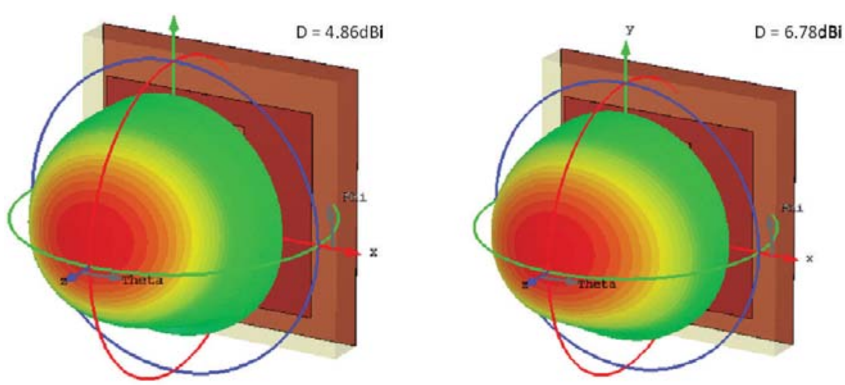
1. At *https://emfieldbook.com*, readers can find extensive additional information, including ready-to-run CST MWS model files and MATLAB scripts, to extract and process CST simulation data. Click

*Blog* and go to the 5G Broadband Radiator and 5 × 16 Array Thereof section for more results and comments. The raw text files of about 15 GB (3D patterns and complex S-matrix) are available upon request. Just click *Contact* at the top menu and fill out the message window.

2. For example, ROHACELL 51 IG/A with tan δ = 0.0037 can be formed into a finished core in a mold with all patches directly integrated during the foaming process. See: *https://www.rohacell.com/sites/lists/re/documentshp/rohacell-dielectric-properties-en.pdf* and *https://www.youtube.com/watch?v=7ofleYc3bPo*




**8. Return loss versus frequency is given for two beam positions—boresight (red trace) and $\theta_{scan}$ = 45° (green trace).**




**9. These infinite-array environment patterns are similar to those in Figure 6, but with different directivities.**

REFERENCES


1. David Vye and Jack Browne, "Platform Propels RF Designs from Concepts to Products," *Microwaves & RF*, October 2018, pp. 62-63.

2. Jack Browne, "Bringing mmWave Signals to the Masses," *Microwaves & RF*, June 2019, pp. 51-54, 68.

3. Sarah Yost, "First to 5G: Who Will Win?" *Microwaves & RF*, June 2019, pp. 35-36.

4. Kenneth Puglia, "A Brief Tutorial on Microstrip Antennas (Part 1)," *Microwaves & RF*, November 2018, pp. 40-62.

5. J.A. Anasari and R. B. Ram, "Broadband Stacked U-slot Microstrip Patch Antenna," *Progress In Electromagnetics Research Letters*, Vol. 4, pp. 17-24, 2008.

6. Vladimir Volman and Andrzej Jeziorski, *Engineering Electrodynamics*. House of Maxwell's Electrodynamics, 2017, see also *https://emfieldbook.com*.

7. Constantine A. Balanis, *Antenna Theory, 3rd Edition*, Wiley & Son, 2005.

8. David M. Pozar, "A Relation between the Active Input Impedance and the Active Element Pattern of a Phased Array," *IEEE Transactions on Antennas and Propagation*, vol. 51, No. 9, September 2003, pp. 2486-2489, or visit the website: *https://pdfs.semanticscholar.org/4f10/5bda3300308e7771276cf65b6557419f2e1d.pdf*

9. John S. Williams, "Electronic Array Design," *Tutorial*, visit the website: *https://intranet.birmingham.ac.uk/eps/documents/public/emuw2/SCF01.pdf*

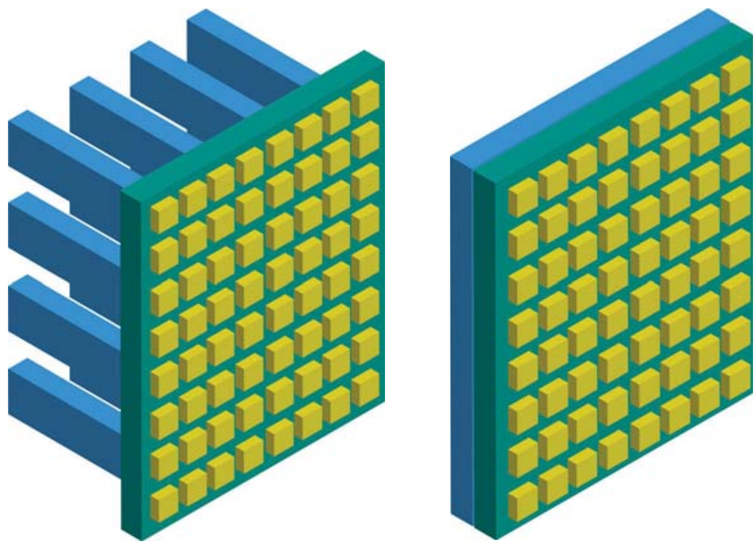
PETER MATTHEWS | Technical Marketing Manager, Knowles Precision Devices
www.knowlescapacitors.com

# Addressing Size and Tolerance Challenges in mmWave Filters

**Millimeter-wave filter technology is a vital building block for implementing mainstream 5G wireless communications, but obstacles exist in terms of physical size, manufacturing tolerances, and temperature stability.**

In the race to implement mainstream 5G wireless communications, focus has shifted to increasing bandwidth capacity using frequencies greater than 20 GHz in the millimeter-wave (mmWave) spectrum. Because of the known range and path loss limitations of high frequencies, mmWave signals require much smaller antennas, which can be tightly packed together to create a single, narrowly focused beam for point-to-point communication with greater reach.

The design challenge becomes finding the right RF filter technology that can fit into the size constraints of integrated beamforming antennas. In addition, the filter's manufacturing tolerances and temperature stability can also affect bandwidth capacity.



1. Different mechanical approaches can be taken to implement phased-array antennas.

### THE SIZE CONSTRAINTS OF mmWAVE TECHNOLOGY

In a traditional antenna-array system, an inter-element spacing of less than half the wavelength (λ/2) is required to avoid the generation of grating lobes. This principle holds true in a 5G beamforming antenna in which, for example, a 28-GHz band antenna would need approximately 5 mm of inter-element spacing. Such a requirement, therefore, calls for very-small-form-factor components in the array.

Phased arrays used in mmWave applications are commonly designed in a plank architecture, such that the antennas (gold area) are mounted in a printed-circuit-board (PCB) (green area) and the circuit "planks" (blue area) are attached 90 degrees from the array. Space is already tight on these circuit planks, but now manufacturers are considering a more compact flat-panel architecture, which means filtering and other circuit blocks would need to be even smaller to fit directly on the back of the antenna PCB *(Fig. 1)*.

### IMPACT OF MANUFACTURING TOLERANCES FOR mmWAVE FILTERS

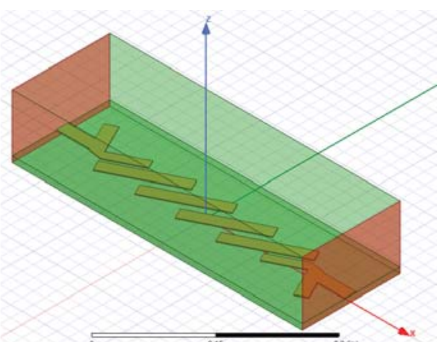
Considering the importance of miniaturizing mmWave filters, manufacturing tolerance plays a crucial role. Tolerance not only affects filter specifications (i.e., planned versus realized performance) and potential loss of bandwidth, but it also impacts the cost of implementation if one considers the cost of rejecting out-of-compliance boards. Plus, poor tolerance encroaches on potential board space or layers that could be used for adding other devices or functionality. To further examine these factors, we compared three different 26-GHz filter manufacturing approaches:

- Integrated microstrip approach on PCB
- Integrated stripline approach on PCB
- Thin film microstrip in a small-form-factor surface-mount (SMT) package

Discussions in the public domain[1] use Monte Carlo methods with very aggressive tolerances compared to the typical tolerances that are seen in production. In general, similar results were observed with our simplified worst-case analysis, which aimed for the reasonably tight manufacturing parameters seen in the *table*.

### TOLERANCE IMPACT ON PCB MICROSTRIP FILTERS

The design of the PCB microstrip bandpass filter (BPF) in *Figure 2* was implemented with a sixth-order, edge-coupled topology on 10 mil of RO4350B laminate and 2-oz. electrodeposited (ED) copper for metallization.

