



eBook

# Design Innovations in mmWave MMICs

October 2020



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## Design Innovations in mmWave MMICs

The expansion of activities in the areas of SATCOM, automotive radar, 5G, security and others are pushing semiconductor technologies higher in frequency. The design of mmWave MMICs is much more difficult than those at lower frequencies as everything becomes much more sensitive in the design tradeoffs that affect performance. In this eBook we have collected some of the latest information on testing and designing mmWave MMICs to help in your selection and understanding of these devices.

The first article is a survey of mmWave semiconductor test solutions as some new players have developed capabilities in this area. With the rollout of mmWave 5G, the expected volume of mmWave MMICs will increase rapidly so many companies are now offering production solutions for these devices. The next article looks at innovations in AESA and MIMO radars using new products that are built upon highly integrated system-on-chip custom ICs and MMICs along with advanced packaging and integrated subsystem products for applications in the aerospace and defense market. It uses a holistic approach to achieve optimized aperture to data systems.

Next, we have an article that describes some of the scenarios for the spectrum above 90 GHz, coveted by the cellular industry for 6G. A benchmark of semiconductor technologies is discussed to highlight promising candidates and channel-bonding architectures as a suitable option for the implementation of extremely broadband RF radios with acceptable power consumption. The next two articles cover specific MMIC devices, the first covers distributed or wideband amplifiers including their features and how to best use them in a microwave system. The next one covers the design of a Doherty amplifier for mmWave applications in the 28 GHz range for 5G. Finally, the last article covers how GaN is changing the SATCOM RF Front-End utilizing its high power and efficiency.

We hope that this eBook provides some insights for your new system designs in the mmWave frequency range. Thank you to RELL and Qorvo for sponsoring the eBook so that we can bring it to you for free.

*Pat Hindle, Microwave Journal Editor*

# Survey of mmWave Semiconductor Test Systems

*Including Anritsu, Focus, FormFactor, Keysight, Maury, NI, R&S, Roos and Teradyne*

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Patrick Hindle  
Editor, *Microwave Journal*

**W**ith the roll out of 5G mmWave systems, automotive radar and higher frequency SATCOM systems, we thought it would be timely to survey the various test solutions available at these higher frequencies. We surveyed most of the companies involved in high frequency testing about their offerings in mmWave semiconductor testing. We received inputs from Anritsu, Focus, FormFactor, Keysight, Maury, NI, R&S, Roos and Teradyne. Below is a summary of the various offerings from the leaders in the industry.

## ANRITSU

During the design process of modern microwave and mmWave communication systems, designers must characterize devices (transistors, capacitors, inductors, etc.) over a broad range of frequencies from near DC to well beyond the operating frequencies of the design. The process of device characterization generates models used during circuit simulation and the accuracy of the model determines the accuracy of simulation and consequently, the chances for first turn success. An important element for model accuracy is characterization of devices well beyond the operating frequency of the circuit and, in many cases, characterization well beyond 110 GHz is desirable. An ultra-wide broadband VNA, such as the VectorStar™ ME7838G with 70 kHz to 220 GHz single-sweep capabilities, provides industry-leading measurements and enables optimal device characterization for accurate models and circuit simulations.

The Anritsu VectorStar ME7838 series broadband systems offer a number of unique attributes and performance capabilities through the use of Nonlinear Transmission Line (NLTL) technology in a unique proprietary design. The NLTL mmWave module provides source frequencies starting at 54 GHz that is coupled to the main transmission line through substrate couplers up to 110, 125, 145 and 220 GHz depending on the module model. The use of couplers ensures optimum raw directivity for optimum calibration and measurement stability. The Test and Reference harmonic sampler receivers are located next to the test port for accurate signal monitoring and operate from 30 to 220 GHz.

A critical aspect of high frequency broadband VNA systems is the connection to the device under test (DUT) measurement plane. For on wafer semiconductor measurements the DUT input is typically coplanar waveguide (CPW). Typically, connection from the VNA to the DUT is through a threaded coaxial connector such as the 1 mm connector. Connection to the DUT is therefore through the 1 mm transition inside a CPW probe and limited to the 110/125 GHz range.

To address the continuing requests for higher frequencies, Anritsu began development of the 0.6 mm coaxial connector for 220 GHz measurements. To avoid the negative consequences of connector thread wear at higher frequencies, the 0.6 mm coaxial connector was designed with an alternative guiding system for the connection to the CPW probe. The module to probe



connection uses the UG-387 flange (see Figure 1), whose tolerances support precise alignment for 220 GHz mmWave measurements, and thus accurately pre-aligns the male/female center pin connection with excellent repeatability.

Design of the probe body and tip was developed by MPI Corporation. The MPI probes, the TITAN T220, directly mates with the Anritsu MA25400A module and are available in 50, 75 and 100 micron pitches for support of a wide range of DUT pad connections.

As application frequencies migrate upward, differential receiver front-ends with wide dynamic range, high sensitivity and low noise floor are becoming critically important. A 4-port differential broadband VNA is therefore an important element during the design of microwave and mmWave communication systems. The modular concept of the VectorStar ME7838 series of broadband VNAs offers the opportunity to upgrade from 110 to 145 and 220 GHz through the use of appropriate frequency NLTL module. Likewise, a 2-port broadband VectorStar ME7838 system can be upgraded to 4-port configuration by adding additional test sets and modules. For example, the VectorStar ME7838D4 is a 4-port broadband system operating to 145 GHz with true differential measurement capability (see Figure 2). The industry has expressed a need for 220 GHz differential measurements and Anritsu will be collaborating with other industry leaders such as MPI during the development of a 220 GHz 4-port differential broadband VNA system.

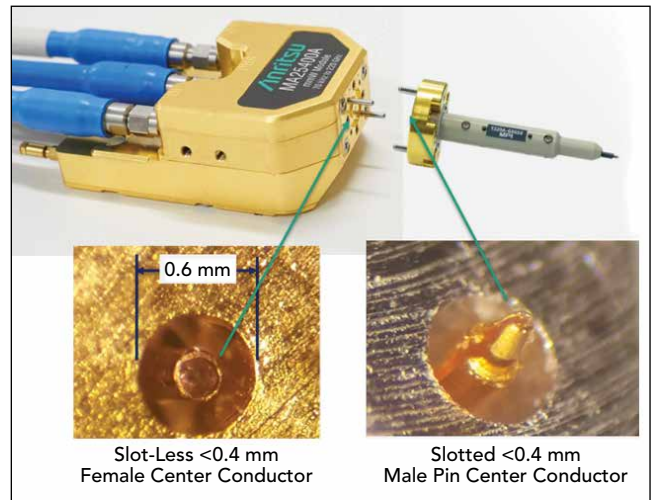
## FOCUS MICROWAVE

Focus Microwaves and Keysight have collaborated to develop a turnkey solution which makes it possible to perform high frequency fundamental and harmonic load pull up to 110 GHz with great accuracy. Combined with Keysight's very small footprint N5290A 110 GHz PNA-X, Focus Microwaves DELTA tuners offer a very simple and efficient system which elegantly integrates on wafer.

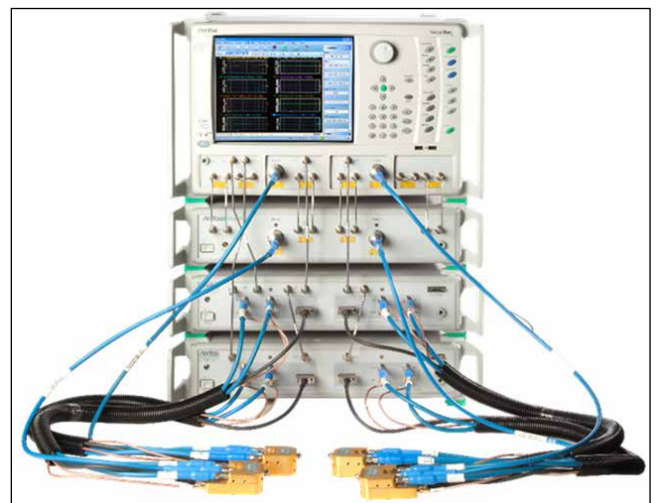
### Key Features:

- On wafer load pull measurements up to 110 GHz
- Measure and optimize key nonlinear parameters
- Perform both scalar and vector load pull
- Focus Device Characterization Software to control instrumentation and collect data
- Measure multiple parameters over multi-octaves of frequency

mmWave on wafer load pull has always been a challenge for both test and design engineers as the inherent loss at high frequencies would limit the tuning and dynamic range on any load pull system. Keysight and Focus have collaborated to develop a turnkey solution which solves those problems making now possible to perform high frequency fundamental and harmonic load pull up to 110 GHz with great accuracy. Combined with Keysight's very small footprint N5290A 110 GHz PNA-X, Focus Microwaves DELTA tuners offer a very simple and efficient system which elegantly integrates on wafer.



▲ Fig. 1 Anritsu NLTL mmWave module with DC coaxial connector mating of MPI probe using UG-387 interface.

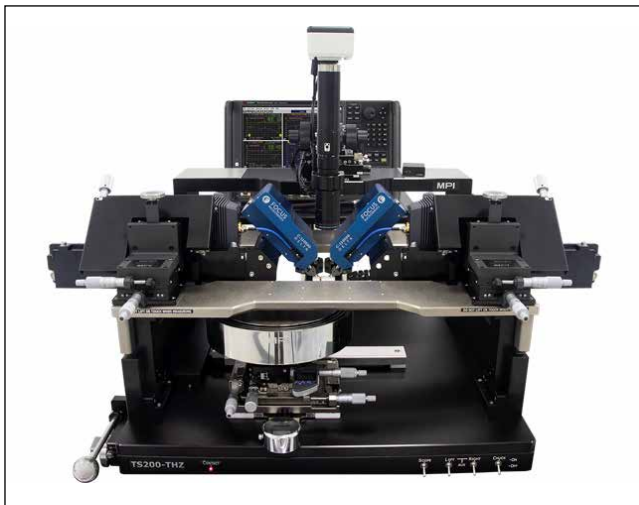


▲ Fig. 2 VectorStar ME7838D4 4-port 145 GHz Broadband VNA.

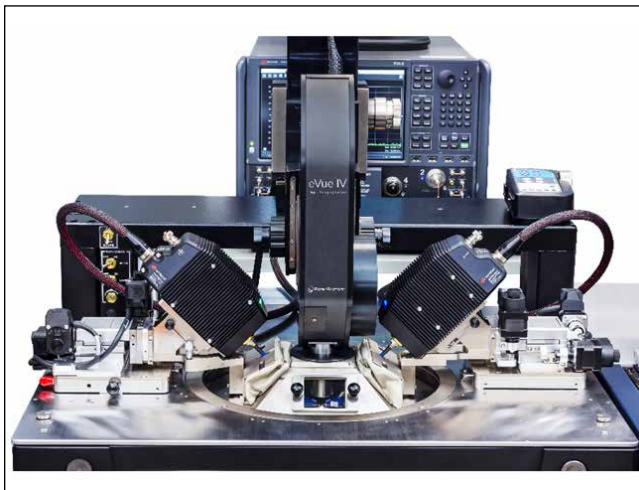
Focus Microwaves' new DELTA series of electro-mechanical tuners is designed specifically for high frequency on wafer measurements. The tuner's low profile allows it to be placed within the wafer perimeter and allows for a direct connection between the probe tip and the tuner, eliminating all possible insertion loss between the DUT and the tuner. This revolutionary new tuner design enables the engineer to achieve optimum tuning range, with a tuner whose footprint and weight has been dramatically reduced.

The PNA-X is a key component in this joint solution as it is the heart of the signal generation and analysis of the load pull solution. The PNA-X Series of microwave network analyzers are the culmination of Keysight Technologies, Inc. 40-year legacy of technical leadership and innovation in radio frequency (RF) network analysis. More than just a vector network analyzer, the PNA-X is the world's most integrated and flexible microwave test engine for measuring active devices like amplifiers, mixers and frequency converters.

In this example, Focus has partnered not only with Keysight but MPI Corporation for the on wafer probing



▲ Fig. 3 TS-200-THz test system.



▲ Fig. 4 Autonomous RF Measurement Assistant prober.

capability. The rigid MPI Engineering Probe Systems are the ideal choice for RF and mmW measurement applications. The compact footprint ideally fits to the requirements of integration with complex RF power and noise characterization systems. Accurate and back-lash free RF MicroPositioners provide precise positioning of the RF probes.

MPI explicitly designed and mmW dedicated, manual probe systems TS150-THZ, TS150-AIT & TS200-THZ (see Figure 3), the high-end mmwave MP80 MicroPositioner and the single-tube MPI SZ10 or MZ12 microscopes with unique combination of high magnification and long working distance Optics enable integrating the mmW, sub-mmW VNA frequency extenders and automated impedance tuners, closest possible to the DUT, for the shortest signal path and guaranteeing best possible measurement directivity and accuracy. MPI TITAN™ RF Probe Series with its unique design and MEMS manufactured tips provide unique visibility, low resistance and high consistency of the contact even on hard to probe Aluminum pads.

## FORMFACTOR

Devices in the consumer, infrastructure and defense markets, are going higher and higher in frequency. This

includes devices such as 5G (28-40 GHz), automotive radar (77 GHz) and Vehicle to Everything, as well as next generation Wi-Fi (60 GHz). These higher frequencies make it more challenging to design, fabricate and test these new RF devices. IC designers use PDKs (process design kits), which, to reduce design cycles, must be modeled and characterized very precisely – not only at the operating frequency of the circuit, but way beyond and over a very broad band. Typically, 40 GHz 5G devices would use transistors characterized up to 120 GHz with no room for error in a transistor model. Considering the latest generation processors contain billions of transistors, small errors accumulate, meaning the IC will not perform as intended, and a new design iteration is required. Ultimately the more accurate the PDKs, the higher the success rate of IC designs and faster time to market.

Accurate measurements in the engineering lab start with the best instrumentation, RF wafer probes, proven and traceable calibration standards and a repeatable calibration algorithm. However, over time and process variations and under different conditions such as bias and temperature, large volumes of measurements need to be taken from many thousands of devices. This characterization process is extremely time consuming and requires skilled engineers to operate.

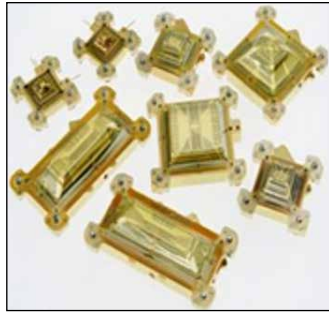
One new productivity technology recently introduced allows engineers to measure more devices, and ensures known accuracy of the measurements, leading to better quality PDK's and faster time to market. This new technology is the Autonomous RF Measurement Assistant (AutoRF, see Figure 4).

With AutoRF operators can make measurements 24 hours a day, seven days a week, even when measuring thousands of transistors, on up to 50 wafers at a time and over multiple temperatures. The test cell can be left running with confidence unattended overnight and weekends. AutoRF will constantly monitor calibration accuracy, and automatically re-calibrate when the error exceeds a defined limit. It also re-calibrates when changing test temperature, corrects for any thermal errors introduced, and automatically aligns the probe to the pads during each touch down. This ensures confidence that measurement accuracy is always within a known limit and removes measurement uncertainty. This new technology is fully autonomous and can controlled and monitored remotely, something that is important to all of us during these challenging times of social distancing.

In production RF wafer test, the development and rollout of 5G is driving most of the growth in RF test in semiconductor with high volume manufacturing requirements for fast, and cost effective, throughput. The carrier aggregation, as well as higher density MIMO and the addition of 20+ GHz bands, are the primary drivers leading to a five times increase in the number of RF analog semiconductor devices (handset and base station).

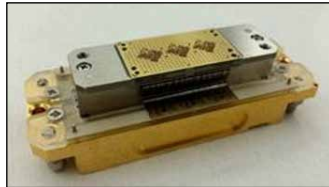
FormFactor ProbeFormFactor has a few wafer probing technologies for production test. This includes our flagship Pyramid Probe (see Figure 5) that has been used in wafer test for many years in both RF Front End Devices (< 5 GHz filters, switches, power amplifiers), high speed devices including high speed digital com-

ponents for infrastructure, and coming to automotive radar devices that operate up to 81 GHz. Pyramid Probe has been shown in test to be fully capable of volume production support to the largest semiconductor manufacturers, with capability to multi-site probing with full RF calibration for the most accurate measurements for wafer sort.



▲ Fig. 5 Pyramid Probe.

FormFactor contactsIn addition, FormFactor has been developing the Pyrana technology for even higher multi-site capability with RF performance for 5G devices (see Figure 6).



▲ Fig. 6 Pyrana technology using vertical MEMS contactors.

It is using vertical MEMS contactors that provide mechanical robustness and repairability that customers require, as well as good signal integrity out to 10 GHz. FormFactor has also been working to release a new implementation of Pyrana, called ePyrana, that will be able to support test up to 45 GHz bandwidth for 5G device. This new product will be released in the second half of 2020.

## KEYSIGHT TECHNOLOGIES

mmWave semiconductor testing is a key part of the Keysight offering since the 1997 with the launch of the 8510XF Network Analyzer. This system has been designed to make fully calibrated, single-sweep measurements of broadband devices to 110 GHz, in 1.0 mm coax. The 1.0 mm connector was used to carry the signal to the DUT without the limitation of the waveguide transmission lines, previously used at this very high frequency. Cascade Microtech (now FormFactor) designed a wafer probe station and probes for the first time enabling the possibility to perform fully calibrated on wafer measurement with a single touchdown. This solution marks the start of a successful collaboration between the two companies that, during the last three decades, jointly launched several solutions, always with the objective to collaborate and maximize knowledge and competence. Today, the wafer level measurement solution is a clear example of this synergy. With guaranteed system configuration, integration and support, a wafer level measurement solution from Keysight Technologies and FormFactor provides accurate and repeatable testing, minimizing the time to first measurement, while enabling data correlation between multiple locations.