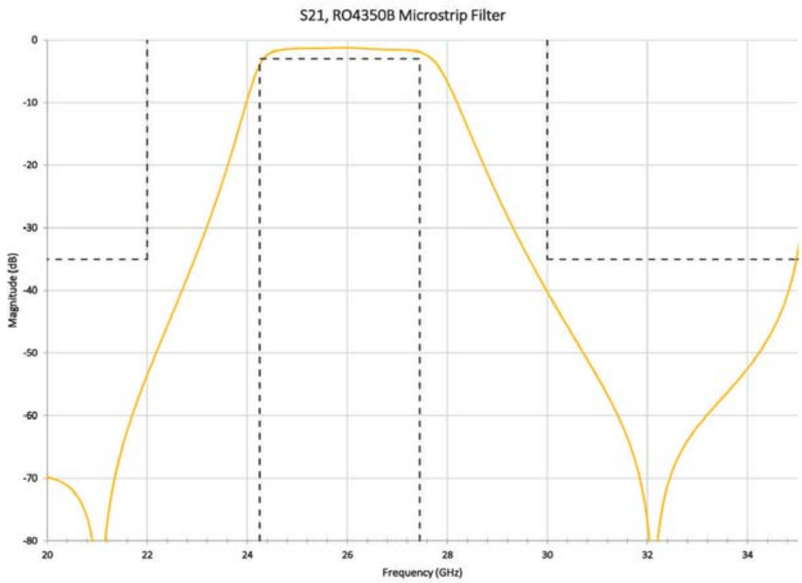


2. This is a PCB microstrip implementation of a 26-GHz BPF.

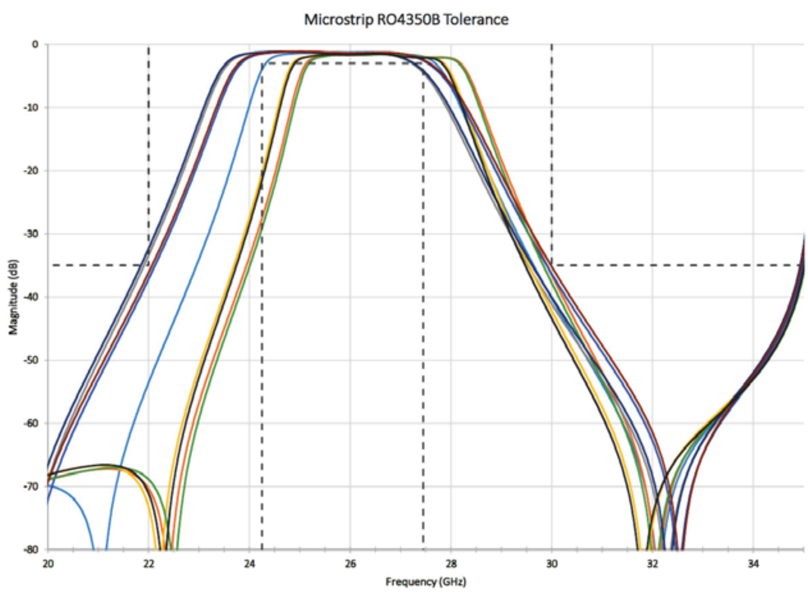
Because of the inherent transmission zeros produced by the edge-coupled microstrip filter, the nominal design passes the close-in rejection requirements with margin *(Fig. 3)*. Although the passband shows less margin and the high-side harmonic response is less than ideal, we chose not to further tune the design, since adding complexity drives up insertion loss and sensitivity to tolerances.

To study tolerance impact on this hypothetical PCB microstrip filter, eight versions of the design were created with varying substrate thickness, etching tolerance, and dielectric constant tolerance—all within the limit lines. *Figure 4* shows a significant shift in the filter's low-side performance for both the rejection and 3-dB points.

Also, the low side of the 35-dB common-mode rejection point shifted over by 2 GHz. Based on this simplified

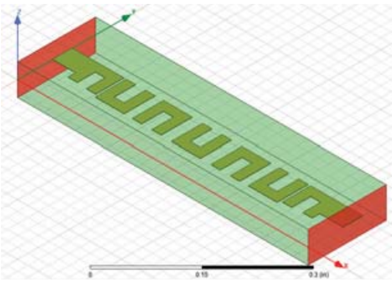



3. The simulated nominal design performance of a PCB microstrip 26-GHz BPF reveals that the filter passes the close-in rejection requirements.

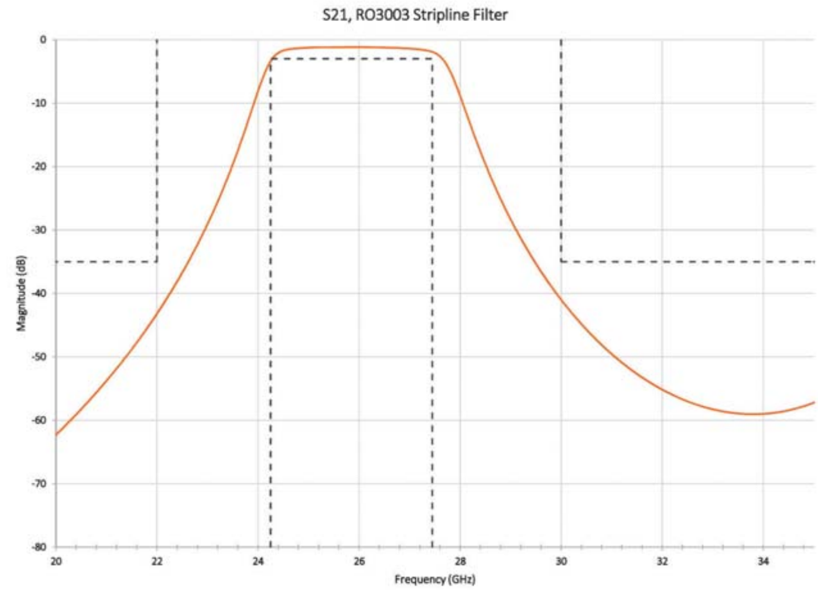



4. The simulated tolerance response of the PCB microstrip 26 GHz BPF shows a significant shift in performance.

worst-case analysis, such a filter is unusable in manufacturing due to the variation over tolerance. In fact, the entire PCB would be rendered out of specification even before measuring performance variation due to other components and factors.



5. Shown is a PCB stripline implementation of a 26-GHz BPF.



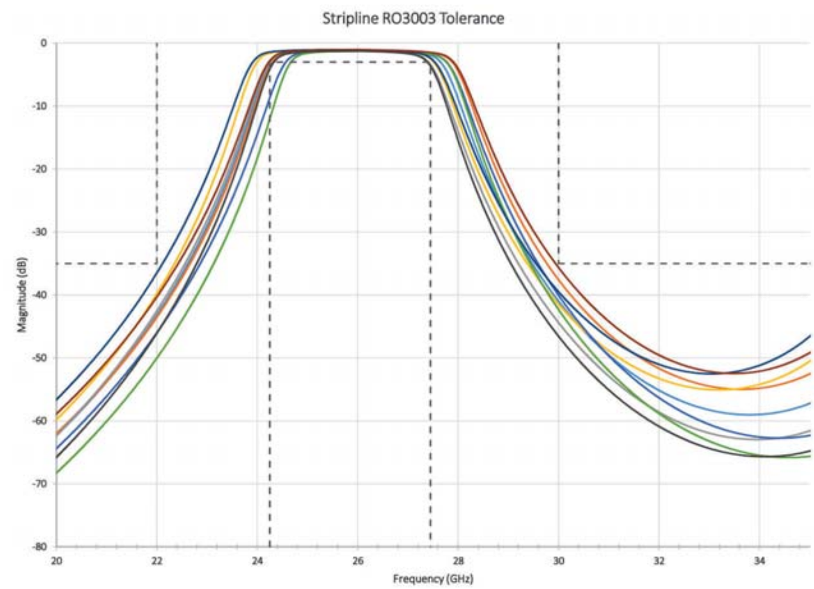

6. This is the simulated nominal design performance of the stripline 26-GHz BPF.

## TOLERANCE IMPACT ON PCB STRIPLINE FILTERS

The design of the stripline approach in *Figure 5* is a seventh-order hairpin with 30 mil of RO3003 laminate on the top and bottom, and 0.5 oz. of rolled (RA) copper.

The hairpin stripline design does not have as steep of a skirt as the edge-coupled microstrip filter. Plus, the same harmonic performance challenges on the high side of the stopband were seen, as was the case with the PCB microstrip filter *(Fig. 6)*.

Like the previous PCB microstrip experiment, eight variations of the stripline filter were created, varying in substrate thickness, etching tolerance, and dielectric material tolerance within the ranges stated in the *table*. The worst-case analysis in *Figure 7* reveals a smaller shift in filter performance compared with the PCB microstrip design. However, tolerance margin must still be added to the target specification to allow for the variation in frequency response. For example, the low side of the 35-dB point is shown to fluctuate by approximately 1 GHz.




7. The simulated tolerance response of a stripline 26-GHz BPF indicates a smaller shift in filter performance than the microstrip design.

## TOLERANCE IMPACT ON SMT MICROSTRIP FILTERS

For the surface-mount microstrip implementation, the Knowles Precision Devices *(www.knowlescapacitors.com)* B259MC1S 26-GHz BPF was selected. The topology and material details are proprietary, but the same nominal simulated design performance and simulated tolerance response to the three tolerance variables are shown in *Figures 8 and 9*, respectively.

Subjecting the simulated version of the SMT microstrip filter across the same three design variables revealed a much smaller sensitivity to manufacturing tolerances *(Fig. 9, again)*. The simulated 35-dB attenuation shift at the low end is approximately 130 MHz. While the simulated filters do not threaten the stopbands, a small shift

was observed in the static passband. However, given that these devices are discrete SMT components subject to quality testing, only filters within performance compliance are shipped to the end user, thus improving the pass rate of the entire circuit and saving overall costs.

*Figure 10* compares the nominal performance of all three filter approaches, as well as the filter surface area. The compact SMT filter design takes up less than a quarter of the space allocated to PCB microstrip and stripline filters with the same target specifications. Also, considering the previous discussion on the importance of half-wave-length sizing for mmWave antenna arrays, only the SMT thin-film dielectric filter is smaller than the approximately 5.7-mm inter-element spacing required at 26 GHz.

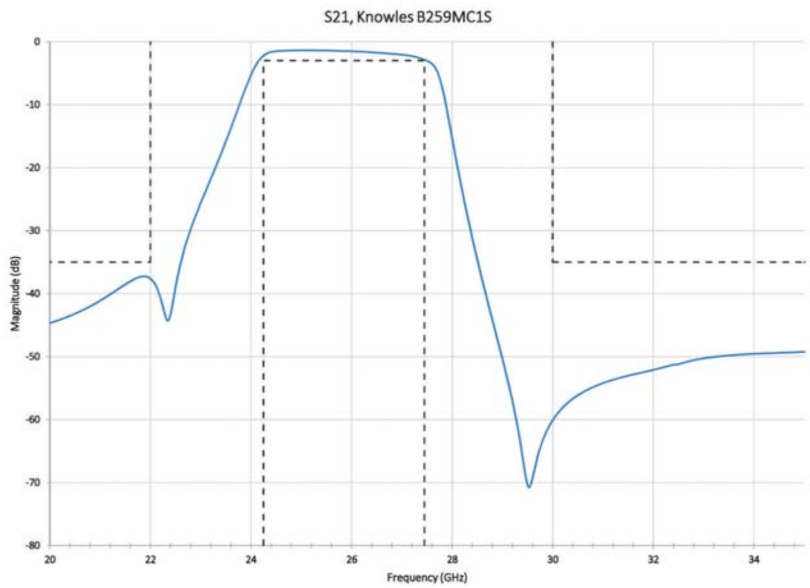
Turning 5G wireless communication into a widespread reality requires mmWave filter technology for 20 GHz and higher. However, certain obstacles exist in terms of physical size, tolerances, and temperature stability.

### IMPACT OF TEMPERATURE STABILITY ON BANDWIDTH

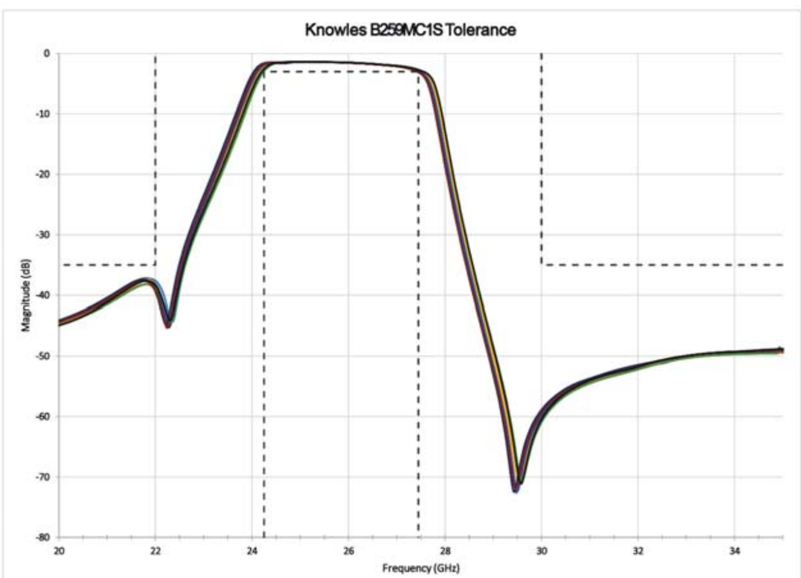
As manufacturers continually push the spectral efficiencies of RF filters, these valuable advances in available bandwidth can be lost due to not only manufacturing tolerances, but also temperature variation. Millimeter-wave antenna arrays may be found operating in extreme cold or hot outdoor conditions, and heat dissipation issues may

MANUFACTURING TOLERANCES FOR A WORST-CASE ANALYSIS

| Tolerance | Stripline on RO3003 | Microstrip on RO4350B |
|---|---|---|
| Thickness | 30 mil ± 1.5 mil | 10 mil ± 1 mil |
| Etching Tolerance | ±0.5 mil | ±2 mil |
| Dielectric Constant (Dk) Tolerance | 3 ± 0.04 | 3.66 ± 0.05 |




8. The plot illustrates the simulated nominal design performance of an SMT microstrip 26-GHz BPF.




9. Judging by the simulated tolerance response of a SMT microstrip 26-GHz BPF, one can see that it's less sensitive to manufacturing tolerances.

arise from the miniaturized, crowded circuitry. The filter must have the ability to perform within specification over a wide range of temperatures, with a good temperature stability of approximately 3 ppm/°C.

A key component of temperature stability in microstrip filters is the selection of substrate material. For example, *Figures 11 and 12* compare the filter performance of two SMT designs for 18-GHz BPFs. One lot was manufactured with alumina board and the other lot with CF custom dielectric substrate. The filter responses were taken from temperatures ranging from −55 to +125°C.

At the 35-dB rejection point, the alumina-based filter shifts by 140 MHz, whereas the CF dielectric filter only displays a shift of 17 MHz at the 35-dB point. By designing with the right dielectric material and filter topology, temperature-stable SMT filters with high rejection and low loss can be produced.

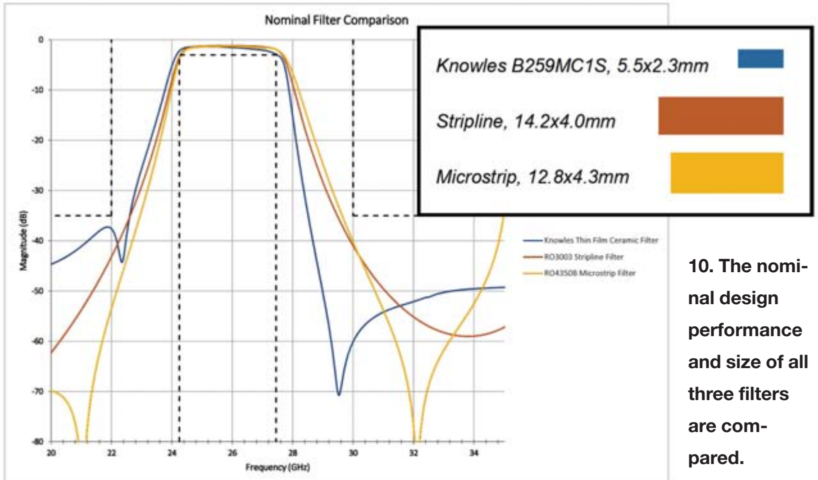
## CONCLUSION

Turning 5G wireless communication into a widespread reality requires mmWave filter technology for 20 GHz and higher. However, certain obstacles exist in terms of physical size, tolerances, and temperature stability. Variation in production quality may result in significant loss of performance from the simulated design to the real-world manufactured part, thereby diminishing the gains from using the mmWave spectrum.

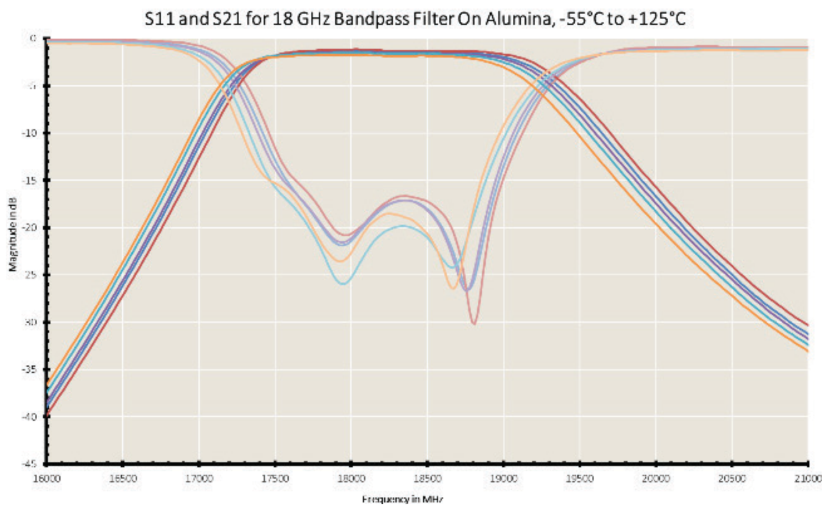
As a result, one must carefully consider tolerances and the need for guard bands for the design. In general, SMT devices are shown to provide better shipped tolerances compared with the PCB approach, as long as the impact of the SMT filter's temperature stability on bandwidth capacity is taken into account. mw


REFERENCE

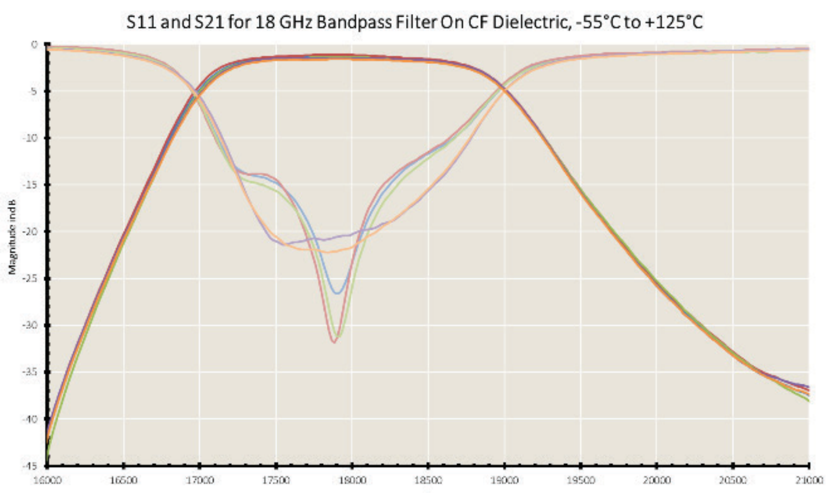
1. On mm-wave filters and requirement impact, 3GPP TSG-RAN WG4 meeting #85, R4-1712718


10. The nominal design performance and size of all three filters are compared.




11. This is the temperature response of a microstrip 18-GHz BPF on alumina.




12. The temperature response of a microstrip 18-GHz BPF on CF dielectric reveals a shift of only 17 MHz at the 35-dB rejection point.

JIM HOLBROOK | Director of Customer Engineering, SiTime Corp.
www.sitime.com

# The Time is Right for Programmable MEMS Timing

**MEMS oscillators offer programmable features that open the door to customizable frequencies and other performance-enhancing advantages.**

Oscillators have changed substantially since they were first developed in the early 1900s. When MEMS-based oscillators came on the scene in the early 2000s, the pace of innovation accelerated dramatically. One of the biggest transformations has surrounded the flexibility and scope of programmable timing features available, along with the resulting benefits.

MEMS oscillators are complete timing systems based on a programmable architecture. Because all aspects of the timing system are included—resonator, oscillator sustaining circuit, phase-locked loop (PLL), temperature compensation, on-chip power-supply regulators, and filters—an extremely large and flexible portfolio of programmable features can be offered to customers.

By contrast, many quartz suppliers (but not all) are merely systems integrators rather than technology developers. For example, a quartz supplier might procure the quartz ingots from one supplier, the ceramic package from Kyocera or Sumitomo, the oscillator circuit from AKM or Cypress, and merely assemble and test the components developed by other companies.

By contrast, MEMS oscillator vendors usually develop all of the subcomponents of the complete oscillator solution in house and can therefore offer more innovative and programmable oscillator solutions. The *table* shows many of the features available when using a programmable timing system.