A typical configuration will include instruments from Keysight such as a PNA or PNA-X network analyzer, a B1500A Semiconductor Device Parameter Analyzer, and a N6705C DC power analyzer together with Keysight's WaferPro Express (WaferPro-XP) measurement software platform. This is integrated with a FormFactor semi-automated wafer probe station, WinCal XE cali-



▲ Fig. 7 Keysight N5291A Broadband Network Analyzer.



▲ Fig. 8 Keysight N4372E 110 GHz Lightwave Component Analyzer.

bration software and Impedance Standard Substrates for calibration. The N5291A 900 Hz to 120 GHz PNA system is the instrument of choice for this solution (see Figure 7). This powerful single-sweep solution with compact frequency extenders deliver very accurate and stable measurements fully traceable at the probe tips, making this solution unique in the market. Two and four ports configuration are available to test the most challenging devices.

Integrated Photonic Test is another important area where Keysight and FormFactor are joining forces. Integrated Photonics, often called Silicon Photonics, promises additional benefits for industrial segments such as intra data center communication and data center interconnects (DCI), Telecom, 5G and automotive connectivity, high-performance computing, LIDAR, sensing and medical. The joint solution includes: Keysight's N4372E 110 GHz Lightwave Component Analyzer, shown in Figure 8, that delivers unprecedented bandwidth for both optical receiver testing and optical transmitter testing with guaranteed specifications for electro-optical S-parameter measurements for device traceability.

The FormFactor CM300xi-SiPh, with automated wafer level photonics positioning combined with Keysight's industry standard IL/PDL engines and N7700C Photonics Application Suite (PAS), to support wavelength repeatability of  $\pm 1.5$  pm at two-way sweeps up to 200 nm/s within 1,240 to 1650 nm to ensure accuracy and repeatability from O- to L-band.

The KS8400A Keysight Test Automation Platform (TAP) allows fast execution, test flow visualization, analysis and insights. Keysight Test Automation on PathWave (TAP) is a modern Microsoft .NET-based ap-



plication that can be used standalone or in combination with higher level test executive software environments. Instrument plugins provide test steps that can be added to work-flow sequences without needing to use instrument level programming commands. The N4370P01A LCA TAP Plug-In steps further simplify the Electrical/Optical (E/O) and Optical/Electrical (O/E) measurements by handling the interface to both the PNA instrument and the LCA optical hardware and software. The PNA settings needed for LCA measurements are provided in the test steps for easy configuration. To ensure ease of use, the FormFactor's SiPh software enables automated calibrations and alignments and simplifies integration with Keysight's PathWave software platform, as well as optical instrumentation.

## MAURY MICROWAVE

There is a growing demand for device characterization and modeling solutions above 28 GHz to support applications such as 5G frequency range 2 (FR2) and automotive RADAR as well as next generation semiconductor technology evaluation. These applications are not only driving frequencies higher but are also pushing the envelope on modulation bandwidths. To address these challenges, our state-of-the-art semiconductor test solutions push the boundaries of load pull with extreme modulation bandwidths as well as expanded frequency coverage to 1.1 THz.

The introduction of 5G is unlocking new levels of mobile communication performance with high speeds, low latencies and ultra-high reliability. This will be enabled in part by using the FR2 frequency bands around 28 and 38 GHz, with channel bandwidths in the hundreds of MHz. These bandwidths pose a challenge for passive impedance tuners, where the phase variation over frequency results in the loss of impedance control and degrades ACPR, EVM and PAE performance when using wideband modulated signals. To overcome this challenge, Maury designed the MT2000 mixed signal active load pull system, which corrects for impedance phase variations and allows users to set arbitrary impedances over a bandwidth of up to 1000 MHz at frequencies up to 40 GHz (see Figure 9).

With wideband impedance control, Maury can now synthesize the load conditions presented by realistic matching networks and antennas and accurately characterize the vector-corrected performance of a DUT. To achieve this capability, they designed the MT2000 from



▲ Fig. 9 Maury MT2000 mixed signal active load pull system.

the ground up as a standalone one-box solution, which replaces the functions of a VNA, vector signal generator, vector signal analyzer and automated impedance tuners, thereby reducing the overall system cost and complexity while simultaneously ensuring an excellent measurement accuracy. Additional features of the MT2000 include high speed CW and pulsed-CW measurements, baseband impedance control, time-domain nonlinear analysis, behavioral model extraction for 5G circuit design, and I/Os for digital pre-distortion and envelope tracking tests.

When active devices are characterized at frequencies beyond 5G, additional challenges for passive impedance tuners arise, especially for on wafer measurements. Traditional on wafer passive load pull systems suffer from a degraded tuning range at the DUT reference plane due to the insertion loss of the RF probes used to make a connection with the DUT. While a standalone passive impedance tuner may be able to present a  $|Γ| > 0.9$  at 75-110 GHz, the system loss may reduce the tuning range to  $|Γ| = 0.6-0.65$ , often below the expectations of a modeling or design engineer. The latest vector-receiver load pull system using IVCAD software, designed in partnership with AMCAD Engineering, enables hybrid-active load pull up to 110 GHz, and is able to increase the tuning range to  $|Γ| = 0.92$  or higher at the DUT reference plane. The increased tuning range allows engineers to fully characterize their transistor technologies, determine ideal matching conditions for amplifiers and circuit designs, and better validate their nonlinear models. To best support their customers, the company is expanding the MPA-series amplifier product line to include high-power mmwave amplifier modules in bands between 50 and 110 GHz for active and hybrid-active load pull.

At frequencies above 110 GHz, the system losses become so high that the impedance tuning range of passive tuners is significantly limited. As an example, a 4 dB insertion loss of a waveguide probe at 300 GHz would reduce a hypothetical tuner's  $|Γ| > 0.9$  to less than 0.3 at the probe tip. To overcome this challenge, Maury offers fully active load pull up to 1.1 THz with their strategic partner Vertigo Technologies and our MMW-STUDIO solution. MMW-STUDIO uses standard VNAs and waveguide extenders (e.g. Keysight and R&S VNAs using VDI or OML extenders) and enables high-resolution amplitude- and phase-controlled S-parameter, power sweep and load pull measurements with  $|Γ| > 0.9$  at the probe tip at frequencies up to 1.1 THz (see Figure 10). With MMW-STUDIO, engineers can now extract and validate transistor models, full characterize transistors and circuits, optimize amplifier design and validate the performance of circuits and systems under mismatched load conditions at mmW and sub-THz frequencies.

## NI (NATIONAL INSTRUMENTS)

Many companies working on mmWave devices for 5G applications are still defining the final architecture of their devices, how to package them and what level of performance they can achieve. Since these factors are not final, engineers working on applications need flexible mmWave test and measurement solutions. NI is in

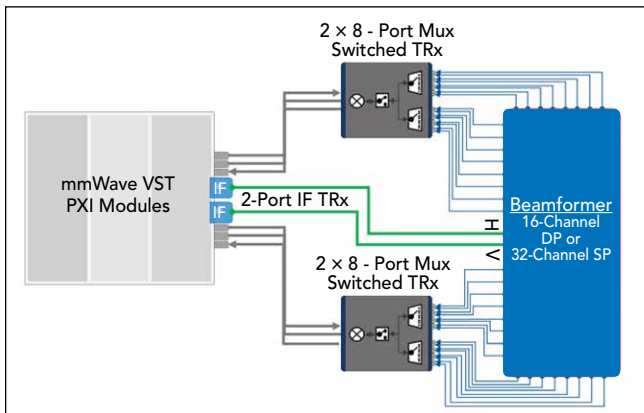




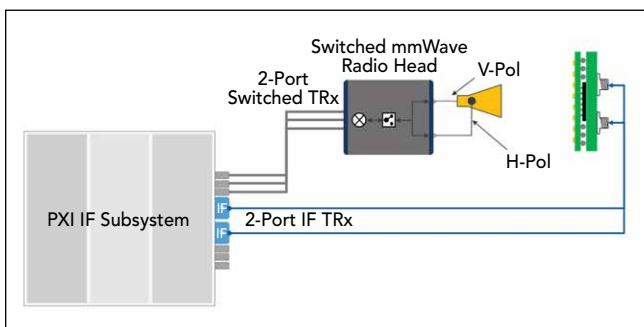
▲ Fig. 10 Active load pull up to 1.1 THz with their strategic partner Vertigo Technologies and our MMW-STUDIO solution.



▲ Fig. 11 NI VST, mmWave modules and software for 5G mmWave testing.



▲ Fig. 12 NI mmWave VST connected to a 32-channel – IF-RF Beamformer.



▲ Fig. 13 NI mmWave VST configured for over-the-air (OTA) testing of IF to RF Antenna Modules.

a unique position to offer this flexibility and the speed required to take measurements on a broad range of mmWave device types.

Taking advantage of the modularity of the software-connected PXI platform and mmWave Vector Signal Transceiver (VST), NI offers a test solution that is easy to configure to fit the needs of 5G mmWave devices. The mmWave VST, a wideband instrument that combines a vector signal generator and vector analyzer, is capable of covering both 5 to 21 GHz intermediate frequency (IF) and 5G frequency range 2 (FR2) mmWave bands. The compact mmWave test heads, which are external to the PXI chassis, minimize signal loss by bringing the signal closer to the DUT interface and are easy to adapt to physically different test setups (see Figure 11).

In addition, engineers can select either direct or switched-path configurations of the NI mmWave test heads. This flexibility helps achieve the best measurement performance depending on the DUT types, whether they are higher-power devices or multichannel types such as beamformers. Figures 12 and 13 show different types of test configurations taking advantage of the mmWave VST architecture.

5G semiconductor companies continue to forge new developments in antenna-in-package (AiP) and antenna-in-module (AiM) devices. NI introduced a 3D-scanning mmWave OTA validation solution that helps characterize the spatial radiation performance of these devices 5 to 10 times faster than traditional scanning techniques. This solution can be adapted to high volume parametric OTA production test using the same instrumentation, which helps ensure reliable AiM performance once assembled as part of a system.

Additionally, NI's modular instruments, like the mmWave VST, readily deploy to high volume semiconductor manufacturing floors within the NI Semiconductor Test System (STS). The STS takes advantage of the same measurement science and high-precision lab instrumentation in a robust automated test equipment (ATE) FormFactor. STS maximizes yield on the production floor by leveraging lab-grade measurement performance while applying highly optimized measurement algorithms to accelerate test speed. Furthermore, our vision is to connect the performance insights from a large amount of characterization and sample data to create more targeted and efficient test methodologies and sequences. Then, by mining production data, we can understand how to improve the initial design and validation stages, and further accelerate the rapid design-to-production cycle of mmWave devices.

NI offers a test solution that empowers engineers across different stages of mmWave device testing – from validation to automated characterization to production test. The commercialization of mmWave devices is new and exploding. NI's high-performance, flexible mmWave test solution solves the challenge of testing a variety of devices in a condensed timeline while ensuring the highest device quality.

## ROHDE & SCHWARZ

To provide turnkey solutions for semiconductor test, Rohde & Schwarz cooperates with a variety of partners.

In particular, network analyzers from Rohde & Schwarz provide the essential measurement data. Partners have chosen these instruments due to their high accuracy, high speed and reliable performance, all meeting the specifications diligently documented in data sheets.

Wafer level characterization is a critical part of RF and microwave semiconductor design and debug, including modeling modern high-performance semiconductor devices. For on wafer characterization of RF and mmwave components, Rohde & Schwarz collaborates with long-term partner the MPI Corporation in Taiwan, to offer turnkey solutions for measurements on semiconductor components. Rohde & Schwarz contributes network analyzers directly supporting frequencies up to 110 GHz with frequency converters extending the range up to 1,100 GHz, developed to work in conjunction with MPI wafer probes in all-in-one solutions designed for precision analysis of 150 and 200 mm wafers:

- The TS150-THZ is the first 150 mm wafer dedicated probe station on the market designed explicitly for mmwave and THz on wafer measurements.
- The TS200-THZ for 200 mm wafers adds active impedance tuner integration providing accurate tests for the combination of requirements for mmwave, THz, and automated impedance tuner applications (see Figure 3).

For developing active components such as power amplifiers running under compression showing nonlinear behavior such as impedance variance and reflection effects, load pull varies the load impedance at the DUT to determine the optimum matching. R&S partners Focus Microwaves and Maury Microwave provide packages featuring R&S ZNA, ZNB (see Figure 14), and ZVA network analyzers for load pull measurements from 10 MHz to 110 GHz.

For modulated tests of semiconductors in 5G or satellite links, according to the target application the wideband vector signal generator R&S SMW200A supports up to 2 GHz of bandwidth and 44 GHz RF frequency, the signal and spectrum analyzer R&S FSW even goes up to 90 GHz with an with an internal demodulation bandwidth of 8.3 GHz due for release in July.

For production and characterization of 5G FR2 RFICs, the radio communication tester R&S CMP200 offers a unique highly integrated solution supporting CW and modulated tests in the FR2 frequency range. The combination with the IF connections enable cost-efficient test of highly integrated RFICs with an IF connection. The compact shielding chamber for OTA test R&S CMQ200 pairs ideally with the communication tester for packaged 5G FR2 RFIC devices, which typically also include a mmWave antenna.

For modulated tests, the internal and fully calibrated demodulation bandwidth of the signal analyzer R&S FSW is unique on the market. Up to 8.3 GHz bandwidth for analyzing wideband radar chips or linearization using wideband DPD algorithms for mmWave power amplifier transistors and integrated ICs.

The new high-end network analyzer R&S ZNA offers high dynamic range ensuring highest measurement speed paired with exceptional repeatability and accuracy. In addition, R&S ZNA – together with its predecessor

R&S ZVA – are the only integrated network analyzers offering four independent sources to enable fast and in-depth mixer characterization.

The multiport network analyzer R&S ZNBT with up to 24 ports and frequencies up to 40 GHz is ideal for parallel testing of multiple devices as well as the latest high-integrated ICs such as multichannel active beamformers for 5G or satellite links, which have typically from 5 to 17 ports. The high integration in the R&S ZNBT platform simplifies the handling and the calibration of the multiport test setup.

Future enhancements include the high-end vector network analyzer platform R&S ZNA increasing its frequency range and adding functions for semiconductor testing needs. The signal and spectrum analyzer FSW internal demodulation bandwidth will increase from 2 to 8.3 GHz for automotive and industrial radar chipsets and beyond 5G research is launching soon.

## ROOS INSTRUMENTS

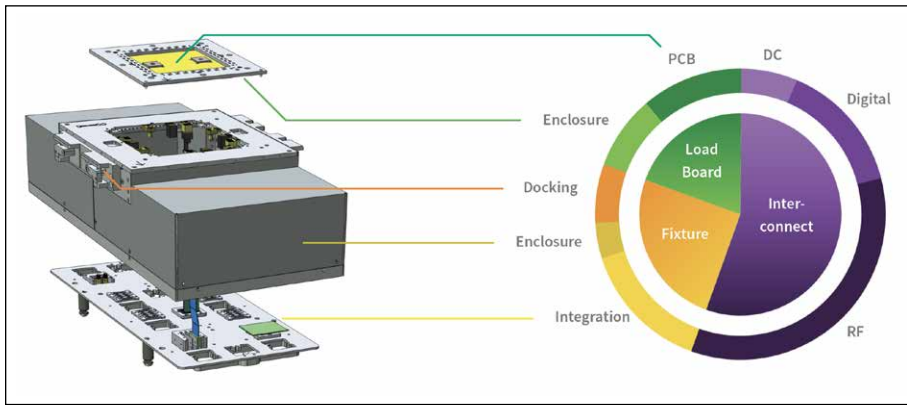
While mmwave has traditionally been considered a niche application that is largely ignored in high volume production, with the advent of automotive radar and now 5G NR, these frequencies are becoming more mainstream. To successfully transition mmwave devices from laboratory bench-top setups into production test requires a holistic test strategy that addresses the added complexity of high volume economics and cost dynamics. With over 15 years of experience working with custom production mmwave applications, Roos has gained valuable insight into the challenges their customers face at these frequencies. This has helped the company develop novel solutions in four key aspects of the test system that determine success at millimeter frequencies:



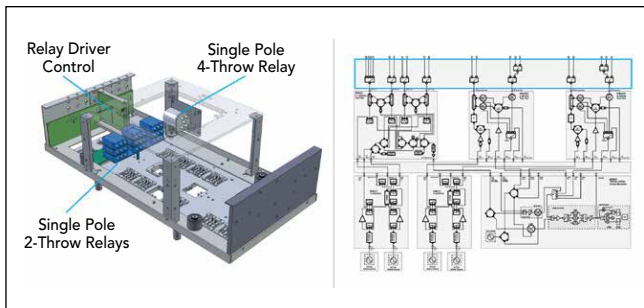
▲ Fig. 14 R&S ZNB vector network analyzer.



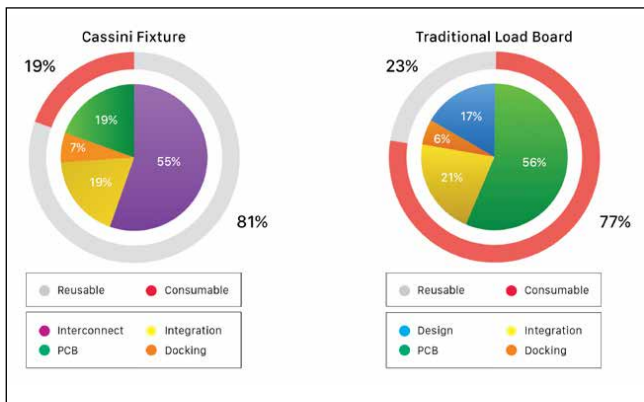
▲ Fig. 15 Test Set instruments provide drop-in, multiport VNA test port capability for the Cassini ATE System.