## OPTIMIZED SYSTEM PERFORMANCE

MEMS oscillators have several programmable features that improve system performance, including options for frequency output and waveform tuning. Starting with customizable frequency, designers can optimize performance by selecting the best output frequency for their application, which can be programmed from 1 Hz to 725 MHz, and out to 6 decimal places of accuracy. For applications that require voltage-controlled crystal oscillators (VCXOs) or digitally controlled crystal oscillators (DCXOs), MEMS oscillators have programmable pull range from ±6.25 parts per million (ppm) to thousands of ppm to support integration into control loops, including discrete jitter attenuator loops.

The pull-range flexibility of MEMS timing devices is created by using a fractional PLL rather than pulling the resonator itself with variable capacitive loading, as is done for most quartz-based VCXOs. Because of the limited quartz resonator pull range, quartz VCXOs are usually limited to a maximum absolute pull range (APR) of ±50 to ±100 ppm. The limited pull range of quartz devices reduces the applications they are able to support because a ±50-ppm VCXO, for example, would not be able to track an Ethernet clock in which frequency can be within ±100 ppm, as specified in IEEE 802.3.

| | | | |
|---|---|---|---|
| Any Frequency | 1 Hz | 725M options | 725 MHz |
| Any Stability | ±0.005 ppm | 18 options | ±50 ppm |
| Any Voltage | 1.2V | 8 options | 3.3V |
| Temperature | -55°C | 10 options | +125°C |
| Any Output Type | | 6 options | |
| NanoDrive Output | 200 mV | 4 options | Rail-to-rail |
| Spread Spectrum | ±2% | 48 options | –4% |
| Package | 1.5 x 0.8 mm | 14 options | 25 x 22 mm |
| FlexEdge Rise/Fall Times | 0.25 ns | 8 options | 4.0 ns |
| Control Input | | 6 options | |
| VC Pull Range | ±25 ppm | 10 options | ±3200 ppm |
| In-System Programmability | SPI | 2 options | I²C |

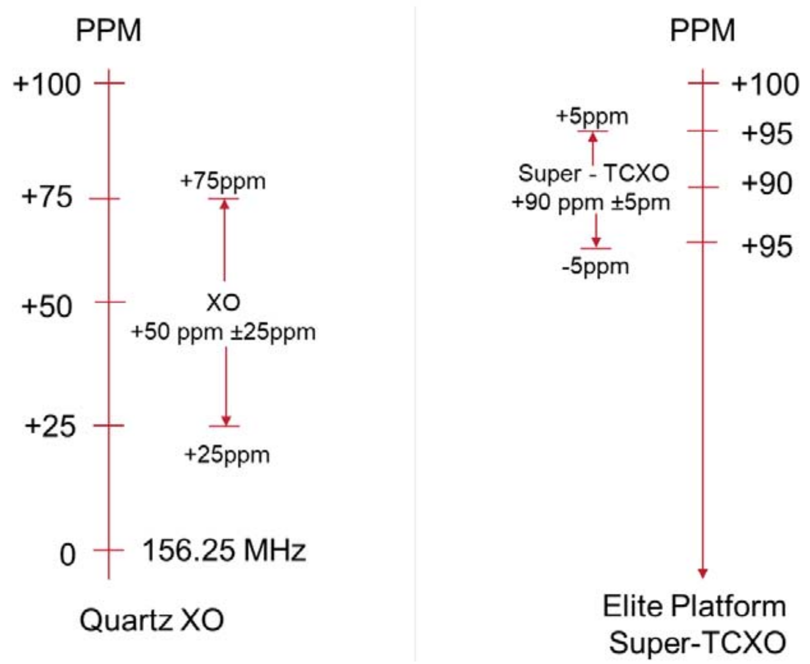
**A wide range of programmable MEMS timing options exist.**

Another programmable-oscillator application is dynamic frequency control. In-system programmable (ISP) oscillators can be used to boost computer performance through overclocking by slightly increasing frequency, or conversely, the frequency can be throttled back to lower system power during idle or low load conditions. Processors and memory systems can usually accommodate reference clock-frequency variation on the order of a few percent, making this dynamic frequency control an excellent means to throttle the clock frequency depending on processing load.

Communications systems usually have frequency tolerance specified in ppm rather than percentage, but they can benefit from higher than nominal frequencies, too. In Ethernet networks, it's desirable in some situations to bias the average frequency higher to improve overall system performance and minimize the probability of buffer overflow and dropped frames.

The Ethernet standard requires a frequency accuracy of ±100 ppm. If ±100-ppm oscillators are used to build system boards, the oscillators will meet the Ethernet standard. Over a large production run, the Ethernet ports will span the frequency range from −100 to +100 ppm with a mean frequency of 0 ppm, as one expects when purchasing large numbers of ±100-ppm oscillators.

To bias the average frequency higher and improve overall performance while minimizing dropped frames due to buffer overflow/underflow, "spiked" oscillators are available. Spiked oscillators have the average frequency centered at some offset, usually +25 ppm or +50 ppm, above the nominal frequency. This means the quartz blank needs to be cut with this frequency offset, which may impact availability and price. And higher frequency spikes mean that the frequency-versus-temperature tolerance and aging specifications must be tighter so that the +100-ppm Ethernet specification is not exceeded.




**1. The frequency spiking of a quartz oscillator is compared to a MEMS Elite Platform Super-TCXO.**

For example, 156.25 MHz is a common oscillator frequency for 10-Gb Ethernet. A +50-ppm variant of this oscillator means the oscillators ship with an average frequency of 156.25 MHz + 50 ppm, which equals 156.2578125 MHz. The maximum allowable variation over temperature aging and other factors would need to be ±50 ppm to not exceed the +100-ppm Ethernet specification. Therefore, such oscillators would range from 0 to 100 ppm with a mean value of +50 ppm (156.2578125 MHz).

To allow for some margin to the +100-ppm Ethernet limit, oscillators spiked +50 ppm usually have a total stability specification of ±25 ppm. In this case, the highest frequency over a large population of devices would be +75 ppm (50 + 25) and the lowest frequency would be +25 ppm (50 – 25).

With the higher precision and lower aging of MEMS oscillators along with the programmable PLL technology, this frequency-spiking concept can be taken to the next level. Because a good MEMS temperature-compensated crystal oscillator (TCXO) has a total stability over 20 years of less than ±5 ppm, the center frequency could be set to +90 ppm. This would allow for a frequency range over a large population of devices of +85 ppm to +95 ppm (leaving 5 ppm of margin to +100 ppm).

*Figure 1* compares frequency spiking of a quartz oscillator versus a MEMS Elite Platform Super-TCXO. Note that the MEMS TCXO frequency scale uses a zoomed-in view relative to the quartz oscillator (XO) scale. In this comparison, the average quartz frequency is +50 ppm versus the average MEMS TCXO frequency of +90 ppm. Thus, using the MEMS TCXO delivered an 80% improvement. And this improvement from the MEMS TCXO does not require a different resonator, but merely programming the PLL to the +90-ppm center frequency.

To learn more about the advantages of digital control, check out SiTime's *(www.sitime.com)* application notes entitled "I2C/SPI Programmable Oscillators" and "Improved System Performance with Digital Frequency Tuning in Precision Super-TCXOs."

**REDUCING EMI**

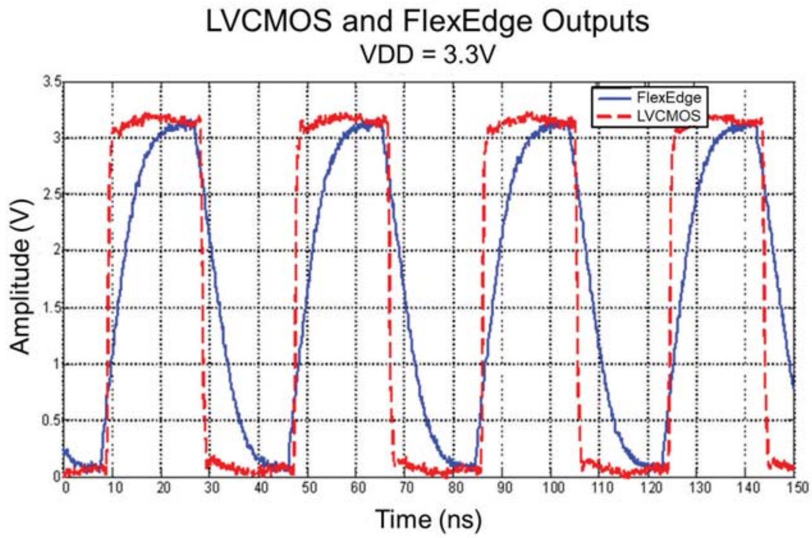
Programmable features can also reduce radiated clock emissions, which result in electromagnetic interference (EMI). For example, FlexEdge is a programmable feature for reducing EMI by increasing the rise and fall time of the clock waveform, which decreases the drive strength. FlexEdge effectively attenuates the clock's power at higher-order harmonics and is especially effective for mitigating EM sourced from the clock trace. It has little to no impact on short-term jitter such as cycle-to-cycle jitter.

The impact of rise/fall time adjustment on harmonic power can be seen in *Figure 2*, which shows the oscilloscope waveform, and in *Figure 3*, which illustrates the impact of the slower rise/fall time in the frequency domain as measured on a spectrum analyzer. In *Figure 3*, the 19$^{th}$-harmonic of the slower rise/fall time waveform had 24.4 dB lower power than the 19$^{th}$-harmonic from the faster rise/fall time waveform.