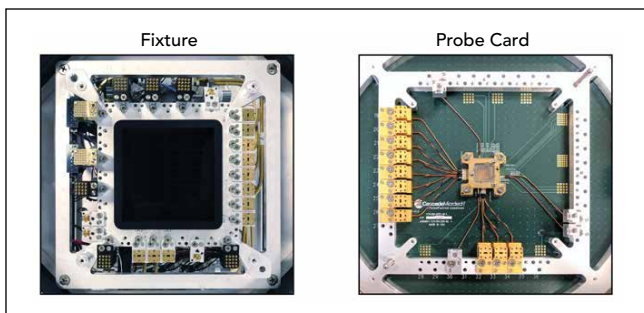
▲ Fig. 16 Cost Breakdown of a Cassini device Interface for mmwave application.



▲ Fig. 17 Paralleling microwave and mmwave resources inside the fixture (left). This provides cost effective port expansion to the existing test system architecture for specific applications (right).



▲ Fig. 18 Cost Breakdown Consumable/Reuse Comparison of a Cassini Device Interface and traditional multi-layer load board for mmwave applications.



▲ Fig. 19 Interspersed 80 GHz waveguide and 40 GHz blind-mate signal interface for use with a FormFactor/Cascade Microtech probe card.

instrumentation, interconnect, interfacing and integration.

Starting with the instrumentation, the key aspect of the Cassini ATE is a modular and configurable instrument architecture. This enables drop-in test set instruments that extend the frequency capability of the standard 20 GHz source and vector measure core with VNA measurement capability and performance comparable to bench instruments (see Figure 15). This provides better device correlation while allowing the test system to be tailored to the frequency or application requirements.

The configurable nature of the system architecture provides capital expense control and greater port efficiency while allowing for future frequency and capability expansion well into the 100 GHz range.

The fixture provides a configurable environment that extends the test system's measurement port capability with reusable off-the-shelf relays, switches, microwave cabling and waveguide, within a rugged, RF-shielded enclosure (see Figure 17).

This enables a less complex socket/probe card design, that is both better performance at mmwave frequencies (lower losses, less parasitics, and optimized ground plane) and a more cost effective production consumable (see Figure 18).

The ubiquitous nature of microwave and mmwave interfaces between instruments and the device interface layers belies their critical function in the overall solution. Cassini's interface provides both a repeatable setup for successful calibrations that translates to accurate and repeatable measurements, while also satisfying production floor requirements of no specialized tooling or operator training for setup and servicing. Roos' patented blind-mate microwave and waveguide interfaces provide self-alignment and pressure contact compliance without any tooling or manual manipulation. This insures consistent and repeatable setup of the test system and test bench that is suitable for high volume insertions. They have partnered with several leading manufacturers of probe and socket cards such as Cohu, Form Factor and Yokowo to offer interfaces on their products and ease the introduction of mmwave test into production (see Figure 19).

Traditionally, the integration of the test system and device-specific fixturing is left to the customer due to the custom nature of the application. By contrast, Roos provides a complete mmwave production solution in both the instrument system architecture and the software to provide; tester configuration management, dynamic instrument and test system integration, and most importantly, layered vector calibration to de-embed measurement results. Ultimately this is where the production proven instrumentation, Interconnect and Interface experience of Roos Instruments and the Cassini platform pay big dividends in time to market, risk mitigation and cost savings for our customers.



## TERADYNE

Teradyne has been pretty quiet about its offerings but has 5G test solutions provide customers with an easy upgrade path from traditional sub-6 GHz testing into the mmwave frequency range. This enables customers to re-deploy their UltraFLEX ATE installed based with mmwave test capability.

For example, Teradyne's UltraWave-MX44 instrument the UltraWave24 (sub-6 GHz) capability up to 44 GHz to address the 5G-NR standard while maintaining full DIB and docking compatibility with existing sub-6 GHz UltraFLEX ATE testers. The UltraWaveMX44 is a single slot instrument in the UltraFLEX system and acts as an extension to the UltraWave24 RF instrument. It provides dedicated mmWave frequency blind-mate coaxial DIB connections which are designed to withstand the challenges of a production environment while providing the performance to source and measure high quality 44GHz test waveforms to the device.

The UltraWaveMX44 seamlessly integrates into the manufacturing flow by maintaining fully legacy compatibility with existing applications. Existing RF DIBs can continue to be used with a system configured with the UltraWaveMX44 instrument without any system reconfigurations.

There are 32 mmWave ports available on the UltraWaveMX44 making DIB design significantly easier be-

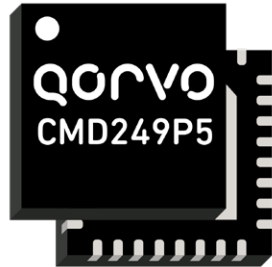
cause sensitive signal switching is not required on the DIB. And, the system can be configured with up to 128 mmWave ports which may be required when scaling for high site count multi-site testing.

A patented active thermal control within the instrument guarantees temperature stability to ensure that high-performance specifications are met in the engineering and production environments. The UltraWaveMX44 features an integrated power detector which provides specification traceability. The instrument's frequency range covers 6 to 44 GHz. The instrument has 800 MHz bandwidth and can achieve greater than 2 GHz bandwidth through its high-performance path. It supports RF and IF interfaces for both 5G IF transceiver and 5G RF Beamformer device coverage. There is a dedicated low phase noise DUT reference clock operating from 100 MHz to 6 GHz to supply a precision reference clock for devices with integrated PLLs.

Teradyne's extendable 5G test solutions are used for testing 5G devices in characterization and in mass production at wafer probe, package and OTA module test insertions. Teradyne's UltraWaveMX44 mmwave test solution provides an easy ATE upgrade path from traditional sub-6 GHz to mmwave testing. This is a key feature as manufacturers have a large installed base of sub-6 GHz ATE equipment (previously used for 4G) and desire to re-deploy such installed base with mmwave testing capability for 5G. ■

### **DC-20 GHz High Linearity Distributed Power Amplifier with Positive Gain Slope**

Qorvo's CMD249P5 is DC to 20 GHz wide-band GaAs MMIC distributed power amplifier housed in a leadless 5x5 mm plastic SMT package.



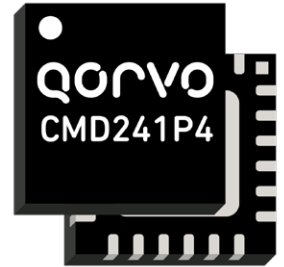
The amplifier delivers 12.5 dB of gain with a positive gain slope which can simplify overall circuit design, and with a corresponding output 1 dB compression point of +28 dBm and an output IP3 of 39 dBm at 10 GHz. The CMD249P5 is a 50 ohm matched design, eliminating the need for RF port matching.

[Learn More](#)



### **2-22 GHz Distributed Amplifier with Excellent Return Losses**

Qorvo's CMD241P4 is 2 to 22 GHz wideband GaAs MMIC distributed low noise amplifier housed in a leadless 4x4 mm SMT package.



The amplifier delivers greater than 13 dB of gain with a corresponding noise figure of 2.3 dB and an output 1 dB compression point of +21 dBm at 11 GHz. The CMD241P4 is a 50 ohm matched design, eliminating the need for external DC blocks and RF port matching.

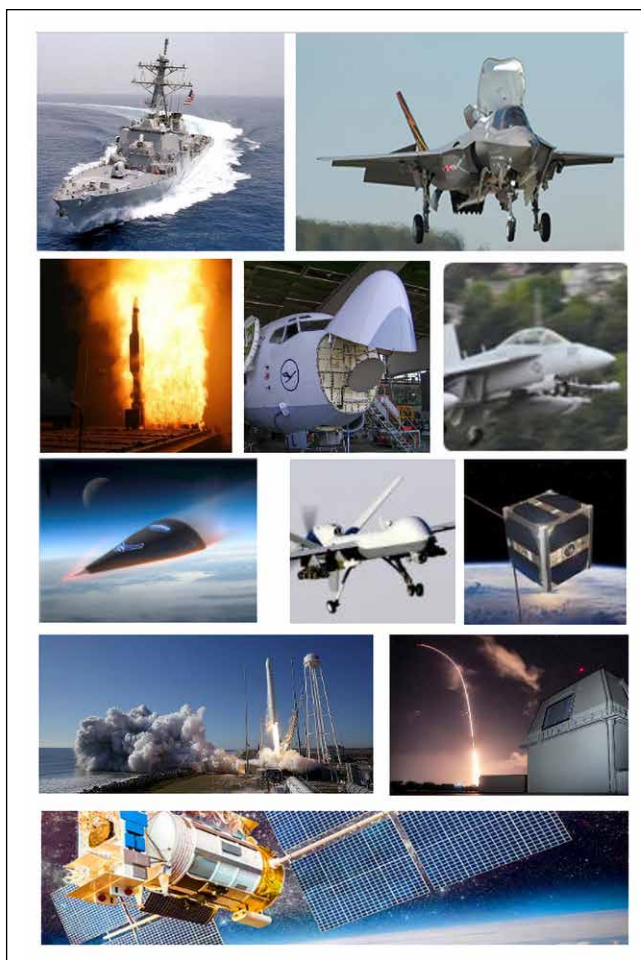
[Learn More](#)



# mmWave AESA Phased Arrays and MIMO Radar Trends: Aperture to Data

Mark Walker

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▲ Fig. 1 Evolving role of AESA arrays and radar.

Radar plays an expanding role with wide-ranging applications in the world today. Many defense contractors are developing active electronically scanned array (AESA) technologies for mission-critical systems in support of radar, EW, missile/munitions, space, communication, navigation and IFF (CNI) applications. These technologies can be found on major platforms in diverse environments: from destroyers and missile defense radar systems to space deployments in GPS, AEHF, Iridium Next, Orion, the Mars rover and the International Space Station (see **Figure 1**). Through advanced ICs and packaging, miniature multi-mode custom arrays can offer customers a new set of capabilities with “aperture to data” to support the U.S. military in today’s environment of evolving threats to enable enhanced performance at lower cost and simple implementation.

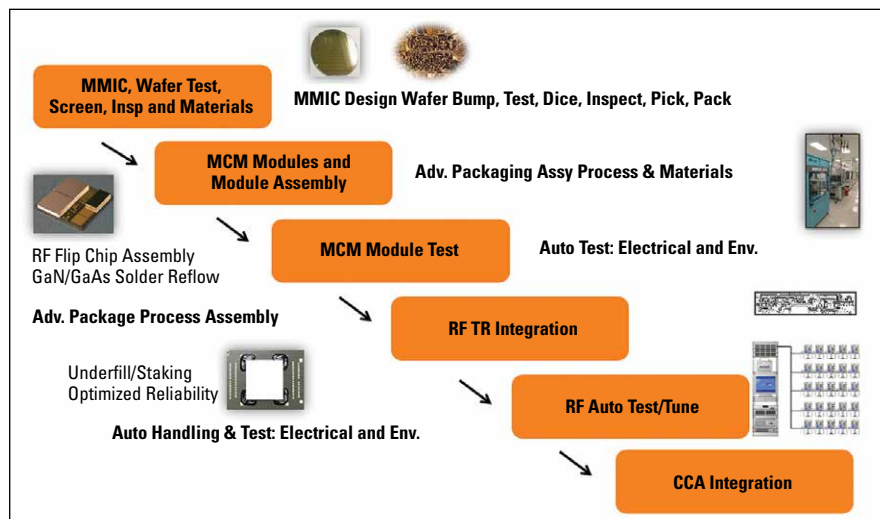
The U.S. DoD must leverage historical technology and embrace new commercial technologies against advancing security threats. Investments in phased array and multiple inputs multiple outputs (MIMO) radar technologies—along with underlying IC and packaging technology—are required to meet demanding threat detection requirements. Today’s solutions must be affordable and capable of rapid deployment. Solutions for these radar products are built upon highly integrated system-on-a-chip (SoC) custom ICs and MMICs along with advanced packaging and integrated subsystem products for applications in the aerospace and defense market. Unique combinations of differentiated technology aggregated with advanced packaging and automation is making it possible to build small lightweight integrated AESA solutions.

Advanced technology integration is required to be an integrated solution provider from aperture to data. New technology roadmaps coupled with close relationships with fielded applications offer a fresh new look at the AESA technologies. It is critical to offer cutting-edge sensor technologies in partnership with system providers to deliver solutions aligned with program needs and the needs of our warfighters. Advanced packaging of SoC solutions with fully integrated subsystems widens opportunities to deliver a strategically important supply to defense primes and key subsystem providers (see **Figure 2**).

Circuit loss and performance come at a premium when operating in the mmWave frequency range. Recent FCC news regarding the multi-billion dollar bids for mmWave frequency bands along with expansive 5G roll-out indicate long term technology development. Connector and waveguide technologies are improving to support the growing need for and uses of mmWave frequency expansion. Leveraging long-standing RF expertise, defense contractors can now offer broad solutions and capabilities including antenna systems, transmit/receive (T/R) electronics and beam-formers, up/down converters, digitizers, interconnects and positioners. Utilizing advanced packaging technologies, digital and direct conversion technologies have become part of the signal chain. The result is a unique integration of the complete signal chain into an integrated mmWave solution with higher power, wider bandwidth and high reliability in austere environments. Integration lowers size, weight, power and cost while meeting stringent application requirements for highly sensitive solutions with optimum probability of detection.

Several years ago, development on mmWave AESA started with cooperative research with AFRL. Cobham Advanced Electronic Solutions (CAES) has enjoyed many years of successful technology development transitions into multiple DoD programs for MMICs and phased array programs. Going forward, constant independent research and development (IRaD) funding has been applied toward developing this critical new technology. When CAES acquired Aeroflex Corporation in 2014, the CAES technology portfolio expanded to include many new, reliable, advanced packaging and assembly options, including flip-chip, bumped die and packages. Among those technologies, the incumbent semiconductor business with broad and deep experience for the high reliability space and medical semiconductor industry—including LEAN Rel™—is enabling small integrated AESA arrays for DoD applications. With ongoing development, these advanced process options are constantly upgrading.

A tailored approach to building AESA systems utilizing new technology offers cost, size, reliability and performance advantages. AESA markets under consideration include—but are not limited to—air surveil-



▲ **Fig. 2** Vertical integration needed for small mmWave AESA.

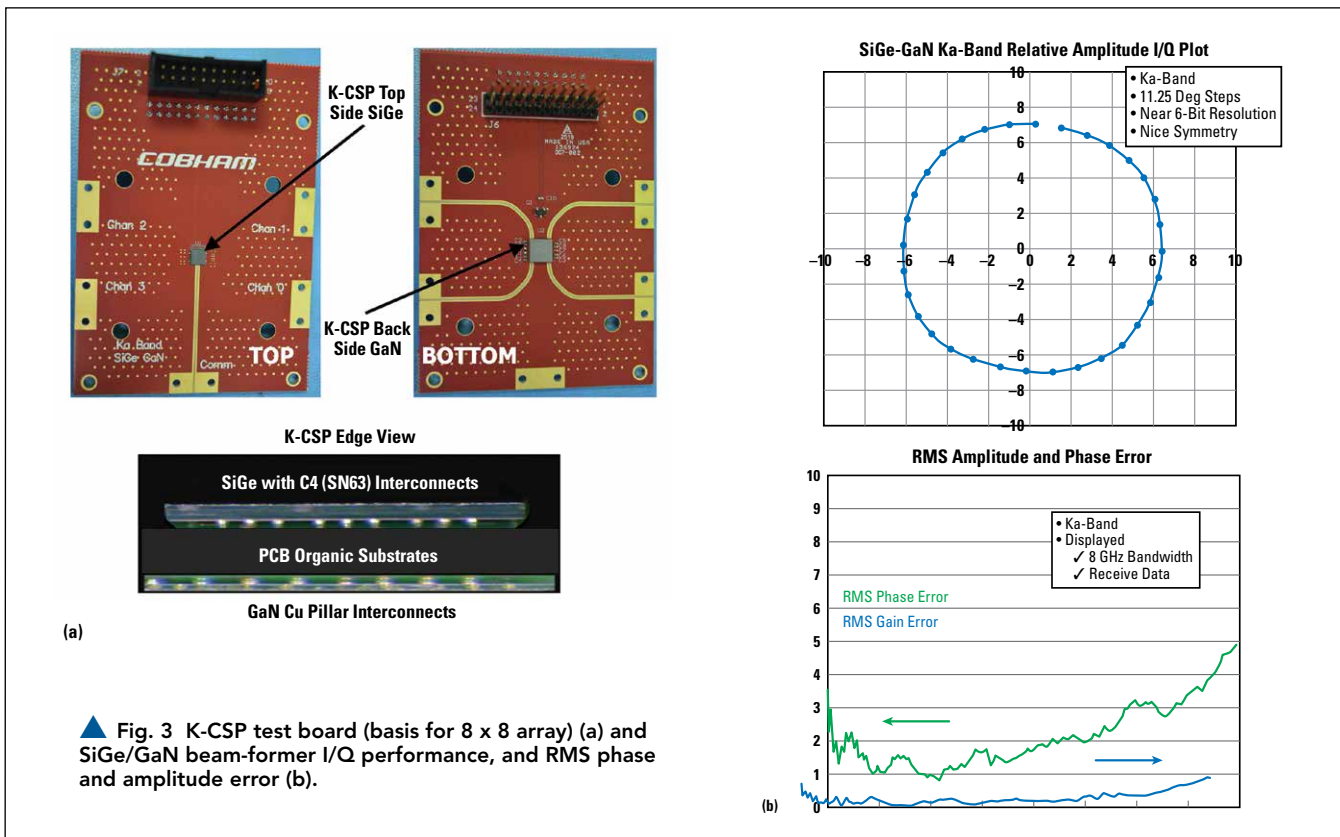
lance including airborne early warning radar, intercept or acquisition control, ballistic missile warning and acquisition, surveillance, mapping and missile tracking and guidance. Frequencies under consideration include Ka-Band and W-Band. These mmWave steerable systems track target range, position and velocity vectors. Target detections must be resolvable from each other even when targets are substantially contrasting in reflection cross-sections at variable range. Key performance criteria include simplifying the array control and system interfaces with higher levels of integration.

## TECHNOLOGY APPLICATION

mmWave phased array dimensions with typical  $\lambda/2$  element spacings are very small (approximately 5 mm at 30 GHz to 1.9 mm at 80 GHz). Therefore, placing transmit and receive elements at the aperture is feasible and is nearly ideal for T/R electronics at lower mmWave frequencies using quad-channel MMICs and Silicon ICs. Communication arrays are well suited for these form factors with transmit power at less than 0.2 W/element where silicon technologies match the application. Phased array with transmit powers greater than 0.75 W/element require more sophistication in TR electronics and often require active cooling within the array. Fortunately, exotic cooling substrate materials and techniques are not required for power densities lower than 10 W/element. The total transmit power for small arrays is primarily limited by available prime power and the dissipated power in the form of heat generated from each element's T/R amplifiers RF conversion efficiency. At mmWave frequencies, the factor limiting operation is typically heat dissipation. Power added efficiency at mmWave—established by semiconductor technology and circuit implementation—should be 5 percent or higher for a multi-stage MMIC amplifier.

There are many mechanical concerns in constructing mmWave arrays. Key concerns include—but are not limited to—supply voltage current density on voltage supply lines, location of the RF, DC and control lines. In the case of higher transmit power, active cooling may be required for long term operation.





Higher operating drain voltages of GaN MMICs help lower current density in connectors and distribution networks. GaN on SiC MMICs offer the thermal advantages of SiC to spread the heat from the transistor and passive heat sources within the MMIC. DC and RF connectors and interconnects present problems as they are a notable source of RF losses and increased product cost.

Likewise, space-consuming interconnects have a direct impact on array scalability and overall cost. It is challenging to build scalable mmWave phased arrays with  $\lambda/2$  spacing while using the smallest available RF connectors, in addition to being cost-prohibitive. While there have been many advances in mmWave and RF connectors over the past few years, the best way to leverage their impact is through higher levels of integration within the array aperture. Further, the implementation of these arrays into application platforms demands as much simplification as possible to optimize size and performance, and for electrical and thermal interconnects. When building arrays within the Ka-Band frequency range, it has become increasingly obvious that higher levels of integration with customized SoC and automated assembly processes drive performance and affordability toward planar phased array architectures.

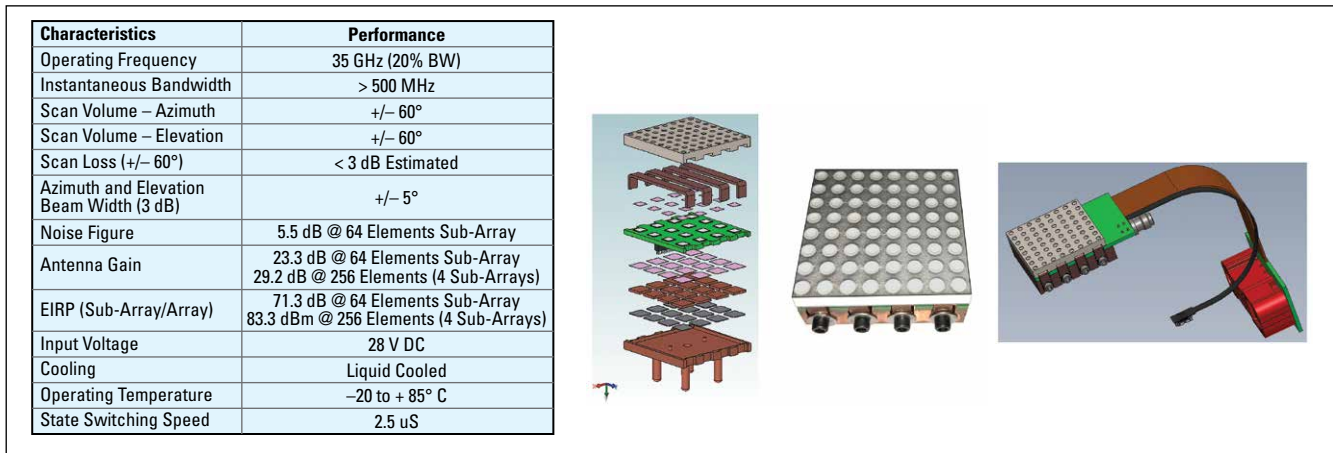
## KA-BAND PHASED ARRAYS

Since 2016, core building blocks built from custom ICs and packaging technology have been specifically created for Ka-Band AESA hardware. Key pieces of the development include, 1) multi-channel Silicon-Germanium (SiGe) beam-former ICs, 2) multi-channel GaN T/R MMIC with PA, LNA, switches, et. al., 3) chip-scale

flip-chip packaging (K-CSP) for both die on organic substrate, 4) integrated heat sink and 5) I/O RF, DC and control signals. The silicon die utilizes solder bump flip-chip technology, and the GaN MMIC die utilizes Cu pillar flip-chip technology. The K-CSP configuration leverages production flip-chip processes developed and qualified to QML Class-Y. These are automated processes for environmentally extreme rugged use conditions. The MMIC and mmWave SoC combination was designed a few years ago with specific features needed for phase array operations.

Currently, the GaN T/R MMIC is a multi-channel mmWave RFIC with approximately 15 percent bandwidth and electrical channel-to-channel symmetry. The T/R MMIC has  $\geq 1$  W/channel transmit output power and  $\leq 5.5$  dB receive noise figure as integrated with low insertion loss T/R switches. PA efficiency, LNA noise figure and T/R switch power handling and loss were optimized to near performance limits offered by short gate length GaN technology. The SiGe SoC was set up for an analog beamforming to work specifically with the GaN T/R MMIC in a 3D stack. The SiGe SoC has 30 dB amplitude control, and near six-bit phase control. The I/Q performance plane is corrected with built-in coefficients for small and simple calibration stored within on-chip register space. Calibration tables are very small and allow a single 64-bit serial beam-steering command to re-point the entire array with potentially many hundreds or thousands of elements.

**Figure 3** pictures the SiGe/GaN test boards used to characterize the channel characteristics, RF and thermal performance and is the basis of the ongoing 8 x 8



▲ Fig. 4 64-element planar Ka-Band test sub-array and performance goals.

phased array modules optimized for organic substrates. With nearly six bits of phase resolution channel performance, the test demonstrated RMS error of 2.4 degrees mid-band phase error and 0.36 dB of mid-band gain error.

Figure 4 illustrates a 64-element sub-array and vertically integrated assembly. Extensive reliability analysis (including solder stress and mechanical stress predictions) and environmental test verification offer a path to reliable automated assembly processes for IC integration. These small integrated arrays (38.1 × 38.1 × 20.3 mm) are assembled to withstand austere environments with reliable operation both mechanically and thermally. The use of commonly available organic substrates provides the opportunity to tailor array pattern variation with custom printed circuit board shapes (i.e. round, rectangular, octagonal, etc.). The GaN MMIC has fractional-power modes and may be scaled up in output transmit power to 8 W/element or more for array architectures with a limited number of elements.

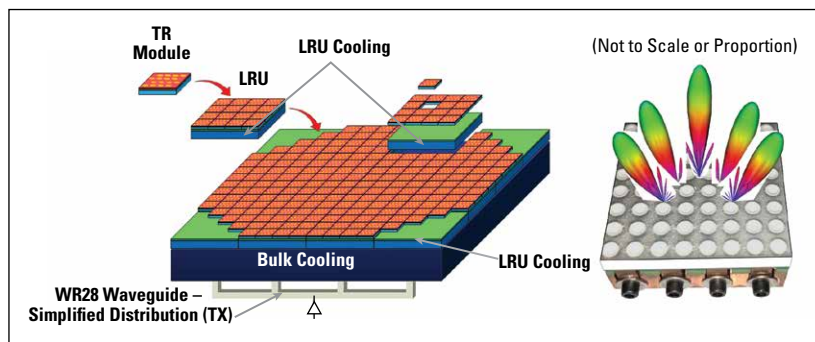
The array has a 120-degree field of view with 3 dB beam width of ± 5 degrees and less than 3 dB of scan loss at ± 60 degrees. The effective isotropic radiating power for a 256-element array is approximately 83.3 dBm (≥200 kW) with beam state switching speed of less than 2.5  $\mu$ s. The radiating elements are circularly polarized, and the current demonstration array is half-duplex. Dual polarization configurations are also under development. The arrays are liquid cooled—with PAO or other suitable cooling liquids—to maintain a uniform temperature and low

thermal gradients across the array. Integration of the Ka-Band AESA architecture is scalable into large arrays, or scalable down into arrays with fewer elements as shown in Figure 5.

Fully scalable arrays require all signals to be routed through the backside of the array (including thermal) and require a blind-mate interconnect solution for both electrical (RF, control and DC) and mechanical (fluid). Each sub-array has a single RF port to be used with a sum and difference mono-pulse comparator for direction finding and tracking. This technology is manufacturable and reliable, with field-replaceable upgrades and improvements. It is also adaptable to changing requirements and technology upgrades, including polarization diversity and other advancing technologies. The applied technologies are quickly advancing manufacturing readiness levels toward production capability.

### MMWAVE AESA TECHNOLOGY EVOLUTION—APERTURE TO DATA

Performance advancements in recent years in small geometry Si CMOS technology (including RF CMOS), have allowed higher levels of integration to become a reality. Work extending the multi-channel planar approach of the Ka-Band array to include other key pieces of the radar is underway with architecture studies and demonstrations. This new integration will make ultra-small advanced capability arrays with digital conversion a reality in the coming months and can be shown using mmWave radar demonstrations.



▲ Fig. 5 AESA topology scalable from a few elements to 1,000s of elements with LRU building blocks.

IRaD is currently underway to evolve the up/down converters, transmit signal synthesis (DAC) and receive digitization (ADC) at rates exceeding 1 GS/s and to include radar detection and digital-signal-processed datasets directly in the aperture electronics. This architecture enables multi-beam software-defined digital beamforming (or mixing of digital and analog beamforming). This capability enables digitally modulated radar sensor operation utilizing beamforming and code division multiplexed MIMO radar capabilities. The MIMO feature offers extended virtual receive channels, improved

angular resolution and interference immunity associated with digitally coded channels. These extended capabilities also offer improved range resolution, better signal to noise ratio at similar frame rates and faster updates with short system cycles. The system can also switch between phase array modes and massive MIMO processing mode or a combination thereof. Advance digital processing ICs utilizing these capabilities result in 4D detection datasets with spatial position and velocity for many targets. This is the new world of aperture to data.

This architecture offers other advantages. The integration of the RF converter, ADC/DAC and radar data processor into the aperture electronics will drastically simplify interconnect solutions. Traditionally, the direct digital conversion and processing functions have been power-hungry; now these capabilities may be included more efficiently, with less prime power and lower heat generation. mmWave RF connections (coax or wave guide) are no longer needed to route signals throughout the application platform. Interconnect simplicity is achieved by way of high-speed data uplinks (10/100 Gbit/s) through Ethernet or proprietary vehicles—along with simple DC supply line distribution—making radar and sensor aperture deployment easier and faster. Further, widely used production processes for fully automated assembly processes are utilized to minimize human touches, improve reliability, eliminate tuning and ruggedize the platform for austere environments and challenging operating conditions. Improved system performance (associated with RF signal loss), simpler interconnects, faster integration, smaller size and weight and lower cost offer overall system value.

## SUMMARY

The extended capabilities and value proposition associated with integrated and multi-mode mmWave array technology include:

- Advanced packaged 3D electrical and thermal integration at the aperture
- SiGe beam-formers and advanced custom CMOS ICs for advanced functionality
- Higher transmit power and rugged assemblies for integrated multi-channel GaN T/R MMICs
- Multi-channel digitally coded phased array, MIMO sensor capabilities
- Mono-pulse direction finding
- Advanced angular resolution
- Improved Doppler
- Multiplicity of scans in compressed scanned times
- Fast uplink
- Simpler integration and deployment
- Smaller packages (size and weight)
- No tuning automated assembly
- Lower cost
- Scaled solutions (from a few elements to 1,000s of elements)
- Integrated “aperture to data” architecture

It is a great time to be involved in today’s battlefield, which is simplified by the value proposition of advanced technology solutions for broad deployment to the warfighter. ■



# Spectrum Above 90 GHz for Wireless Connectivity: Opportunities and Challenges for 6G

Didier Belot, José Luis González Jiménez, Eric Mercier, Jean-Baptiste Doré  
CEA-Leti, Grenoble, France

The spectrum above 90 GHz is foreseen as a key enabler for the next generation of mobile networks. The large amount of spectrum paves the way for high capacity wireless links. Many challenges still need to be overcome to make this technology a success. This article describes some of the scenarios for the spectrum above 90 GHz, coveted by the cellular industry for 6G. A benchmark of semiconductor technologies is discussed to highlight promising candidates and channel-bonding architectures as a suitable option for the implementation of extremely broadband RF radios with acceptable power consumption. Opportunities, challenges and some recent experimental results of D-Band transceivers implemented in CMOS technologies are discussed.

**N**ext generation wireless networks are imagined to be faster, more reactive, ultra-reliable and denser. Therefore, the exploitation of new and wider bandwidths at higher frequencies is a promising solution toward very high data rates (100+ Gbps) and ultra-low latency (sub-ms). The frequency from 90 to 300 GHz, and the terahertz spectrum above 300 GHz, are definitively foreseen as key enablers for 6G communication systems.<sup>1</sup> Several applications can already be imagined: high capacity back-haul/front-haul; short-range high data rate hot spots and device-to-device Gbps ultrashort-range communications as depicted in **Figure 1**.

There are many challenges that need to be addressed to achieve high data rate communications for future deployments above 90 GHz. Performance and quality-of-service (QoS) are

the main concerns for efficient adoption of these bands by stakeholders. Industrial concerns will be the most demanding in terms of performance and most promising in terms of market adoption. A specific aspect of very high frequency bands is that they will not provide long terrestrial-distances, as propagation losses make them impractical. Therefore, small cells are expected to be a key in the network and a direct consequence of this is

Extreme Capacity xHaul	Enhanced Hotspot	Device-to-Device
B5G - 100 Gbps 6G - 1 Tbps	B5G 10+ Gbps per Cell 6G 100+ Gbps per Cell	5-100+ Gbps P2P
<ul style="list-style-type: none"> <li>Dense Massive MIMO Network</li> <li>Cell Free Network Architecture</li> <li>Massive Cloud &amp; Edge Computing</li> <li>Enhanced Broadband Fixed Access</li> </ul>	<ul style="list-style-type: none"> <li>High Speed Download</li> <li>Kiosk, Digital Shower</li> <li>Immersive Experience</li> <li>Industrial IoT</li> </ul>	<ul style="list-style-type: none"> <li>Connector Less Applications</li> <li>Server Farm</li> <li>Inter-Chip Communication</li> <li>Intra-Chip Communication</li> </ul>
<ul style="list-style-type: none"> <li>200+ Meters Range</li> <li>Indoor/Outdoor</li> <li>Weak Energy Constraints</li> </ul>	<ul style="list-style-type: none"> <li>10+ Meters Range</li> <li>Indoor</li> <li>UpLink Strong Energy Constraints</li> </ul>	<ul style="list-style-type: none"> <li>cm up to 2+ Meters Range</li> <li>Indoor</li> <li>Strong Energy Constraints</li> </ul>

▲ Fig. 1 Different scenarios for above-90 GHz wireless communication.

the higher number of required elements, implying that low-cost and high energy efficiency will be critical goals.

System developments are usually built from the best individual building blocks. However, above 90 GHz, careful attention to the overall architecture must drive the selection of individual metrics and associated performance, closely related to power consumption and cost. Size may also be regarded as a key point as actual sparsity and sustainability will support environmental considerations and social adoption. All these beginning considerations address more challenging than ever targets to address high performance, given that frequency and expected throughput are very high, and bandwidth is very wide. In addition, it must still be possible to integrate all these features into a low-cost semiconductor process.

Starting from the antenna, a key component at these frequencies, directivity becomes a major issue, as user connection relies on narrow "pencil" beam-forming MU-MIMO (multi-user MIMO) providing higher gain, enhanced selectivity and jammer blocking thanks to spatial division multiple access (SDMA). The best antenna architecture will maintain performance but not at the cost of IC count, which has to be kept low. Antenna array designs too often mean multiple front-end modules (FEM) or transceivers.

Higher bandwidth than the previous generations, spread over multiple channels, has to be addressed without multiplying transceiver building blocks, especially power hungry and IC-area-consuming frequency synthesizers. So, PHY optimization is key to be supported by frequency generation, compatible with accessible integration constraints, over which high integration on a mainstream CMOS process is to be considered.