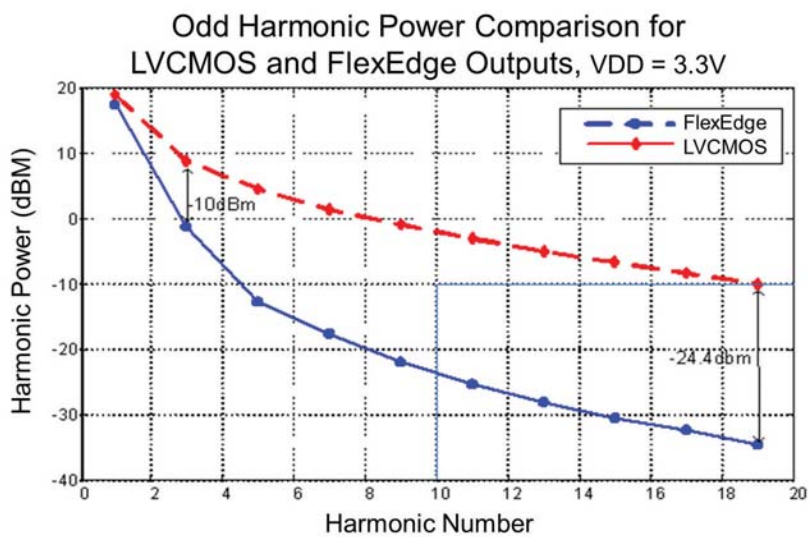
Spread-spectrum clocking is another programmable-oscillator feature used to reduce EMI. This is particularly helpful in mitigating EM at the system level, reducing power peaks in the frequency domain of fundamental and harmonic components of the clock signal. Designers can use both spread-spectrum clocking and FlexEdge in combination to combat EMI, lowering noise by up to 17 dB on the fundamental frequency and 24 dB on the harmonics.

*Figure 4* demonstrates the spectrum impact of a fixed-frequency clock (red color trace) versus a clock with triangular spread-spectrum modulation (blue). As shown, the peak power of the carrier frequency was reduced by 17 dB by using spread-spectrum modulation.

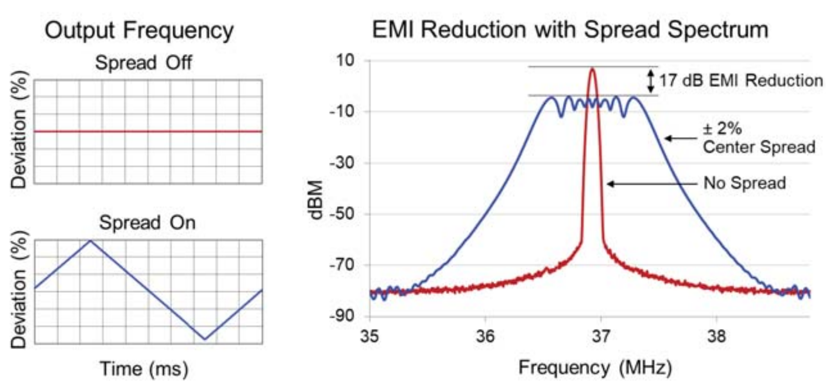
These programmable emissions-reducing features come with a range of options. For example, the SiT9005 oscillator from SiTime has eight configurable FlexEdge settings, with slew rates from 0.25 to 40 ns, plus a wide spread range up to 4.0% peak-to-peak through two spread profile options: triangular or




**2. Shown are oscilloscope waveforms of LVCMOS and FlexEdge outputs.**




**3. Slower rise/fall times can positively affect harmonic power.**




**4. Depicted is the spectrum impact of a fixed-frequency clock (red color trace) versus a clock with triangular spread-spectrum modulation (blue).**

Hershey kiss. This type of flexibility is especially useful during the final stages of design when needing to pass compliance tests. Because MEMS oscillators come in several industry-standard footprints, they can be used as drop-in replacements for quartz oscillators without any printed-circuit-board (PCB) layout changes or use of bulky mechanical shielding.

**LOWERING POWER CONSUMPTION**

Reducing power consumption continues to be increasingly important, and programmable timing features help in this capacity as well. As mentioned, MEMS oscillators have programmable frequency. Because the frequency of SiTime MEMS oscillators can be programmed down to 1 Hz, it's possible to drop the output load current to the lower end of the MCU/IC operating frequency range to reduce power consumption (power dissipation is proportional to $C \times V^2 \times F$, where C is capacitance, V is the supply voltage, and F is frequency).

For example, reducing the output frequency from 2 MHz to 500 kHz decreases the unloaded operating current by about 70%. In contrast, quartz crystals are physically larger at lower frequencies, so quartz devices with frequencies less than 32.768 kHz are very uncommon.

Programmable NanoDrive is another power-saving feature available in low-frequency (1 Hz to 32 kHz) MEMS oscillators. With NanoDrive, the output and associated voltage swing can be programmed to match the downstream MCU or PMIC, from full LVCMOS (rail-to-rail) all the way down to an output swing of just 200 mV, significantly lowering current draw. Using lower-frequency MEMS oscillators in combination with low supply voltage and NanoDrive output is a potent combination for reducing power.

**FLEXIBLE, PROGRAMMABLE TIMING SYSTEMS**

The frequency output, waveform tuning, EMI reduction, and power-reducing features mentioned can be used with other configurable features that impact performance. For example, a range of frequency-stability, supply-voltage, and output options are available with MEMS oscillators. These programmable features are usable in any combination within the device's broad operating range to meet the specification needs of the system. In summary, the programmable architecture of MEMS oscillators creates a flexible timing solution that can improve system performance in multiple ways. mw

CHRIS DeMARTINO | Editor


# Advanced Materials Processing is this Firm's Primary Mission

**Greg Sexton, Accumet's president and CEO, discusses his company's history, its many capabilities, and some of the challenges he is seeing going forward.**

**First, can you tell us a little about what Accumet does?**

I'd like Accumet *(www.accumet.com)* to be known as an advanced materials processing house—not just a laser and lapping service provider. Since purchasing Laser Services back in 2007, I quickly learned that lapping and polishing were complementary businesses. At Laser Services, we routinely subcontracted to Accumet for our lapping and polishing needs. Likewise, Laser Services was Accumet's go-to laser house.

Accumet Engineering has been around since the 1970s and is widely known for lapping and polishing of ceramics and other materials. I decided to purchase Accumet in 2015 so that I could offer our clients "one-stop shopping" in relation to materials processing. The combination of the two allow us to process a vast variety of materials to precisely match client specifications.

Our service offerings include laser scribing, drilling, cutting, welding, and etching, as well as lapping, grinding, and polishing finish steps. We work closely with our clients to understand their needs, timelines, and ultimate expectations.

**How are the company's laser processing services enabling RF/microwave applications?**

Again, we are not just a laser or lapping house or stock distributor. We have it all under one roof to manage client jobs with the corresponding materials that enable a smart supply-chain approach.

When I purchased Accumet and decided to merge the two companies, I had to make the decision of what to name the combined companies. Should it be Laser Services or Accumet? Both company names had been around for 50 years, so the decision was not taken lightly. I ultimately made the decision to name the merged companies Accumet. I felt that the Laser Services name incorrectly implied that we are only laser-centric. Yes, we are a large laser house, but we do so much more. We have a sourcing network that allows us to reliably provide the building block, or "substrate," upon which so many work products are created.

**Tell us about the company's laser ablation services.**

Laser ablation is a process that we use to remove layers of material while leaving the substrate intact. This process is routinely used for removing material to create solder dams, but it can also be used to remove unwanted traces on circuit boards to salvage parts instead of scrapping and remaking. In fact, years ago, that's how we came upon this service. In response to a recognized need, we came up with this method to help out a client and we ended up saving a big production run for them.

**Lapping and polishing are two services provided by the company. Can you talk more about these services and why they're important?**

As I mentioned previously, we provide the substrate. If our part of the project is not done precisely correct, the whole project can be adversely affected. If lapping isn't done properly, for example, the client may experience an adhesion issue. Or if the holes aren't clean, there may be a conductivity issue.

**In terms of RF/microwave applications, what are some of the more difficult challenges you're seeing from clients, and how is the company overcoming them?**

Two come to mind initially. The first of which is when clients are pushing us to lap and/or polish to thinner thicknesses and tighter tolerances. I am constantly meeting with my engineering team to get higher yields while improving our processes to further advance our manufacturing capabilities. Repeatability is key to me, as it allows us to maintain competitive pricing and keeps our production schedule moving smoothly.

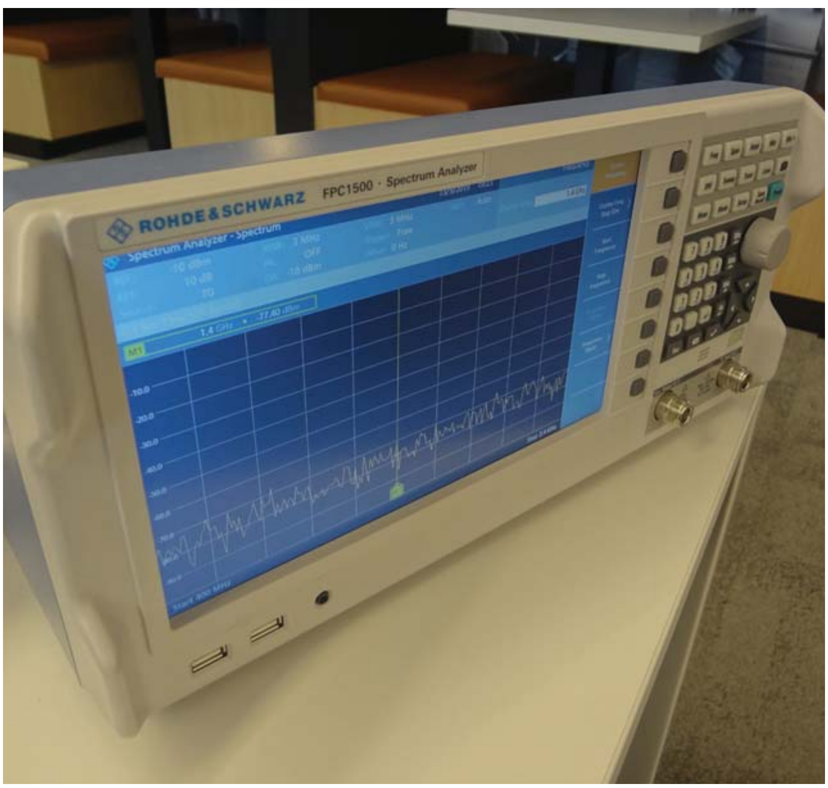
Secondly, client buying philosophies seem to have changed. Years ago, a large percentage of our production schedule was made up of annual blanket purchase orders, with pre-determined monthly release dates. While a fair amount of our clients still issue blanket purchase orders, I am seeing a slight decline in this buying method. I see clients preferring to buy more on an "as needed" basis to cut down on inventory and operating costs on their end. This change has pushed us to hone our production times and scheduling. That is, while we once had months to plan (in the case of a blanket purchase order), we now may only have days.

One last point I would like to mention is that when I merged Laser Services with Accumet Engineering earlier this year, my marketing team wanted me to drop "Engineering" from the Accumet name. But I said no. Engineering is a large part of who we are. We are here to deliver a quality product on a timely basis, but we are also here to help with any design or material questions a client may have. We also have a vast resource of suppliers who can be called upon as needed in the case of any second-tier outsourcing that may be required. mw

CHRIS DeMARTINO | Editor

# Put this SPECTRUM ANALYZER on Your Shopping List

**Though labeled a spectrum analyzer, this economical test instrument goes beyond spectral analysis by offering measurement capabilities like signal generation.**




**1. Shown is the FPC1500, which is the focal point of this article.**

As many RF/microwave engineers and technicians can attest, Rohde & Schwarz *(www.rohde-schwarz.com)* is known as a supplier of premier high-frequency test-and-measurement equipment. But while the company is certainly synonymous with such high-end instruments, these products also come with a (justifiably) high price tag.

However, to prove that quality test-and-measurement equipment doesn't necessarily have to be high cost, Rohde & Schwarz now offers what it has branded as "value" instruments. According to the company, this line of test instruments still offers the quality, performance, and engineering that Rohde & Schwarz is known for—but at much lower costs.

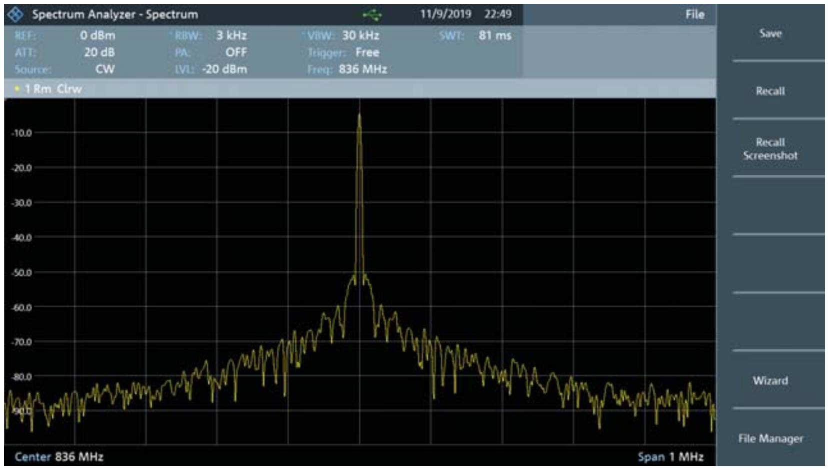
A previous *Microwaves & RF* article provided a general overview of the product line, which covers everything from oscilloscopes to spectrum analyzers to power supplies. In this article, we'll take a hands-on look at one of these "value" instruments: the FPC1500 spectrum analyzer *(Fig. 1)*.

## AN INTRODUCTION TO THE FPC1500

The FPC1500 base model covers a frequency range of 5 kHz to 1 GHz. However, customers can extend the frequency range to either 2 or 3 GHz by purchasing additional upgrades. The FPC1500 also features a built-in continuous-wave (CW) source, meaning that it can actually operate as a signal generator as well as a spectrum analyzer. And with a built-in tracking generator, the FPC1500 can essentially perform scalar-network-analyzer transmission measurements, too.

Customers can purchase several optional upgrades to enhance the FPC1500's functionality. One of them enables the instrument to perform vector-network-analyzer (VNA) measurements. When equipped with this option, the FPC1500 could essentially be described as three instruments in one—a spectrum analyzer, a signal generator, and a VNA.

Other optional upgrades for the FPC1500 include a spectrum-analyzer preamplifier as well as modulation analysis for AM, FM, ASK, and FSK. On top of that, there's a receiver application, advanced measurement capability, and Wi-Fi connection support.




**2. The FPC1500 offers the typical functions one would find in a spectrum analyzer.**


**3. The built-in tracking generator makes it possible to perform scalar-network-analyzer measurements, such as this measurement of a bandpass filter with a center frequency of 1.4 GHz.**

## GETTING DOWN TO BUSINESS WITH THE FPC1500

Now, let's explore some of the FPC1500's capabilities. For reference, the FPC1500 that's used for these demonstrations comes with an extended frequency range to 3 GHz along with all of the other upgrades.

Pressing the *Mode* button reveals the different instrument modes available. They include *Spectrum*, *Analog Demod*, *Digital Demod*, *Receiver*, and *Vector Network Analyzer*. Of course, *Spectrum* mode, which we'll look at first, corresponds to a traditional spectrum-analyzer measurement environment *(Fig. 2)*.

When operating the FPC1500 in *Spectrum* mode, the signal-source options can be accessed by pressing the *Meas* button followed by selecting *Source*. Users can then choose to have the instrument generate a CW signal, which is accessed through the instrument's output connector. In addition, the *Coupled CW* feature generates a CW signal with a frequency that's always equivalent to the spectrum-analyzer center frequency. That means changing the center frequency of the spectrum analyzer automatically changes the frequency of the CW signal to the same frequency (i.e., the frequency of the CW signal "follows" the spectrum-analyzer center frequency).

In addition, with the *Tracking Generator* feature, the FPC1500 can generate a CW signal with a frequency that's coupled to the measurement frequency. Thanks to this capability, users can perform scalar-network-analyzer transmission measurements of components such as filters. As an example, *Figure 3* shows a measurement of a bandpass filter in *Spectrum* mode with the tracking generator enabled. The specified center frequency of this filter is 1.4 GHz.

## ADVANCED MEASUREMENTS

As mentioned earlier, the FPC1500 can be upgraded to include advanced measurement capabilities. When equipped with this feature, the FPC1500 offers additional measurement options in *Spectrum* mode; these can be accessed by pressing the *Meas* button followed by selecting *Measurement Mode*. Measurement modes include *Channel Power*, *Third Order Intermod*, *Spectrogram*, *Spectrogram Playback*, *TDMA Power*, *Harmonic Distortion*, *AM Modulation Depth*, and *Occupied Bandwidth*.

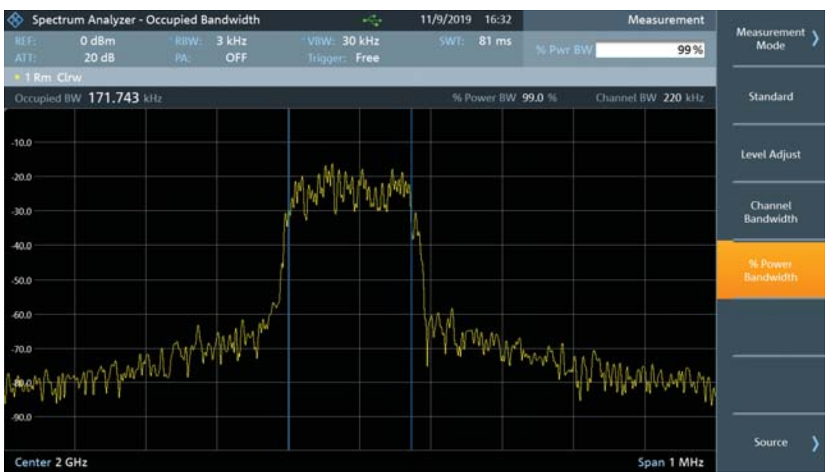
Let's dive into some of these advanced measurement features, starting with *Harmonic Distortion*. This feature is intended to make it easy for users to identify and characterize harmonics. *Figure 4* shows a harmonic-distortion measurement of an amplifier that was driven by an 836-MHz CW signal.

With the harmonic-distortion feature, the fundamental frequency and a user-specified number of harmonics are automatically identified and measured. For the measurement shown in *Figure 4*, the number of harmonics was specified as 2 (fundamental plus the second harmonic). However, users can specify as many as 6 harmonics (fundamental plus five harmonics). And, when making a harmonic-distortion measurement, the frequency span is automatically adjusted so that all harmonics are visible. Furthermore, the total harmonic distortion (THD) is calculated.

The *Channel Power* feature makes it possible to selectively measure the power of modulated signals. With this function, users can perform power measurements of specific transmission channels. Therefore, signals at frequencies outside of the specified channel do not factor into the results.


**4. Thanks to the harmonic-distortion feature, the fundamental frequency and second-harmonic levels were easily determined.**


**5. This screenshot shows a channel-power measurement of a 2-GHz QAM signal.**




**6. Here, the OBW of a 2-GHz QAM signal is measured.**


## *Up to 50 GHz!*

# TEST CABLES

## *Reliability You Can Trust...*

Why do 10,000 customers trust Mini-Circuits test cables? Because they simply don't fail! Our test cables have been performance qualified to 20,000 flexures* and come backed by our 6-month product guarantee, so you can be confident you're getting rugged construction, reliability, and repeatable performance you can depend on. Order some for your test setup at minicircuits.com today, and you'll quickly find that consistent long-term performance, less retesting and fewer false rejects really add up to bottom-line savings, test after test!

*Varies by model. See individual model data sheets for details.

**Mini-Circuits®**

**www.minicircuits.com** P.O. Box 350166, Brooklyn, NY 11235-0003 (718) 934-4500 sales@minicircuits.com 507 Rev K

For example, *Figure 5* shows a channel-power measurement of a 2-GHz 16-QAM signal. Here, a channel bandwidth of 240 kHz was specified, resulting in a power measurement of –5.5 dBm.

The last advanced measurement capability we'll look at is *Occupied Bandwidth*. Occupied bandwidth (OBW), which is an important characteristic of modulated signals, is defined as the bandwidth that contains a defined percentage of the total transmitted power. When making this measurement, users can specify this percentage to be anywhere between 10% and 99%. The FPC1500 will then display the corresponding OBW.

**For those who may be considering purchasing an FPC1500, the base unit carries a price tag of only $2,980. At that price level, it appears Rohde & Schwarz has truly created a "value" instrument.**

*Figure 6* depicts an OBW measurement. Once again, the signal being measured is a 2-GHz QAM signal. As shown in *Figure 6*, setting the power percentage to 99% results in an OBW of 171.743 kHz.