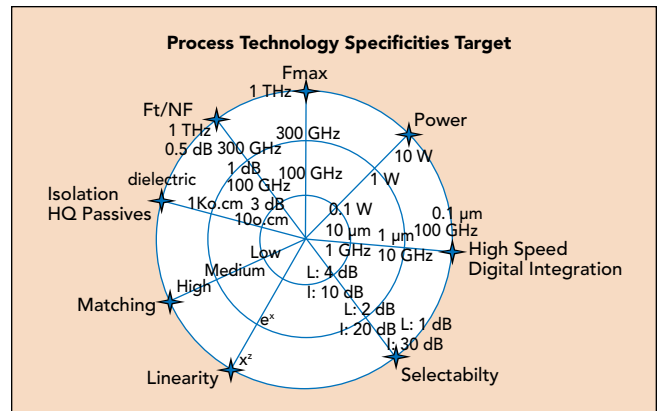
Addressing above 90 GHz bands therefore triggers cross-domain thinking for efficient implementation including small form factors and low-cost. In this article, two topics are highlighted: the choice of semiconductor technologies to address above 90 GHz spectrum as well as some architectural clues for designing low-cost and high performance RF front ends.

## FRONT-END SEMICONDUCTOR TECHNOLOGY CANDIDATES

Silicon-based technologies offer low-cost compromises for RF and mmWave applications. However, the comparison of technologies is always difficult as technical metrics are cross-domain and non-technical parameters are also to be taken into account. We propose a benchmark of technologies focusing on intrinsic performance. In order to compare the technologies, a target representation of what should be requested to fit with the RF and mmWave wireless transceiver challenges is proposed in **Figure 2**.

Different criteria are depicted and will be placed in a target representation:

**Power:** RF output power availability from a technology depends on breakdown voltage (BV), and on the maximum current driven by the transistor ( $I_{max}$ ) values. For a fair comparison, let's define the max power as BV multiplied by 200 mA, which is optimistic for CMOS processes, and realistic for BiCMOS.



▲ Fig. 2 Process technology target.

**High Speed Digital Integration:** RF digital control and digital pre-processing techniques are mandatory for mass-market and cost-efficient solutions. High speed digital integration depends on inverter size and efficiency (transit time/current).

**Selectability:** This is the ability to switch RF and mmWave signals with high isolation.

**Linearity:** The relation between the output current and the input voltage-control signal of the transistor gives the first order of the linearity while  $gm^2$  and  $gm^3$  impact IMD2 and IMD3 of the amplifiers.

**Matching:** This property defines the different behavior between two minimum-size transistors close together.

**Isolation and HQ Passives:** These are given by substrate resistivity and the presence of thick metal levels.

**Ft-NF:** Ft gives the potentiality for high frequency digital-clock and RF oscillator applications, NFmin determines the sensitivity of receivers.

**Fmax:** This the frequency of the 0 dB power gain, which impacts the gain availability of receive and transmit chains. For a linear class A amplifier, the maximum application frequency is lower than  $F_{max}/3$ , (used in the comparison) for a switch-mode class-D amplifier, it is lower than  $F_{max}/10$  in an ideal case.

Advanced CMOS processes are very attractive for developing mixed RF systems-on-chip, as they offer very high integration potential and still, node after node, demonstrate better RF performance. Four different families in the 45 to 22nm node ranges are evaluated to address above 90 GHz applications: The bulk planar family is represented by a CMOS 40nm VLSI (TSMC); the partially depleted SOI family by a RF 45nm SOI CMOS (GlobalFoundries); the fully depleted SOI family by a FDSOI 22nm CMOS (GlobalFoundries) and finally, the FinFET family by a 22nm FinFET CMOS (see **Figure 3**). The Fmax limitation of these processes drives the only thin gate-oxide-transistor (or GO1) use, to perform RF functions, including power amplifiers targeting applications above 90 GHz.

40nm bulk CMOS, with up to 70 GHz in frequency cannot cover above the 90 GHz band. 45nm PDSOI covers up to 120 GHz mmWave applications. FDSOI 22nm offers very nice performance with the best in class CMOS applicative frequency of 130 GHz. FinFET family provides solutions for applications up to 110 GHz.

Concerning the RF output power, 28 dBm is a frontier, the 45nm SOI having the best global behavior for RF applications with the wider target filled.

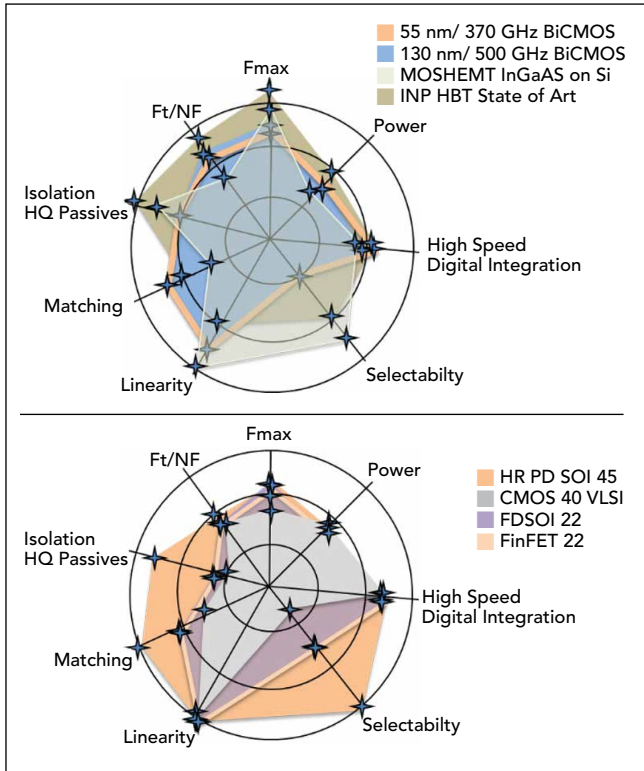
Silicon-germanium HBT processes overcome the current issue of silicon N-FET transistors with emitter-collector currents in the range of 10s of mA per  $\mu\text{m}^2$  emitter area. In addition, the  $1/f$  noise-cut frequency of HBT is very low, in the 10s of Hz, which makes them very attractive candidates for oscillators and low-pass filters, functions which are critical in wireless links. The BV is proportional to the base thickness, therefore decreases with the HBT generations are targeting higher and higher Ft.

We analyze and compare a 370 GHz SiGe HBT over 55nm CMOS process,<sup>2</sup> targeting high frequency applications with high CMOS integration, and a 500 GHz HBT over 130nm CMOS targeting very high frequency applications.<sup>3</sup> Both are compared to state-of-the-art III-V processes, InGaAs MOSHEMT from Fraunhofer IAF,<sup>4</sup> and INP HBT from Teledyne. It should be emphasized that state-of-the-art SiGe HBT exceeds 700 GHz Fmax.

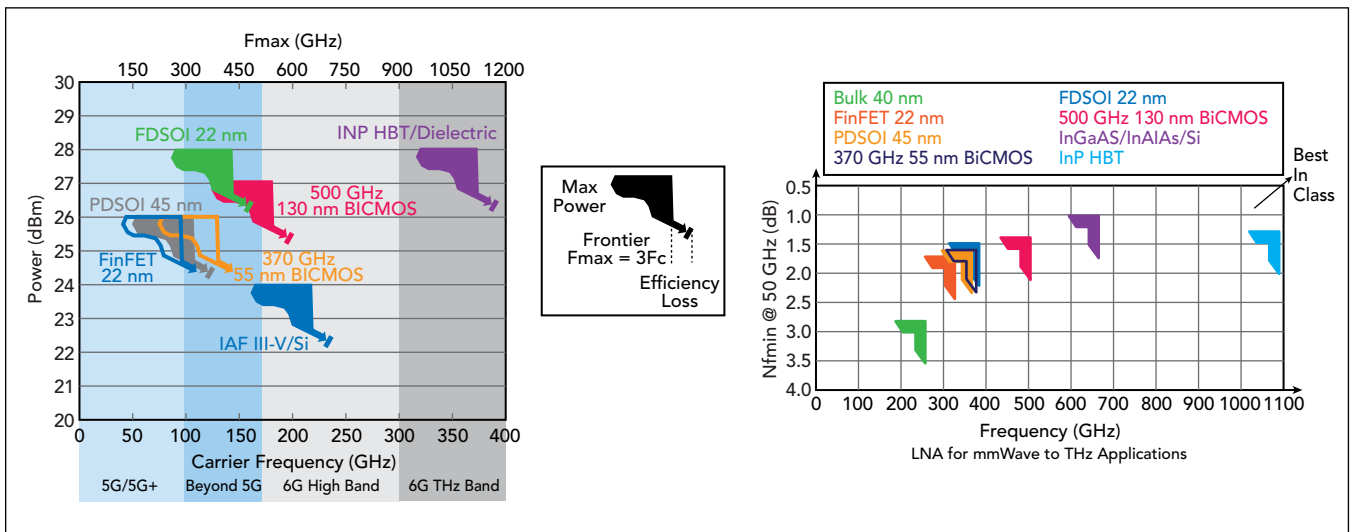
BiCMOS 370 GHz/55nm process covers applicative frequencies up to 120 GHz, while the BiCMOS 500 GHz/130nm process covers applicative frequencies up to 160 GHz, their output power remaining under 28 dBm. The 55nm process has higher capability for digital integration, while it is within the average for the other RF properties. The InGaAs MOSHEMT from Fraunhofer IAF presents a very attractive Fmax with 640 GHz, allowing it to cover up to 210 GHz applications with power output under 24 dBm. In addition, pretty good RF characteristics are demonstrated. The weakness is the integration of digital, which is not yet possible. Equivalent conclusions are for INP HBT and exceed 1 THz Fmax<sup>5</sup> and open all the doors for applications up to THz frequencies.

A summary is depicted in **Figure 4** to answer mmWave to THz applicative requirements for PA and LNA building blocks. The main limitation, in PA design, is the Fmax. Output power can be increased by design, consideration and staking PA array. BiCMOS processes, allying high Fmax HBT with CMOS integration, are very well placed, even if III-V InGaAs and mostly INP HBT are the best in class. The LNA is limited by NFmin and Fmax at the same time, and again BiCMOS is well placed, even if III-V processes obtain very good results, but lack the integration capacity of BiCMOS.

To conclude, cost will be the main factor to earn market share. BiCMOS and RF CMOS processes have already proven to be adequate up to 40 GHz, providing better integration and overall cost than InP HBT. It is acknowledged that the beyond 5G and 6G applications will continue to benefit from CMOS improvements, but new concepts should be proposed to efficiently address the THz band.



▲ Fig. 3 Comparison of technology over the defined key parameter indicators.



▲ Fig. 4 PA and LNA building blocks performance frontiers.



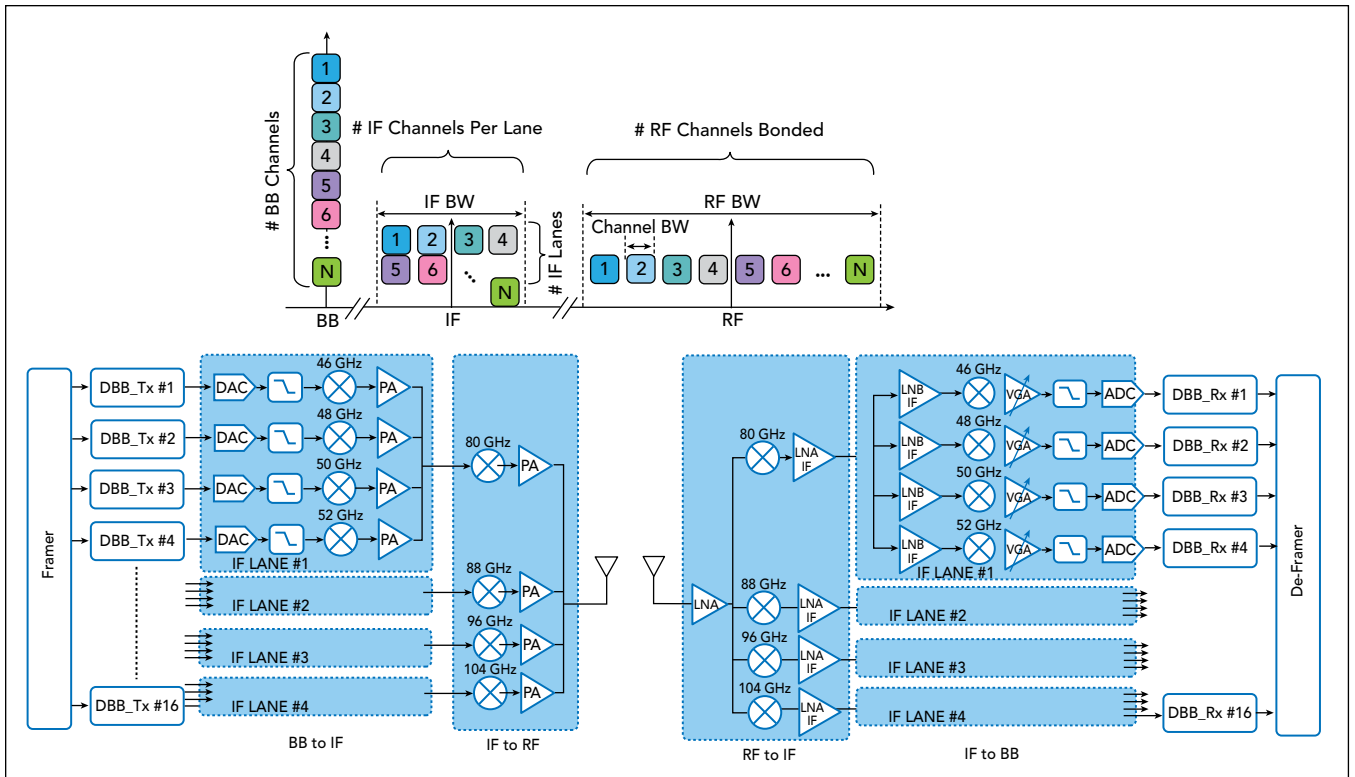
## CMOS FRONT-END ARCHITECTURE FOR CHANNEL AGGREGATION

The RF front-end architecture for extremely broadband applications has to be selected considering both the large amount of bandwidth that is required at the RF section and reasonable sampling frequencies in the radio-to-digital baseband (BB) interfaces. Having this trade-off in mind, channel-bonding techniques seem a natural solution. **Figure 5** shows an example of a Tx-and-Rx radio front-end based on such techniques. In the Tx of this example, 16 BB channels are combined and up converted in two steps up to D-Band (around 140 GHz), where each of the BB channels is found at a different RF sub-channel. The Rx realized the complementary down conversion process providing 16 parallel BB channels. Assuming reasonable D/A and A/D converters with sampling frequencies around 2.5 GS/s, this architecture is able to provide a total raw throughput of 102 Gb/s if 16-QAM modulation is used in each BB channel at a symbol rate of 1.6 Gbauds, and 156 Gb/s for 64-QAM modulation. The required bandwidth at D-Band is 32 GHz.

The main challenge for channel-bonding architectures is that they require many different local oscillator (LO) signals. The frequency plan can be optimized to minimize the number of distinct LO frequencies required as well as to relax the bandwidth requirement of the radio up-and-down conversion blocks. Figure 5 depicts a frequency plan for the above 16 channels radio where only eight different LO frequencies are required. The signal bandwidth that has to be handled by most of the RF blocks is significantly smaller than the final 32 GHz. This approach enables the use of CMOS technologies: a large bandwidth and operation frequency are only re-

quired at the end of output of the Tx or the input of the Rx. The Tx sub-band PAs can be used to separately amplify sections of the output spectrum combined with passive power combiners to generate the full band output signal. In the Rx, a moderate gain broadband LNA can be used to separately amplify sections of the output spectrum combined with passive power combiners to generate the full band output signal. In the Rx, a moderate gain broadband LNA can be considered with subsequent sub-band splitting of the signal, so that the LNA is the only CMOS circuit having to handle the full band signal. CMOS PAs and LNAs supporting this approach have been recently demonstrated,<sup>6,7</sup> as well as the multi-frequency LO generation required.<sup>8</sup>

Very low phase noise LO signals are required for high-order modulation schemes such as 64 QAM and beyond. This is a hard constraint for classical mmWave LO generators based on PLLs and frequency division on top of the complexity of generating multiple LO signals of different frequencies. The technique presented in reference nine can be used as an effective way of simultaneously generating several LO frequencies, all of them integer multiples of the same input reference. It also allows achieving a low phase noise: the generation is based in frequency multiplication, which produces an output phase noise equal to the input phase noise, obtained at much lower oscillation frequency, just scaled up by the integer multiplication factor. The alternative multi-LO generation principle is depicted in **Figure 6**.<sup>9</sup> A signal of a frequency much lower than the desired output LO frequencies is used to synchronously switch on and off an oscillator sized to have a free-run frequency in the LO frequency range. When operated in this way, this pulsed oscillator generates a multi-harmonic signal with terms at integer multiples of the switching input frequency (blue signal in the figure).



▲ Fig. 5 Example of channel bonding transceiver architecture and frequency plan.

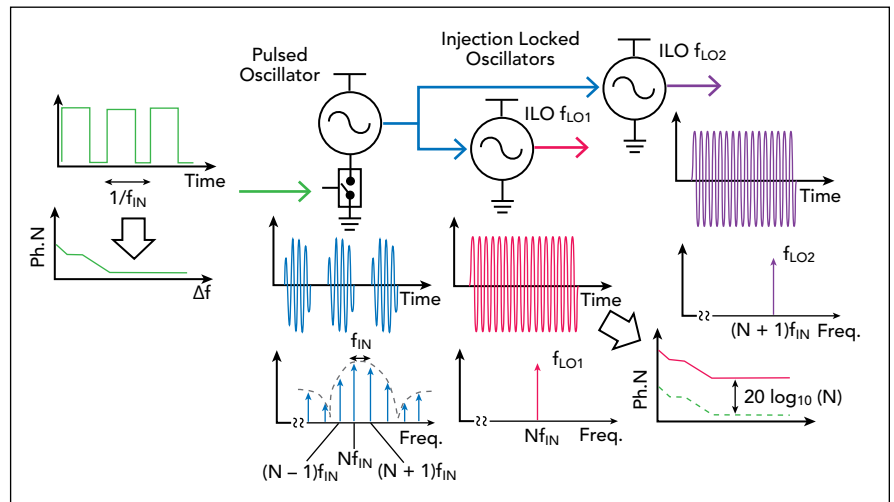
The spectral envelope of this signal is determined by the switching input signal duty cycle and is centered at the oscillator free-run frequency. However, note that the harmonic terms are at exact integer multiples of the input ( $\dots, N-1, N, N+1 \dots$ ) and do not depend on the oscillator free-run frequency, albeit they have maximum amplitude around it. Several single-tone LO frequencies can be extracted from this signal by injection-locked oscillators that are sized to lock on one specific integer multiple of the input and to reject the adjacent terms, as shown in Figure 6. Each of the harmonic terms is synchronized in terms of phase to the input signal and therefore copies the input phase noise with an integer scaling factor (see the red signal in the figure, for example). This multi-LO generation technique has been recently experimentally demonstrated.<sup>8</sup> It can be used for generating the four baseband-to-IF signals that would be required by the first channel-bonding step of the transceiver shown in Figure 5 and easily extended to generate in the same way the other four LO required for the IF to RF second conversion step.

## CONCLUSION

The spectrum above 90 GHz is foreseen as a key enabler for the next generation of mobile networks for 6G. The large amount of spectrum paves the way to high capacity wireless links. Many challenges must be overcome to make this technology a success. First, where the design of CMOS RF modules is still possible for the low part of the D-Band, designing cost-efficient modules to address the THz band remains an open issue. Second, high gain antennas are required to meet the link budget. While the design of fixed-beam antenna is mastered, the holy grail remains the co-integration of RF and antenna to provide an electronically beam-steerable system. This would be significant breakthrough toward the next generation wireless system. ■

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▲ Fig. 6 Multi-LO generation technique.

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# Distributed Amplifiers Are a Unique Circuit in High Frequency Microwave Engineering

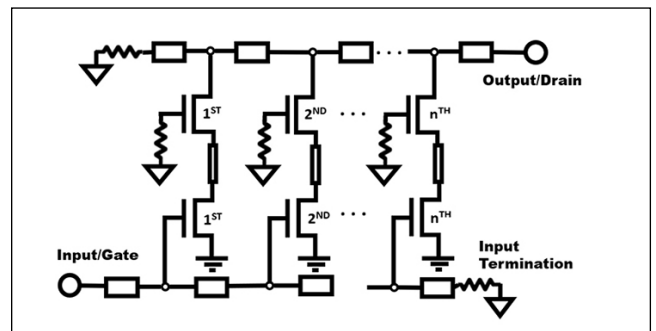
Qorvo

This blog post was first published by Custom MMIC who [joined the Qorvo family](#) in February 2020. Custom MMIC is known for its best-in-class die and packaged components, which augment our power amplifiers to enable multi-chip modules for a broad range of defense, aerospace and commercial applications.

The distributed, or wideband, amplifier is a unique circuit in the field of high frequency microwave engineering. Its architecture can often be misunderstood, however, and this confusion can sometimes result in a non-optimal use of the amplifier. In this note, we will explain the inner workings of a distributed field effect transistor (FET) amplifier and how best to use this circuit in a microwave system.

In a traditional FET amplifier design, the active devices are individually tuned and matched with lumped or distributed networks to obtain a specific frequency response. Designers of such amplifiers must make tradeoffs relative to bandwidth, efficiency, gain and flatness such that a maximum achievable bandwidth is typically no more than one to two octaves.

When a larger bandwidth is needed, designers turn to distributed amplifiers. The concept of a distributed amplifier was first conceived by William S. Percival in 1936<sup>1</sup> and popularized in 1948 by Ginzton, Hewlett, Jasberg and Noe<sup>2</sup>. The distributed amplifier functions by creating a pair of transmission lines. One transmission line connects the inputs, or gates, of the devices in a FET based amplifier, and is then terminated with a resistor. The other transmission line connects the outputs, or the drains, in a FET based amplifier, and provides the output of the amplifier. A distributed amplifier designer must take care to match the delay on the input and output lines in order to ensure the output of each transistor sums in phase with the other devices in the chain. The actual impedances seen by each individual FET vary, however the input and output are both



▲ Fig. 1 Conceptual n-stage distributed amplifier with a cascode configuration.

matched over a wide bandwidth to some characteristic impedance  $Z_0$ , which is typically 50 ohms in microwave applications. This approach makes it possible to achieve performance over an extremely wide bandwidth that is limited primarily by the cut-off frequency ( $f_T$ ) of the technology used to develop the amplifier, rather than the one to two octave practical limitations of an amplifier utilizing a lumped element matching network.

In addition to this distributed approach, many MMIC-based distributed amplifiers use a cascode configuration which consists of a common source FET as the input to the amplifier and a common gate FET driven by that input stage as the output. This architecture offers several advantages, including higher input and output impedances, higher gain and broader bandwidth. A conceptual n-stage distributed amplifier with a cascode configuration is shown in **Figure 1**.

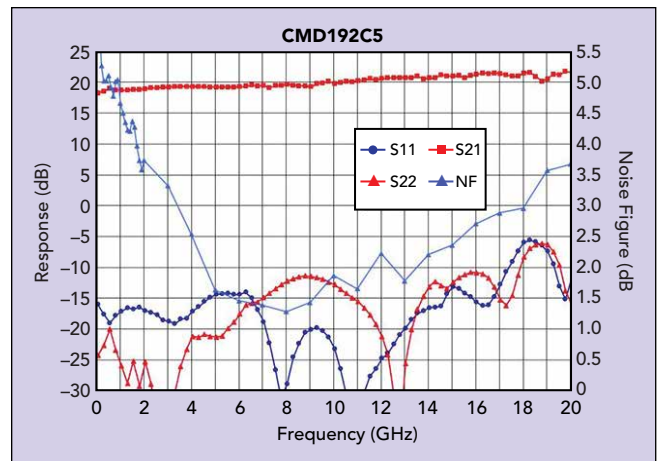


Understanding this architecture is critical in understanding its advantages and disadvantages. As with any amplifier, performance characteristics like gain, return loss, noise figure, power, linearity and efficiency are all very important, but when selecting a distributed amplifier for your application there are several other factors to consider.

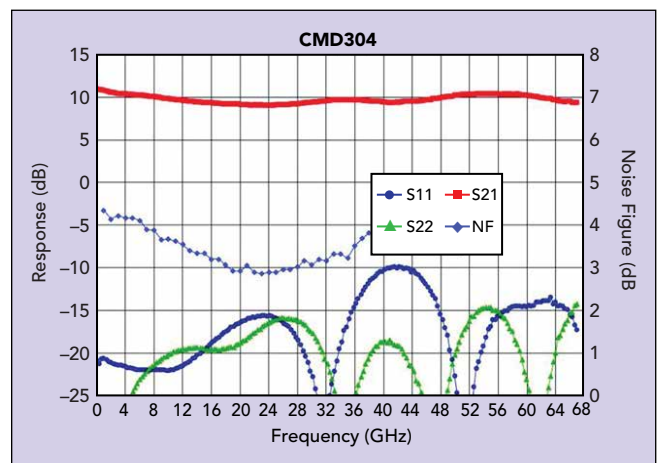
First, transmission lines generally have more loss at higher frequencies than at lower frequencies, mainly due to the skin depth of the metal. Such a phenomenon occurs in distributed amplifiers as well, which can result in a gain that slopes down as the frequency increases. Since most wideband systems require the gain to be flat across a wide frequency range, the selection of a distributed amplifier with negative gain slope will require additional components to equalize the gain, and this solution is not always welcome. However, it is possible to create a flat, or even positive gain slope with respect to frequency. For example, as shown in **Figure 2**, the **CMD192C5** distributed amplifier has a positive gain slope with respect to frequency from DC-20 GHz. Such performance offers considerable advantages to a wideband system designer by eliminating some of these equalization stages and reducing the size, power and complexity of the design implementation. In the case of even wider band systems where positive gain slope may not be achievable, a flat response with respect to frequency offers similar advantages. The **CMD304**, for example, is a DC-67 GHz distributed amplifier with a flat gain response with respect to frequency, as shown in **Figure 3**.

Second, another amplifier characteristic of importance as shown in Figures 2 and 3 is the low frequency noise figure. In a distributed amplifier, the noise figure is not only impacted by the channel and gate noise as it is in other amplifier topologies, but it is also impacted by the thermal noise of the input termination. The noise from this termination is filtered before it reaches the output such that it only has a significant impact below  $B/n$  where  $n$  is the number of amplifier stages and  $B$  is the bandwidth of the device.<sup>3</sup> Returning to Figure 2, it is apparent that the noise figure of the CMD192C5 below 4 GHz is increasing due to noise from the input termination. In Figure 3, however, the low frequency noise figure of the CMD304 is much flatter than the CMD192C5 even at 1 GHz, the lowest measured frequency point for the CMD304. The reason: the CMD304 has many more FET stages than the CMD192C5. Therefore, if low frequency noise figure is an important system consideration, choosing a distributed amplifier with more stages is a preferred solution. Additional techniques can be employed to further reduce the effect of this termination on the low-frequency noise figure and future products featuring these techniques will provide good noise performance well below the  $B/n$  limit.

Next, some wideband applications also require the amplifiers to have low additive phase noise. Such amplifiers are critical for many applications where received power levels can be very low, such as high-end direct conversion receivers or radar systems. In these wideband systems, designers must use an amplifier which does not contribute to the system phase noise, as the



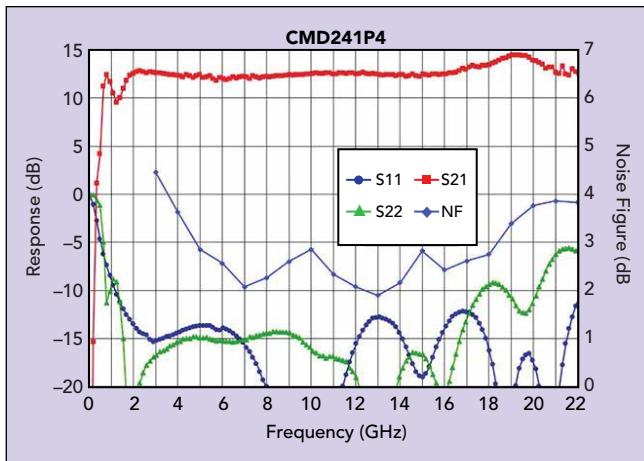
▲ Fig. 2 S-parameters and noise figure versus frequency for the CMD192C5 distributed amplifier.



▲ Fig. 3 S-parameters and noise figure versus frequency for the CMD304 distributed amplifier.

additive noise could potentially obscure the desired signal after mixing with the LO. However, it is well known that the additive phase noise of FET-based amplifiers can be quite high. Therefore, to achieve low-phase-noise distributed amplifiers, circuit designers turn to hetero-junction bipolar transistor (HBT) processes. HBTs are known to have very low  $1/f$  noise, which gives amplifiers of this type extremely low additive phase noise. The **CMD275P4** is an example of an extremely broadband low-phase-noise amplifier. When compared to a similar broadband part designed on a pHEMT process, this component which was developed on an HBT process shows about a 20 dBc/Hz improvement in phase noise at a 10 kHz offset.

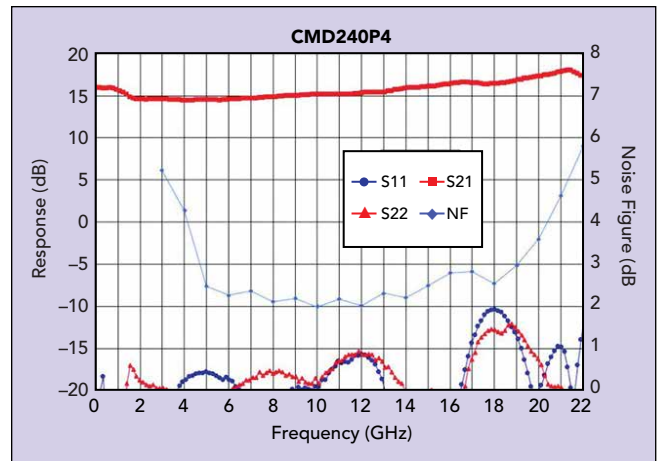
In addition to the RF characteristics of the device, it is important to consider how the DC power will be supplied to a distributed amplifier and how the bias circuit could affect performance. In applications where size of implementation is critical and performance to very low frequencies is not necessary, most designers will select a MMIC such as the CMD241P4 with an on-chip bias choke and DC blocking capacitors on the RF input and output. While reducing the total footprint required by the amplifier, these on-chip components limit performance, not only because the DC blocking capacitors



▲ Fig. 4 S-parameters and noise figure versus frequency for the [CMD241P4](#) distributed amplifier.

will limit the low end, but also because the higher resistance of the on-chip bias choke - when compared to a high-quality conical inductor - affects the high frequency performance as well. In order to understand the limitations, Figures 4 and 5 show the performance of CMD241P4 with on-chip bias structures (Figure 4) along with the CMD240P4, which features the same amplifier design with off-chip biasing (Figure 5).

While small size and ease of implementation are goals of almost any system, in some designs it is critical to get as close to actual DC performance as possible without limiting the high-frequency performance, even at the expense of board space. There are many distributed amplifiers designed for these applications which require an off-chip bias choke and DC blocking capacitors on the RF lines. This architecture allows the system designer to obtain the performance needed by selecting components which will provide the broadest possible performance. Selecting the right external components must be done very carefully to ensure proper performance of the distributed amplifier. First, the designer must select a broadband inductor that can handle the bias current required for the device with sufficient margin and one which does not have any in-band resonances that will affect performance. The DC block-



▲ Fig. 5 S-parameters and noise figure versus frequency for the [CMD240P4](#) distributed amplifier.

ing capacitors also need to be selected without any in-band resonances while being able to pass the lowest frequency required by the application.

With many different factors to consider in addition to the typical amplifier parameters, it is critical that a wide variety of distributed amplifier options be available to wideband systems designers. Custom MMIC's growing distributed amplifier portfolio includes high power, low noise, extremely wide bandwidth and low phase noise options. Most of these amplifiers exhibit flat or positive gain slope with respect to frequency and there are options for both on-chip and external biasing. This [breadth of offerings](#) ensures that wideband systems designers always have an option to meet the ever-increasing demands of high performance across extremely wide bandwidths.

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# Doherty Power Amplifiers Move to mmWave

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*Doherty power amplifiers (PA) are widely used below 6 GHz to improve power-added efficiency (PAE) for communications applications. Although the benefits of the Doherty architecture are compelling, the challenges of designing Doherty PAs increase as the frequency of operation moves toward mmWave. LDMOS, which is commonly used in discrete form below 6 GHz, has limited performance and more integrated approaches are needed to minimize parasitic inductances and capacitances. GaN technology offers significant performance advantages for realizing RF/microwave PAs. More recently, short gate length GaN on SiC MMIC processes have become commercially available, offering the possibility of designing high efficiency Doherty PAs at mmWave frequencies. This article will describe the design of a Doherty PA MMIC for the 5G frequency band at 28 GHz. First-pass design success was achieved using an asymmetric topology fabricated on the commercial 0.15  $\mu\text{m}$  G28v5 GaN on SiC foundry process from Wolfspeed. The MMIC was assembled in a cost-effective, compact 4 mm  $\times$  4 mm QFN package. Details of the design, simulation, layout and packaging will be discussed.*

**A**s GaN on SiC technology advances, new possibilities for PAs emerge. GaN on SiC has been successfully used at sub-6 GHz and to Ku-Band frequencies, but the source-coupled field plates often used to enhance breakdown voltage and increase power density have limited the maximum operating frequency of GaN transistors. Competing technologies such as GaAs and SiGe achieve higher operating frequencies with similar geometries, and these have become preferred high performance semiconductor technologies at mmWave. However, GaN on SiC processes with gate lengths of 0.15  $\mu\text{m}$  are now available through foundries, with attractive performance at mmWave. This means the advantages of GaN on SiC—high power density, higher output impedance and lower  $I^2R$  losses—can be realized in the 28 GHz 5G band.

PRFI has designed GaN PAs using both discrete devices and as custom MMICs, including a GaN on SiC Doherty PA for the 3.5 GHz 5G band.<sup>1</sup> This, com-

bined with the company's experience with mmWave PAs and front-end modules in various GaAs technologies, has been used to extend the Doherty amplifier to mmWave.<sup>2,3</sup>

## DOHERTY PAS

The Doherty amplifier configuration (see **Figure 1**) comprises a main or carrier amplifier, biased in class AB, and a parallel auxiliary or peaking amplifier, biased in class C. The improvement in PA efficiency stems from the complementary operation of the main and auxiliary amplifiers: when the PA is operating at moderate power levels, only the main amplifier is active, which reduces DC power consumption. With high level input signals, the auxiliary amplifier begins to amplify, boosting the output power capability of the PA.

The output matching network of the Doherty PA consists of two impedance transformers: an impedance inverter and a common matching network. Together, they



present optimal impedances to the amplifiers in both compressed and backed-off operation. The impedance inverter at the output of the main amplifier provides a 90 degree phase shift between the main and auxiliary amplifier paths. In large-signal operation, to ensure the outputs from the main and auxiliary PAs are combined in phase, a 90 degree phase shift is added to the input of the auxiliary amplifier.