### A SPECTRUM ANALYZER WITH A BUILT-IN VNA

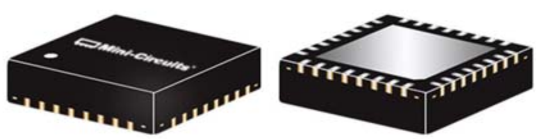
The FPC1500 spectrum analyzer is unique in the sense that it also operates as a VNA when equipped with the optional VNA application. This VNA capability is made possible thanks to the FPC1500's internal voltage-standing-wave-ratio (VSWR) bridge. The VNA application provides users with several measurement options: *Reflection S11*, *Transmission S21*, *1-Port Cable Loss*, and *Distance To Fault*. Among other features available with the VNA application are Smith chart measurement displays.

### THE FINAL WORD

The FPC1500 offers a wide range of performance features in a single box. This article covered some of the key measurement capabilities of the FPC1500, but the instrument offers more than what was discussed here. In any case, it's clear that this instrument offers the functionality that should make it a valuable tool for many engineers.

For those who may be considering purchasing an FPC1500, the base unit carries a price tag of only $2,980. At that price level, it appears Rohde & Schwarz has truly created a "value" instrument. mw

## New Products



### MMIC Power Splitter/Combiner Trims Losses to 18 GHz

**MINI-CIRCUITS' MODEL EP2RKU+** is a two-way, 0-deg., resistive/reactive MMIC power splitter/combiner with a frequency range of dc to 18 GHz. Typical isolation between ports is 13.1 dB from dc to 4 GHz and 26.1 dB from 4 to 18 GHz. Typical insertion loss (above the 3-dB power split) of the EP2RKU+ is 3.3 dB or less from dc to 18 GHz. Amplitude unbalance is typically 0.02 dB across the full frequency range, while the typical phase unbalance is 0.3 deg. to 4 GHz and 1.1 deg. to 18 GHz. The RoHS-compliant power splitter/combiner comes in a surface-mount QFN package that measures just 5 × 5 × 1 mm, but it handles as much as 600 mW of power as a splitter or combiner. The EP2RKU+ exhibits full-band VSWR of 1.50:1 or better at all ports and has an operating temperature range of –55 to +105°C.

**MINI-CIRCUITS,** P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500, https://www.minicircuits.com/WebStore/dashboard.html?model=EP2RKU%2B

### MMIC LNA Quiets 4 to 18 GHz and Beyond

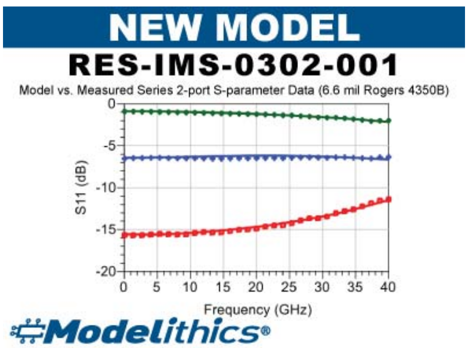
**THE PMA2-183LN+** is a broadband MMIC low-noise amplifier (LNA) designed to operate from 4 to 18 GHz but is still usable to 20 GHz. Small-signal gain is typically 13.2 dB at 4 GHz, 10.9 dB at 15 GHz, 10.2 dB at 18 GHz, and 9.3 dB at 20 GHz. Typical noise figure is 2.7 dB at 4 GHz, 2.5 dB at 18 GHz, and only 2.9 dB at 20 GHz. Based on E-pHEMT technology, the PMA2-183LN+ comes in an eight-lead MCLP surface-mount package that measures 2 × 2 mm but is capable of moderately high output power. Typical output power at 1-dB compression is +16 dBm at 4 GHz, +15.8 dBm at 15 GHz, and +14.6 dBm at 18 GHz. The typical output third-order intercept point (IP3) is +31 dBm at 4 GHz, +28.1 dBm at 15 GHz, and +27.7 dBm at 18 GHz. The LNA draws 48.2 mA from a single +5-V dc supply.

**MINI-CIRCUITS,** P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500, https://www.minicircuits.com/WebStore/dashboard.html?model=PMA2-183LN%2B

## Wideband, High-Gain Coaxial Amplifier Spans 10 MHz to 43.5 GHz


**MINI-CIRCUITS' ZVA-443HGX+** is a wideband coaxial amplifier with high gain and low noise from 10 MHz to 43.5 GHz. Typical gain ranges from 37 dB across 10 MHz to 18 GHz, 33 dB from 18 to 32 GHz, 30 dB from 32 to 40 GHz, and 28 dB from 40.0 to 43.5 GHz. The full-band noise figure of the ZVA-443HGX+ is typically 3.5 dB. Typical output power at 1-dB compression is +10 dBm from 10 MHz to 32 GHz and +8 dBm from 32.0 to 43.5 GHz. Incorporating overvoltage and reverse-voltage protection, the RoHS-compliant amplifier runs on a single bias supply from +9 to +15 V dc. It draws 300 mA typical current from a +9-V dc supply. Well-suited for wideband test and communications systems, the amplifier measures 2.000 × 1.313 × 0.69 in. (50.80 × 33.35 × 17.60 mm) excluding 2.92-mm female input and output connectors.

**MINI-CIRCUITS,** P.O. Box 350166, Brooklyn, NY 11235-0003; (718) 934-4500, https://www.minicircuits.com/WebStore/dashboard.html?model=ZVA-443HGX%2B




## Resistor Model Covers 0 to 1,800 Ω

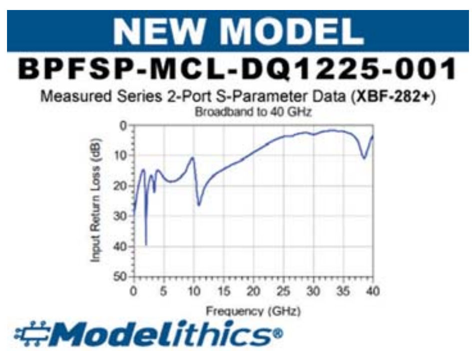
**AVAILABLE FROM MODELITHICS** is an equivalent circuit-based scalable Microwave Global Model for International Manufacturing Services' (IMS) (www.ims-resistors.com) RC4-0302PW series of surface-mount chip resistors. The model, validated up to 40 GHz, features substrate, pad, and part-value scaling from 0 to 1,800 Ω of the resistor series. IMS is sponsoring free 90-day trials of all available models by request and with approval. For more information and to request the free trial, contact sales@modelithics.com.

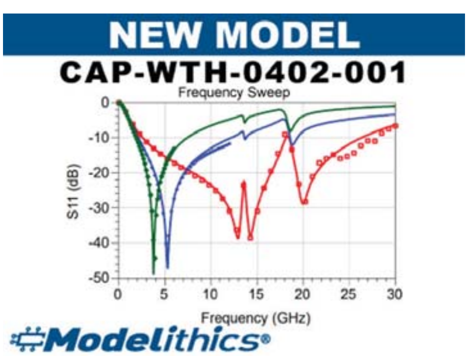
**MODELITHICS,** 3802 Spectrum Blvd., Suite 130, Tampa, FL 33612; (813) 866-6335 or (888) 359-MDLX (6359), www.modelithics.com/mvp/ims

## Bandpass Filter Data Model Aids Designers

**MODELITHICS NOW OFFERS** an S-parameter data model for Mini-Circuits' XBF-282+ surface-mount bandpass filter, which comes in a 3- × 3-mm DQ1225 package. The S-parameters represent typical component performance on 6.6- and 10-mil-thick Rogers 4350B substrates, as well as similar board types (i.e., same thickness and a dielectric constant of 3.66 ± 0.4). Mini-Circuits is sponsoring free model downloads for registered users. For more information, contact sales@modelithics.com.

**MODELITHICS,** 3802 Spectrum Blvd., Suite 130, Tampa, FL 33612; (813) 866-6335 or (888) 359-MDLX (6359), www.modelithics.com/mvp/minicircuits

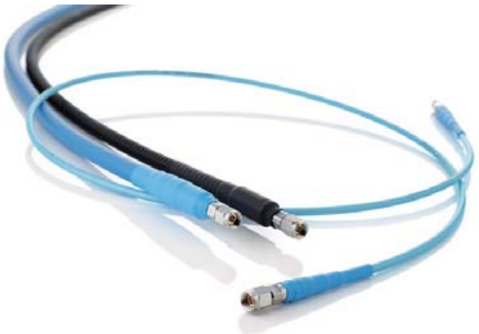



## Capacitor Model Features Substrate, Pad, and Part-Value Scaling

**DESIGNERS CAN BENEFIT** from Modelithics' equivalent circuit-based scalable Microwave Global Model for Würth Elektronik's WCAP-CSRF 0402 surface-mount chip capacitors. The model, validated up to 30 GHz, features substrate, pad, and part-value scaling over the full range of the capacitor series (0.3 to 9.0 pF). Würth Elektronik is sponsoring free 90-day trials of all available models by request and with approval. For more information and to request the free trial, contact sales@modelithics.com.

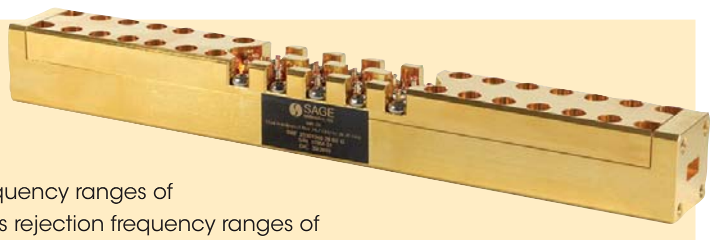
**MODELITHICS,** 3802 Spectrum Blvd., Suite 130, Tampa, FL 33612; (813) 866-6335 or (888) 359-MDLX (6359), www.modelithics.com/mvp/wurth



## Cables Maintain Stability Versus Temperature

**JUNKOSHA'S MWX3 SERIES** of cabling solutions are intended for equipment-wiring applications. Offering performance at frequencies as high as 40 GHz, the MWX3 Series features a porous PTFE dielectric material to ensure superior phase stability when there are temperature fluctuations. The cables (except for the MWX315) have a continuous operating temperature range of –65 to +125°C.