Compared to sub-6 GHz Doherty amplifiers, mmWave PAs add several design challenges. Transmission line and matching element losses are higher, and the transistors have lower transconductance, so gain is more difficult to achieve. Also, parasitic capacitances and inductances have more effect at mmWave frequencies, making it more difficult to present a real impedance ( $R_{OPT}$  in Figure 1) to the main transistor output.

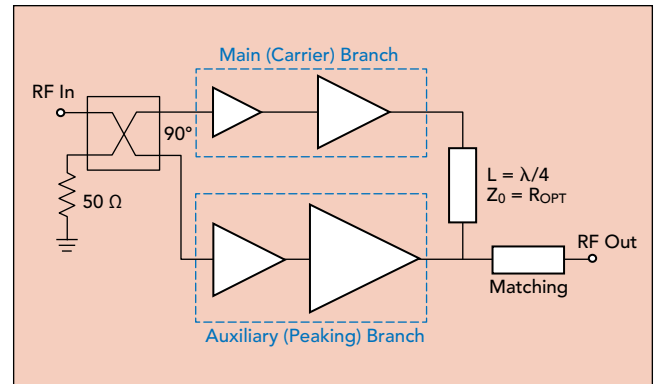
## GAN PROCESS

This PA design uses GaN devices fabricated on Wolf-speed's G28v5 GaN on SiC process. The transistors have 0.15  $\mu\text{m}$  gate length, operate at a bias voltage of 28 V and have a breakdown voltage greater than 84 V. The devices achieve a power density of 3.75 W/mm, compared to less than 1 W/mm for a typical high power mmWave GaAs PHEMT process.<sup>4</sup> While most GaN on SiC processes have a substrate thickness of 100  $\mu\text{m}$  (4 mils), the G28v5 substrate thickness is 75  $\mu\text{m}$  (3 mils), which improves high frequency operation. A variety of transistor layouts are available in the process design kit (PDK), including intra-source and edge via layouts. The gate and drain finger spacing of the FETs can be modified to trade off the thermal resistance, high frequency operation and die area. Self-heating models in the PDK enable designers to predict the operating channel temperatures inside the transistor.

For Doherty amplifiers, GaN on SiC is preferred over GaN on Si for two reasons: the thermal conductivity of SiC is around 3x better than Si, improving the heat transfer from the die, which lowers channel temperature and improves reliability. SiC has less RF loss, so the auxiliary amplifier branch presents a high impedance when pinched off. This avoids loading the main amplifier, yielding better back-off efficiency.

## PA DESIGN

An asymmetric topology was selected for the Doherty PA design to achieve better efficiency at higher back-off powers. Theoretically, a symmetric Doherty PA has a peak efficiency at 6 dB back-off, where an asymmetric Doherty with a 2:1 gate width ratio between the auxiliary and main branches achieves peak efficiency at 9.5 dB back-off. Actual device knee voltages reduce the available voltage swing, so peaks at 8 dB back-off are usual. This is compatible with modulated communications signals, which typically have peak-to-average power ratios of 8 to 10 dB. While an asymmetric configuration has performance advantages over a symmetric design, it requires considerably more design effort. Two separate PAs must be designed and then integrated into the Doherty topology. The phase and amplitude responses must be engineered to ensure the powers from the main and auxiliary branches combine in phase at the output.



▲ Fig. 1 Doherty amplifier architecture.

The asymmetric Doherty PA is shown in **Figure 2**. The main amplifier is at the top and the auxiliary amplifier, with its larger gate width, is at the bottom. Designed to be compact enough to be assembled in a 4 mm  $\times$  4 mm QFN package, the die size is 2.40 mm long  $\times$  2.15 mm wide.

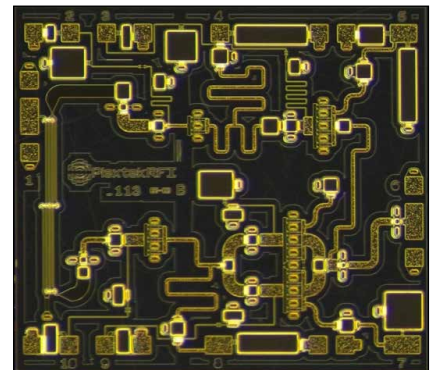
The input split and 90 degree phase shift use a Lange coupler, which was electromagnetic (EM) simulated for maximum accuracy. The spacing between the Lange coupler fingers determines the coupling, hence the power split between main and auxiliary branches. The 50  $\Omega$  terminating resistor on the isolated port of the Lange coupler was sized to dissipate the expected power reflecting into it.

As with all PA designs, the even-mode stability must be ensured across frequency and temperature, and the odd-mode stability of the combined auxiliary branch transistors must be considered. This is important when combining multiple transistors to increase gate width, which is the case with the auxiliary branch. Due to their class C bias, the auxiliary transistors do not provide small-signal gain, so odd-mode stability is ensured. Under large-signal operation, oscillations may occur, so stability simulations were run to determine the appropriate odd-mode stability resistors.

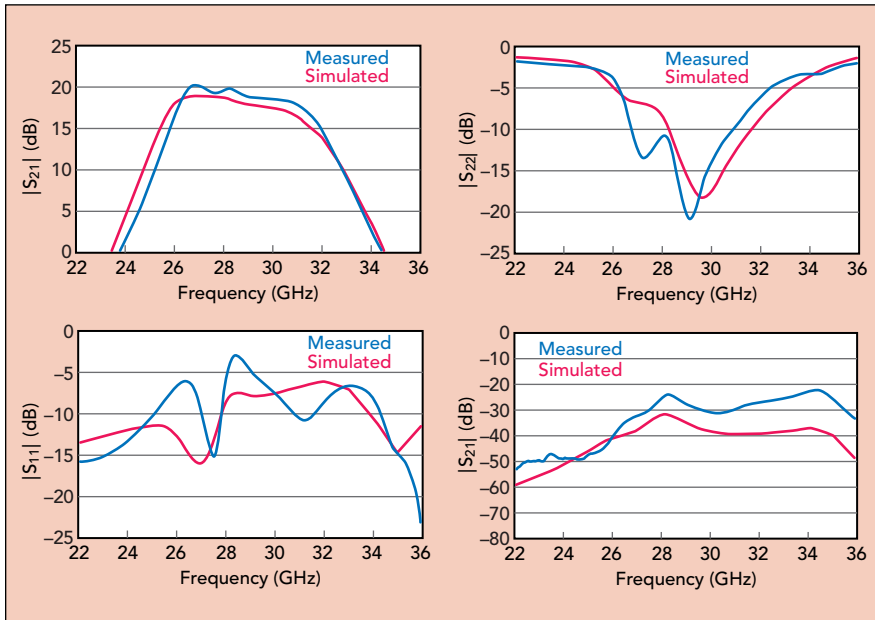
## ON-WAFER MEASUREMENTS

The PA was measured using direct on-wafer RF probes in PRFI's cleanroom, testing both small- and large-signal performance. Because the auxiliary branch is biased to operate in class C, Doherty amplifiers often have low small-signal gain.

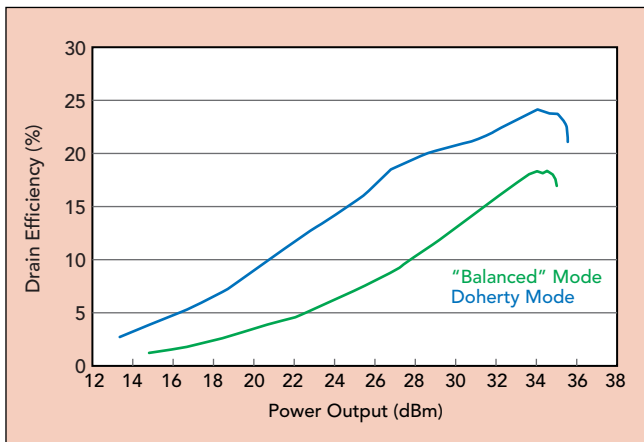
So the measured gain of 20 dB at 27 GHz and 18.6 dB at 30 GHz is notable (see **Figure 3**). Compared to the simulated performance, the measured small-signal gain is slightly higher, while the frequency response matches well with the simu-



▲ Fig. 2 28 GHz Doherty amplifier die.



▲ Fig. 3 Doherty PA simulated vs. on-wafer measured S-parameters.



▲ Fig. 4 Measured on-wafer drain efficiency at 29 GHz.

lations, reflecting the accuracy of both the Wolfsped PDK models and the EM simulations of the on-chip matching networks.

The maximum output power of the Doherty PA was 35 dBm (3.2 W). Because of the cable and probe losses, the driver amplifier could not fully compress the Doherty PA, so the maximum output power is expected to be higher when the packaged PA is measured. To manage the thermal dissipation of the PA, the large-signal measurements used a 100  $\mu$ s pulse width, 10 percent duty cycle RF input. The efficiency of the PA at 8 dB back-off, 27 dBm (0.5 W) output, was 19 percent. This efficiency will likely be higher when the die is packaged and mounted on an evaluation board (EVB) with a better thermal environment. “Tuning” the PA bias may yield further improvement in power and efficiency.

Figure 4 shows the efficiency advantage of the Doherty configuration compared to a conventional class AB PA design. The “balanced” mode was measured by setting the same gate voltages for the auxiliary and main

branch PAs. At an output power of 27 dBm (0.5 W), equivalent to 8 dB back-off, the measured Doherty efficiency is 19 percent, compared to less than 10 percent for the balanced case.

Compared to other published Doherty PAs at mmWave frequencies, this asymmetric GaN design achieved higher output power than GaAs versions and wider bandwidth than other GaN Doherty PAs, whether GaN on Si or GaN on SiC.<sup>5,6</sup>

## PACKAGING

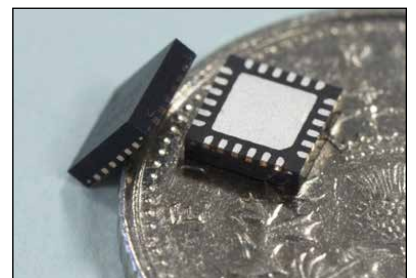
Packaging is a key aspect of PA design, especially at mmWave frequencies.<sup>7</sup> For this design, a cost-effective plastic overmolded 4 mm  $\times$  4 mm QFN package was selected to give adequate protection to the die while being compatible with volume production (see Figure 5). For optimum performance and reliability, the thermal resistance between the trans-

istor channel and the backside of the package should be minimized. While the MMIC substrate is SiC, which has excellent thermal properties, the thermal resistance between the backside of the die and the package die attach paddle (DAP) must be minimized. Typically, the die is attached to the DAP with an epoxy; using a high thermal conductivity epoxy reduces the junction-to-case thermal resistance. In addition to the bulk thermal conductivity of the epoxy, bond-line thickness, curing conditions and shear strength are also important considerations when selecting the epoxy.

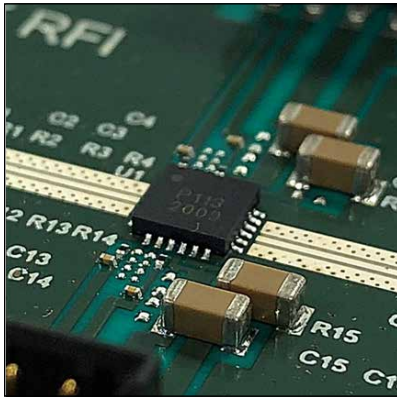
The plastic overmold of the package is expected to shift the frequency response of the PA down. The die was designed for this, reflecting a higher frequency band when measured on-wafer so the packaged PA will be centered around the 26.5 to 29.5 GHz design band. The design includes guard bands above and below to accommodate MMIC and assembly process variations. The packaged PA will be extensively tested on an EVB (see Figure 6) and the measured data compared with die performance. The EVB uses minimal off-chip decoupling components and requires no off-chip RF components, as all RF components are integrated on the MMIC.

## CONCLUSION

Combining PRFI’s experience designing mmWave MMICs and sub-6 GHz Doherty PAs with Wolfsped’s G28v5 process, PRFI designed a Doherty PA MMIC suitable for the 28 GHz 5G



▲ Fig. 5 Doherty PA packaged in a 4 mm  $\times$  4 mm QFN.



▲ Fig. 6 Packaged Doherty PA assembled on an evaluation board.

band. An asymmetric topology demonstrated excellent initial results on the first-pass die design, with on-wafer measurements of at least 35 dBm output power, 27 dBm at 8 dB back-off with 19 percent PAE and 20 dB small-signal gain. The packaged MMIC will next be evaluated on an EVB to compare packaged and die

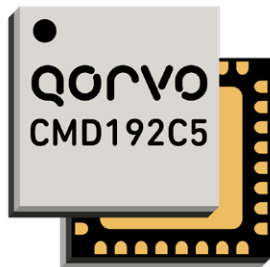
performance. With wide bandwidth and flat gain, the MMIC PA assembled in a low cost 4 mm × 4mm QFN package will be useful for transmitters in 5G mmWave infrastructure systems.■

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## DC - 20 Gz High Output Power Distributed Driver Amplifier with Positive Gain Slope

Qorvo's CMD192C5 is a DC to 20 GHz wide-band GaAs MMIC distributed driver amplifier which is housed in a leadless SMT package. The



amplifier delivers greater than 19 dB of gain with a positive gain slope which can simplify overall circuit design, and with a corresponding output 1 dB compression point of +25 dBm, and noise figure of 1.9 dB at 10 GHz. The CMD192C5 is a 50 ohm matched design, eliminating the need for RF port matching, and is the perfect alternative to higher cost hybrid amplifiers.

[Learn More](#)



## DC-20 GHz Ultra-Wideband Distributed Driver Amplifier with Positive Gain Slope

Qorvo's CMD244K5 is a DC to 20 GHz wide-band GaAs MMIC distributed driver amplifier which is housed in a leadless



SMT package. This amplifier delivers greater than 17 dB of gain with a positive gain slope which can simplify overall circuit design, and with a corresponding output 1 dB compression point of +25 dBm, and noise figure of 2.5 dB at 10 GHz. The CMD244K5 is a 50 ohm matched design, eliminating the need for RF port matching.

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# How GaN is Changing the Satcom RF Front-End

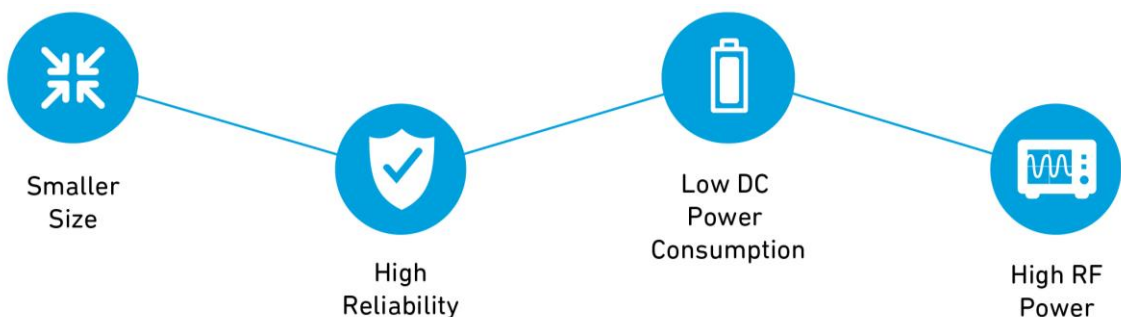
By:  
David Schnauffer, Technical Marketing Manager, Corporate Marketing  
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## Introduction

Solid-state technologies such as gallium nitride (GaN) are transforming satellite communications (satcom). GaN's advantages of high RF power, low DC power consumption, high reliability and smaller size (which reduces system weight) are opening new markets and revolutionizing the RF front-end (RFFE) in existing satcom applications.

For many years the traveling wave tube amplifier (TWTA) and gallium arsenide (GaAs) were the go-to RFFE technologies for power amplification in satcom – with TWTAs used for high-power applications and GaAs employed in lower-power applications and as a pre-driver. But the situation has changed rapidly in recent years, due to advancements in GaN. Now, GaN and GaAs semiconductor technologies are becoming the go-to solutions; GaN has been replacing TWTAs due to its high-power performance and reliability combined with a small form factor. GaN and GaAs are enabling a wide variety of commercial and military satcom applications, such as 5G backhaul, ultra-HD TV transmission, satcom-on-the-move, internet access for aircraft passengers, and manpack (portable) terminals.

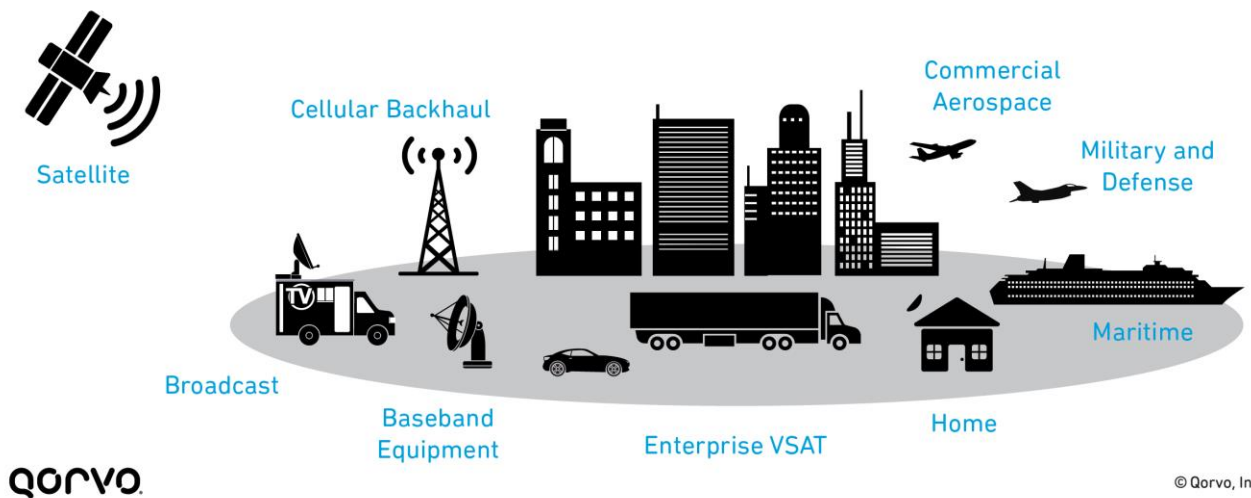
## GaN Advantages



### Satcom Trends

Satcom equipment plays vital roles in the global communications ecosystem and the daily lives of people across the world. It supports a broad and expanding variety of applications in telecommunications, weather monitoring, aeronautical communications, maritime applications, military uses and navigation (see Figure 1). According to [MarketsandMarkets research](#), the satcom equipment market is projected to grow at about 8.5% a year to reach \$30B by 2022. [Strategy Analytics](#) forecasts spending on global military communications systems and services will grow to over \$36.7 billion in 2026, representing a CAGR of 3.5%.