**JUNKOSHA,** 18201 Von Karman Ave., Suite 1080, Irvine, CA 92612; (949) 825-6177, www.junkosha-mwx.com




## Dual-Bandpass Filter Enables Ka-Band Applications

**MODEL SWF-25301340-28-B2-D** is a Ka-band waveguide dual-bandpass filter with passband frequency ranges of 24.25 to 25.25 GHz and 36.25 GHz to 40.0 GHz. It has rejection frequency ranges of dc to 23.8 GHz, 27.0 to 35.5 GHz, and 42.0 to 49.0 GHz. The SWF-25301340-28-B2-D is designed for 5G frequency bands and, particularly, 24- and 38-GHz system applications. Nominal insertion loss is 3.0 dB, with a typical rejection of 40 dB. The passband frequencies can be changed by modifying the design, enabling custom designs to be offered under different model numbers.

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


## Power Amplifier Delivers from 26.5 to 41 GHz

**MODEL SBP-2734132530-KFKF-E1-HR** is a power amplifier with a small signal gain of 25 dB over a frequency range of 26.5 to 41 GHz. Typical output power at 1-dB compression is +30 dBm across this range. The SBP-2734132530-KFKF-E1-HR draws 3 A current from a +8-V dc supply. It's built with female 2.9-mm connectors for both the input and output ports. Other port configurations, such as male 2.9-mm connectors and WR28 waveguide interfaces for either the input or output port, are also available under different model numbers.

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

## VHF Circularly Polarized Antenna Covers 174 to 216 MHz

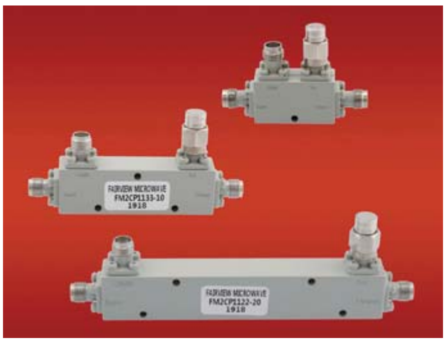
**MODEL CP-1V** is a wideband VHF circularly polarized antenna that covers a frequency range of 174 to 216 MHz with an SWR of 2:1 or better. The 18- × 18- × 4-in. unit is housed in a rugged radome with a heavy aluminum backing. Designed for indoor or outdoor use, the CP-1V is rated for 5 W of power and delivers a gain of 3 dBd (circular) over a 100-deg. beamwidth. Higher power and alternate frequency ranges are available.

**RADIO DESIGN GROUP,** 8925 Rogue River Hwy., Grants Pass, OR 97527; (541) 471-1100, www.radiodesigngroup.com

**2.92-mm Terminations Support a Multitude of Applications**

**CINCH CONNECTIVITY SOLUTIONS,** a Bel group company, now offers 2.92-mm terminations in both genders, plug and jack, for high-frequency applications. The 50-Ω, 2.92-mm terminations are rated for a maximum frequency of 40 GHz. Featuring a passivated stainless-steel body, the terminations achieve a VSWR of less than 1.25:1. Example applications include satellite-communication equipment, cable assemblies, and test-and-measurement equipment.

**CINCH CONNECTIVITY SOLUTIONS,** 299 Johnson Ave. SW, Suite 100, Waseca, MN 56093; (507) 833-8822, www.belfuse.com/cinch



**Directional Couplers Reach 67 GHz**

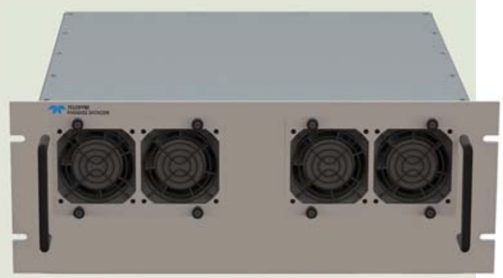
**A LINE OF DIRECTIONAL COUPLERS** consists of 24 models with maximum operating frequencies ranging from 26.5 GHz to 67 GHz. The couplers are available with 6-, 10-, 15-, 20-, and 30-dB coupling levels. They can also handle as much as 30 W of CW power. As an example, model FM2CP1127-10 is a 10-dB coupler that operates from 1 to 67 GHz. The series of couplers is well-suited for point-to-point radio, 5G, satellite-communication, automotive-radar, and aerospace applications.

**FAIRVIEW MICROWAVE,** 301 Leora Ln. Suite 100, Lewisville, TX 75056; (800) 715-4396 or (972) 649-6678, www.fairviewmicrowave.com

**X-Band SSPA Provides 4 kW**

**A 4-KW X-BAND** solid-state power amplifier (SSPA) from Teledyne Paradise Datacom (a division of Teledyne Defense Electronics) is intended for defense applications. The SSPA, which covers a frequency range of 9 to 10 GHz, is designed for installation in a standard 19-in. equipment rack. The amplifier features forced-air cooling with hot-swappable fan trays at the front panel. Each SSPA takes up four rack units. The unit may be connected to a PC via an Ethernet connection for remote monitoring and control.

**TELEDYNE PARADISE DATACOM,** 328 Innovation Blvd., Suite 100, State College, PA 16803; (814) 238-3450, www.paradisedata.com




**Solid-State High-Power Amplifier Delivers 2 kW**

**EMPOWER RF SYSTEM'S** model 2226 is a solid-state broadband high-power amplifier that can supply 2 kW of continuous-wave (CW) power over a frequency range of 900 to 1,600 MHz. The 2226 utilizes high-power GaN devices and is suitable for high-power CW, modulated, and pulsed applications. The amplifier includes a built-in control and monitoring system. Connecting the unit's Ethernet port to a LAN allows for remote management and diagnostics via an embedded web server.

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

*This index is provided as an additional service by the publisher, who assumes no responsibility for errors or omissions.*


Subscription Assistance and Information:
(ISSN 0745-2993)

Microwaves & RF is published monthly. Microwaves & RF is sent free to individuals actively engaged in high-frequency electronics engineering. In addition, paid subscriptions are available. Subscription rates for U.S. are $95 for 1 year ($120 in Canada, $150 for International). Published by Informa Media Inc., 9800 Metcalf Ave., Overland Park, KS 66212-2216. Periodicals Postage Paid at Kansas City, MO and additional mailing offices.

POSTMASTER: Send change of address to Microwaves & RF, PO Box 2100, Skokie, IL 60076-7800. For paid subscription information, please contact Microwaves & RF at PO Box 2100, Skokie IL 60076-7800. Canadian GST #R126431964.

# *Ultra high bandwidth Payload & RF Multipath Link Emulator*

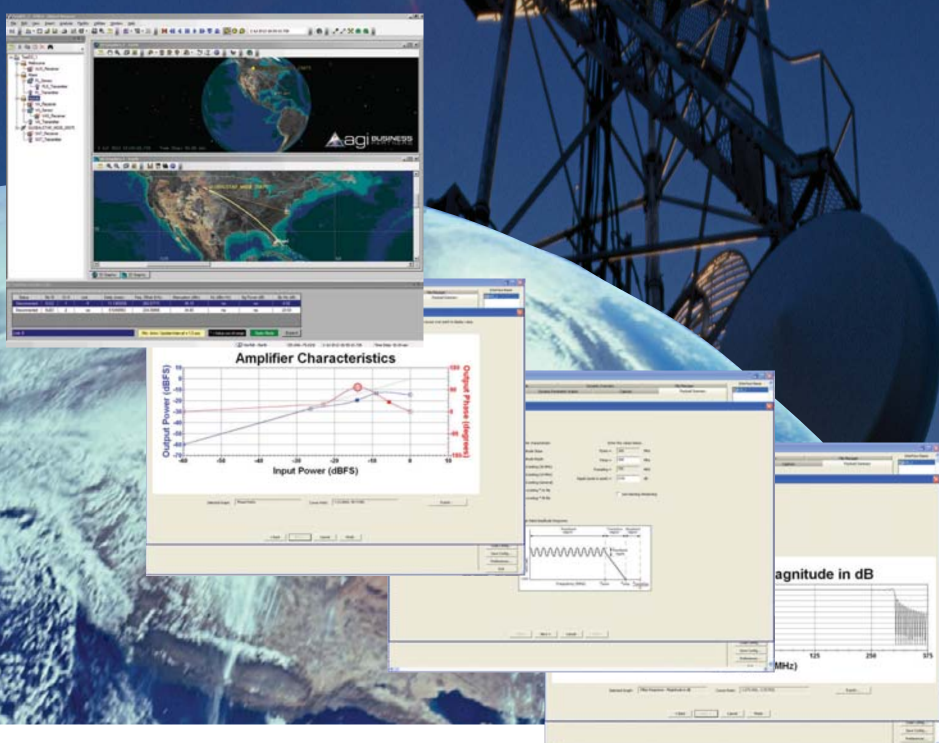
Just released ...

Sophisticated high bandwidth (up to 600MHz) emulation of physical layer RF link effects channel modeling (delay, Doppler, AWGN, Multipath) and hardware in the loop impairments modeling (programmable Group delay, Phase noise, gain/compression distortion and non-linearity AM/AM, AM/PM simulation etc.


Comprehensive range of instruments from 72 MHz to 600 MHz bandwidth with a wide RF frequency tuning range.

Contact dBm for specifications, pricing information and demonstration/evaluation units.

- **RF physical layer Link emulation**
- **Point to Point UHF/VHF radio testing**
- **Real time control for Arial Vehicle (UAV) testing**
- **Payload and ground station emulation**
- **Multipath, 12 paths @ 600MHz BW**




**dBm**

*RF Test Equipment for Wireless Communications*

**email: info@dbmcorp.com**

**dBm Corp, Inc**
**32A Spruce Street ◆ Oakland, NJ 07436**
**Tel (201) 677-0008 ◆ Fax (201) 677-9444**
**www.dbmcorp.com**