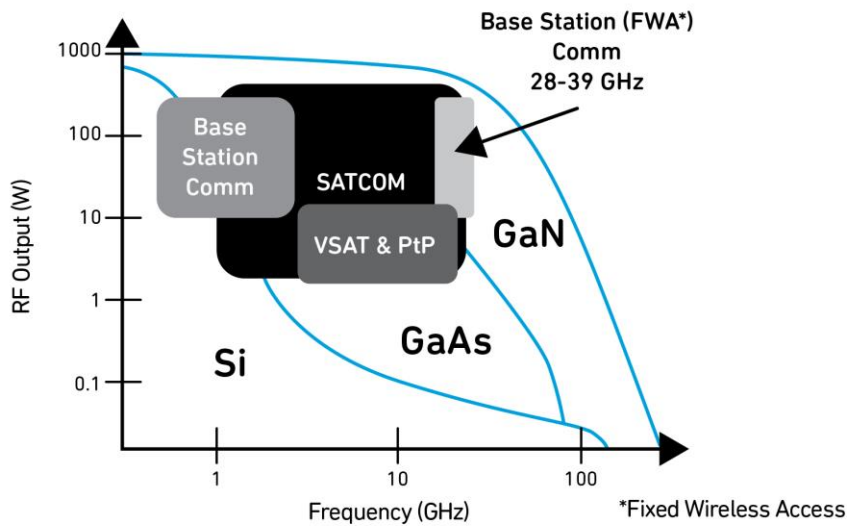
Figure 1. Satcom global markets.



Several broad trends are creating new and more challenging requirements for the RFFE in satcom equipment. The increasing use of smaller satellites and portable, mobile satcom devices is driving a need for more compact, lightweight components with lower power consumption. Additionally, components need to handle much greater bandwidth and data throughput to support advances such as 5G, ultra-HD TV, un-interrupted and secure communications. There's also pressure, to reduce development costs and increase reliability.

These trends are propelling the transition from TWTAs to solid-state devices that support higher data throughput and smaller form factors. Though GaAs and silicon (Si) have been used in some systems, GaN offers significant advantages for high-power amplification in satcom applications. Its high saturation velocity, high breakdown voltage, and thermal conductivity result in an order of magnitude improvement in power density and high reliability under thermal stress. As a result, **GaN** is uniquely suited to the high-power requirements of satcom, very small aperture terminal (VSAT), point-to-point (PtP) and base station applications, as shown in Figure 2.

Figure 2: Suitability of semiconductor technologies to different applications.



GaN’s potential for the space and satellite communications sectors is only beginning to be realized. The high RF power, low DC power consumption, lightweight, small form factor and high reliability will enable manufacturers to downsize the RFFE. For example, GaN is expected to facilitate weight reduction in satellites and aeronautic applications.

## Frequency Bands

The satcom industry has progressively moved to higher-frequency bands to support growing demand for bandwidth, including the X, Ku, K, and Ka-bands as shown in Figure 3. GaN easily supports high throughput and wide bandwidth across these higher frequencies. Today, many of the same satcom components are used across multiple military, space and commercial applications in these bands.

Figure 3. IEEE microwave bands.

IEEE Microwave Band	Frequency Range	Description
L-Band	1 GHz – 2 GHz	Global positioning system (GPS) carriers and also satellite mobile phones, some communications
S-Band	2 GHz – 4 GHz	Weather radar, surface ship radar, and some communications satellites
C-Band	4 GHz – 8 GHz	Primarily used for satellite communications, for full-time satellite TV networks or raw
X-Band	8 GHz – 12 GHz	Primarily used by the military, also used in radar applications
Ku-Band	12 GHz – 18 GHz	Used for satellite communications, fixed satellite services and broadcast satellite services
K-Band	18 GHz – 26 GHz	Used for fixed satellite services and broadcast satellite services
Ka-Band	26 GHz – 40 GHz	Communications satellites, uplink in either the 27.5 GHz and 31 GHz bands, and high-resolution, ctlose-range targeting radars on military aircraft

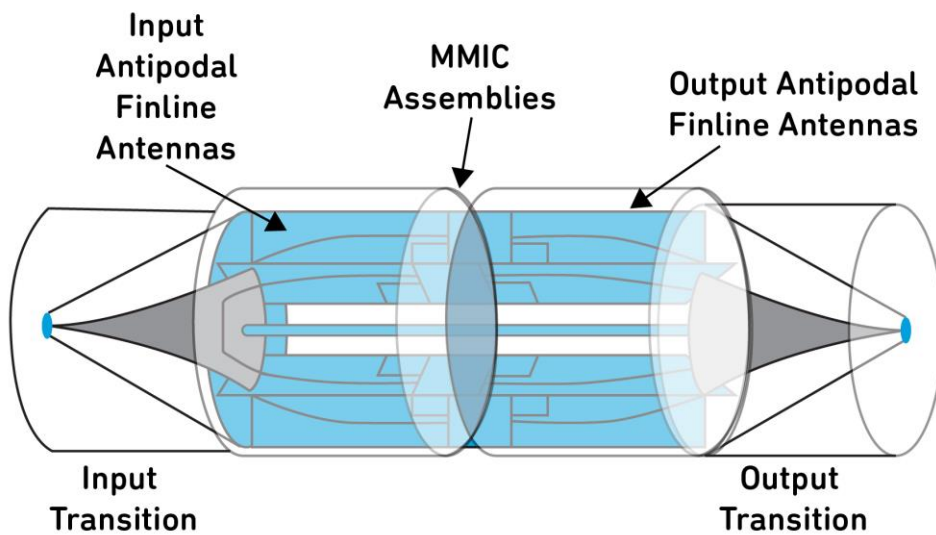
## Replacing TWTAs

Until recently, TWTAs were the mainstay in many satcom applications because solid-state devices weren't capable of producing similar power levels. However, power combining techniques now make it possible to generate much higher power using GaN, enabling the replacement of TWTAs with more-reliable solid-state devices.



The GaN power-combining approach aggregates the output power from several single power amplifier MMICs using fully isolated coupling networks. An example is Qorvo's **Spatium®**, which is a spatial combining product that uses a patented spatial combining technique to offer high RF power, high efficiency and broadband operation. Spatium uses broadband antipodal fin-line antennas as the launch to and from the coaxial mode, splitting into multiple microstrip circuits (see Figure 4). It then combines the power from these circuits after amplification with a power MMIC. A typical Spatium design combines 16 devices, with a combined loss of 0.5 dB. Spatium is used in Ka-band satellite earth stations that operate at 100 Watts and 27-31 GHz, covering both military and commercial bands. Within these stations, it is used in the transmitter side at the antenna hub in block up-converters (BUCs).

Figure 4: [Spatium](#) spatial combining patented design.



This solid-state power-combining approach offers several performance advantages over TWTAs.

- TWTAs need to warm up before they can attain stable RF performance. Warming the tube can take a few minutes. Mitigating the problem requires backup systems running in hot standby. This results in large energy costs. These back-up systems are not required when using Spatium, as no warm up is required.
- TWTAs require high voltage power supplies, typically in the multi-kV range, thus increasing system power consumption. GaN devices do not require high-voltage power supplies.
- Solid-state GaN generates lower noise and has better linearity than TWTAs. Noise figures for medium power TWTAs can be around 30 dB, versus about 10 dB for a solid-state GaN monolithic microwave integrated circuit (MMIC) PA. Another operational benefit of the GaN transmitter is the reduced harmonic content in the output signal.

## GaN Advantages for Satcom

**GaN** offers a range of other advantages over both TWTAs and other solid-state technologies for satcom applications.

**Reliability and ruggedness.** Reliability is extremely important in satcom applications. GaN offers much higher reliability than TWTAs for several reasons. With TWTAs, a failure in the tube causes a total performance breakdown. In contrast, a spatial combining technique like Spatium increases robustness and reliability. The failure of one transistor does not mean the entire unit shuts down; instead it continues to function using the remaining GaN amplifier MMICs. Each solid-state device is also highly reliable: although the lifetime of a transistor is limited due to electromigration, time-to-failure is typically over 100 years.

The higher power-efficiency of GaN also reduces heat output, which further contributes to higher reliability. Furthermore, wide-bandgap GaN tolerates much higher operating temperatures, so the cooling requirements in compact areas may be relaxed without compromising performance and reliability. This reduces the need for cooling fans and heatsinks, which reduces the weight and size of satellites and therefore the cost of launching them into orbit.

**Small, lightweight devices.** Weight and size are becoming critical factors in satcom applications, with the trend to smaller satellites and the growth of other on-the-move satcom applications. GaN's high power output and on-resistance and breakdown voltage allows satellites and other applications to reach target power output levels with smaller devices. Higher power density results in less weight and size per given unit of power output. The high breakdown field allows higher voltage operation and increased efficiency and helps to ease impedance matching requirements, reducing the need for tuning components and helping to decrease board size.

**Low current consumption** means lower operating costs and less heat to dissipate. Lower currents also helps to reduce system power consumption and demand on power supplies. The result is reduced expense for manufacturers and operators.

**Reducing the thermal rise** in a system makes it easier to increase performance and cuts cost for the application. Because GaN technology is highly power-efficient and tolerates higher operating temperatures, GaN technology can help system designers work within tighter thermal related margins, allowing extra performance to be delivered from the RFFE.

**Frequency bandwidth.** Increased bandwidth is being used across the entire communications industry to provide greater capacity to support the ever-growing number of users and insatiable demand for data. The high power density of GaN and its lower gate capacitance enables greater operational bandwidth and higher speeds. Today's GaN modules and power amplifiers deliver broadband operation to support the unprecedented bandwidth requirements of 5G and other emerging applications.

**Integration** is now appearing in **satcom RFFEs**. Demand for smaller solutions for aeronautic applications and satellites is prompting suppliers to replace large multi-technology discrete RF front-ends with monolithic fully integrated solutions. GaN manufacturers are catching this wave, and are developing fully integrated solutions that combine the transmit and receive chain in a single package. This will further reduce system size, weight and time to market for manufacturers.

### Key GaN Satcom Applications

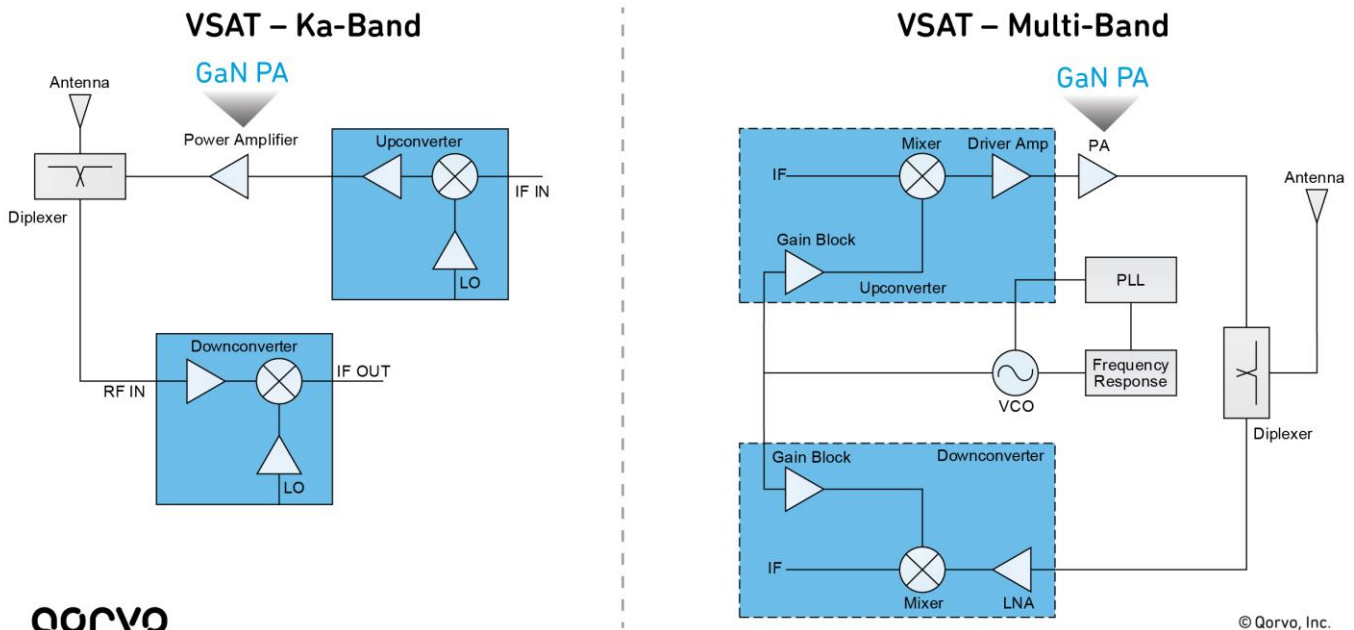
GaN is making its way into many commercial and military satcom applications, including satellites, manpack, satcom-on-the-move, commercial aircraft, and VSAT terminals. In the space industry, GaN is replacing Si and GaAs due to advantages such as size, weight and efficiency. The smaller die size of a GaN device, compared to Si, enables performance improvements in power-switching applications. Parasitics such as output capacitance and layout inductance are reduced, resulting in lower switching insertion loss and higher-frequency operation.

Moreover, new all-electric satellites are currently under study. GaN will be a key enabler in these developments as size reduction, weight and low power consumption are important for success. Some GaN suppliers like Qorvo have space-qualified their technology, underlining the clear opportunities for GaN in this sector.

GaN is also poised to transform the lower-power very small aperture terminal (VSAT) satcom sector. The use of VSAT systems is expanding: they are employed for a wide variety of applications including fixed and portable wideband systems for consumer, commercial, defense and maritime communications, as well as transaction processing, data acquisition and remote monitoring. GaN is replacing and teaming up with traditionally all GaAs systems used in VSAT due to its ability to provide higher output power, which supports higher speeds and increased bandwidth allowing greater data throughput. This accelerates demanding applications, such as commercial two-way data transfers of video and other large files. GaN also outperforms Si in PA-related applications.

GaN's reliability under harsh environmental conditions is also important in this sector. VSAT devices are typically used in environments where they are subjected to harsh conditions. Advances in thermal management using unique packaging are further enhancing GaN's high reliability under these conditions. A two high-level VSAT applications using GaN PA are shown in Figure 5.

Figure 5. Satellite terminal system, VSAT block diagrams.



## Conclusion

GaN is transforming the RF front end across multiple satcom application sectors. GaN is replacing incumbent technologies such as TWTAs, GaAs, and Si, because it is more reliable, more efficient, smaller, and offers higher power density and lower power consumption. Satcom manufacturers are using GaN to improve current satcom products – and to explore new developments and potential new applications.

## The Authors



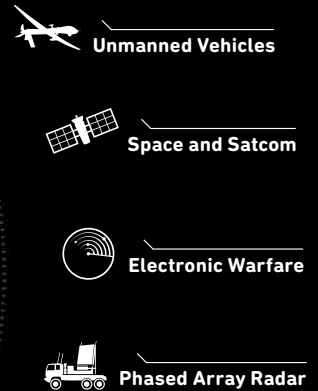
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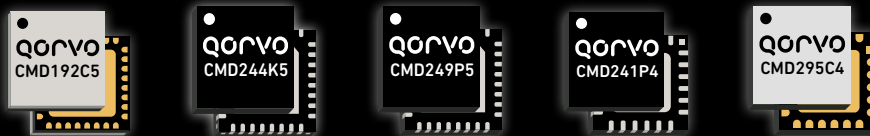
Dean White  
Director of Aerospace & Defense Market Strategy,  
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# Proven mmWave RF Solutions that Connect and Protect™



## For Mission Critical Aerospace and Defense Applications



Part Number	Frequency (GHz)	Voltage (V)	Package (mm)	Description
CMD192C5	DC-20	5-8	5x5 Ceramic QFN	Distributed Amplifier MMIC
CMD244K5	DC-20	5-8	5x5 Plastic QFN	Distributed Driver Amplifier MMIC
CMD249P5	DC-20	10	5x5 Plastic QFN	Distributed Power Amplifier MMIC
CMD292	DC-30	8-10	Die	Distributed Driver Amplifier MMIC
CMD295C4	2-20	2-4	4x4 Ceramic QFN	Driver Amplifier MMIC
CMD241P4	2-22	5-8	4x4 Plastic QFN	Distributed Amplifier MMIC

Since its inception, Qorvo® has focused on helping our customers overcome their toughest design challenges in aerospace and defense applications. Our MMIC design experience, portfolio of GaN/GaAs solutions combined with our extensive knowledge of the entire RF/microwave signal chain enable us to make your next system design a reality.



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