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Microwave Journal

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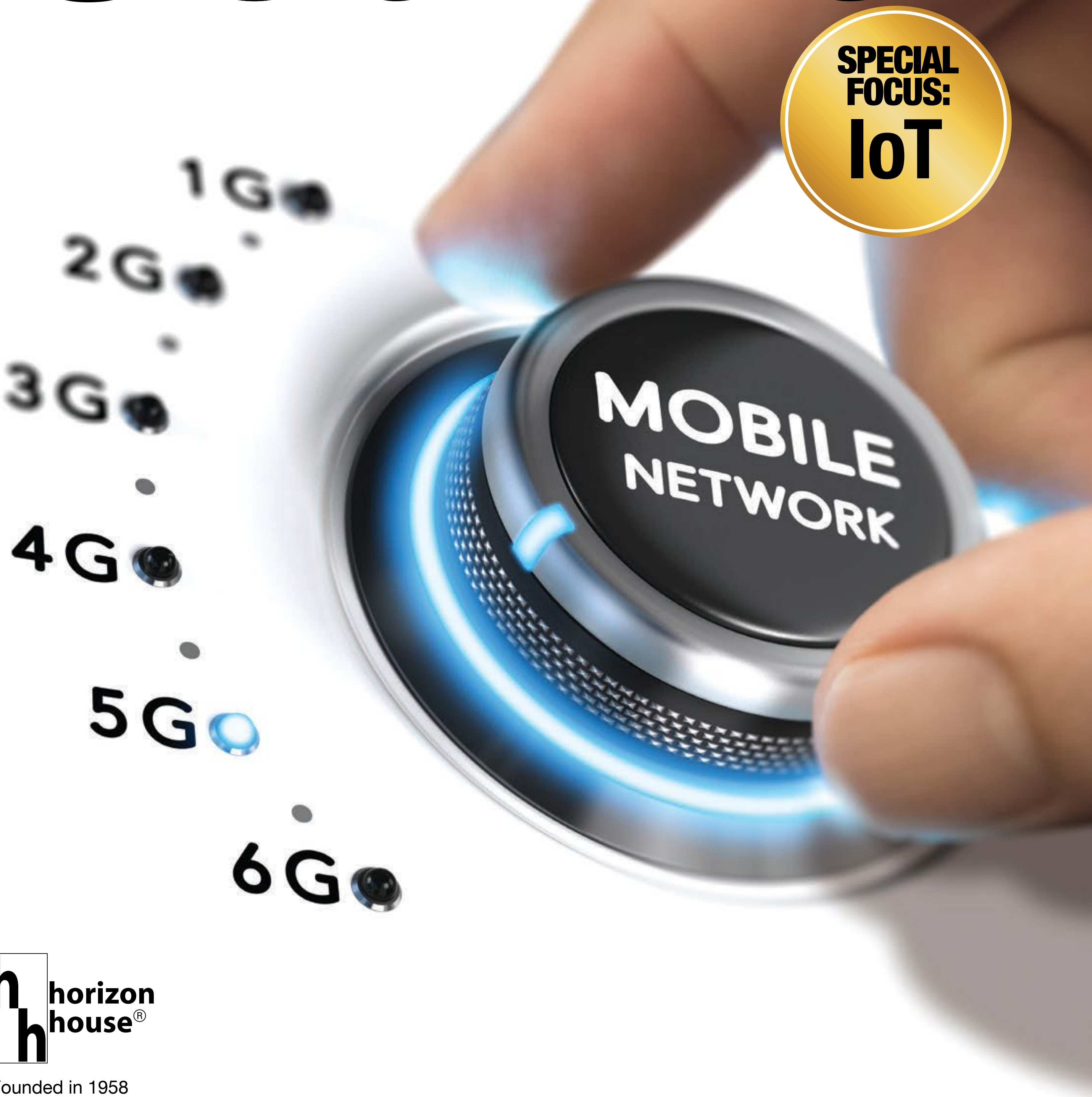

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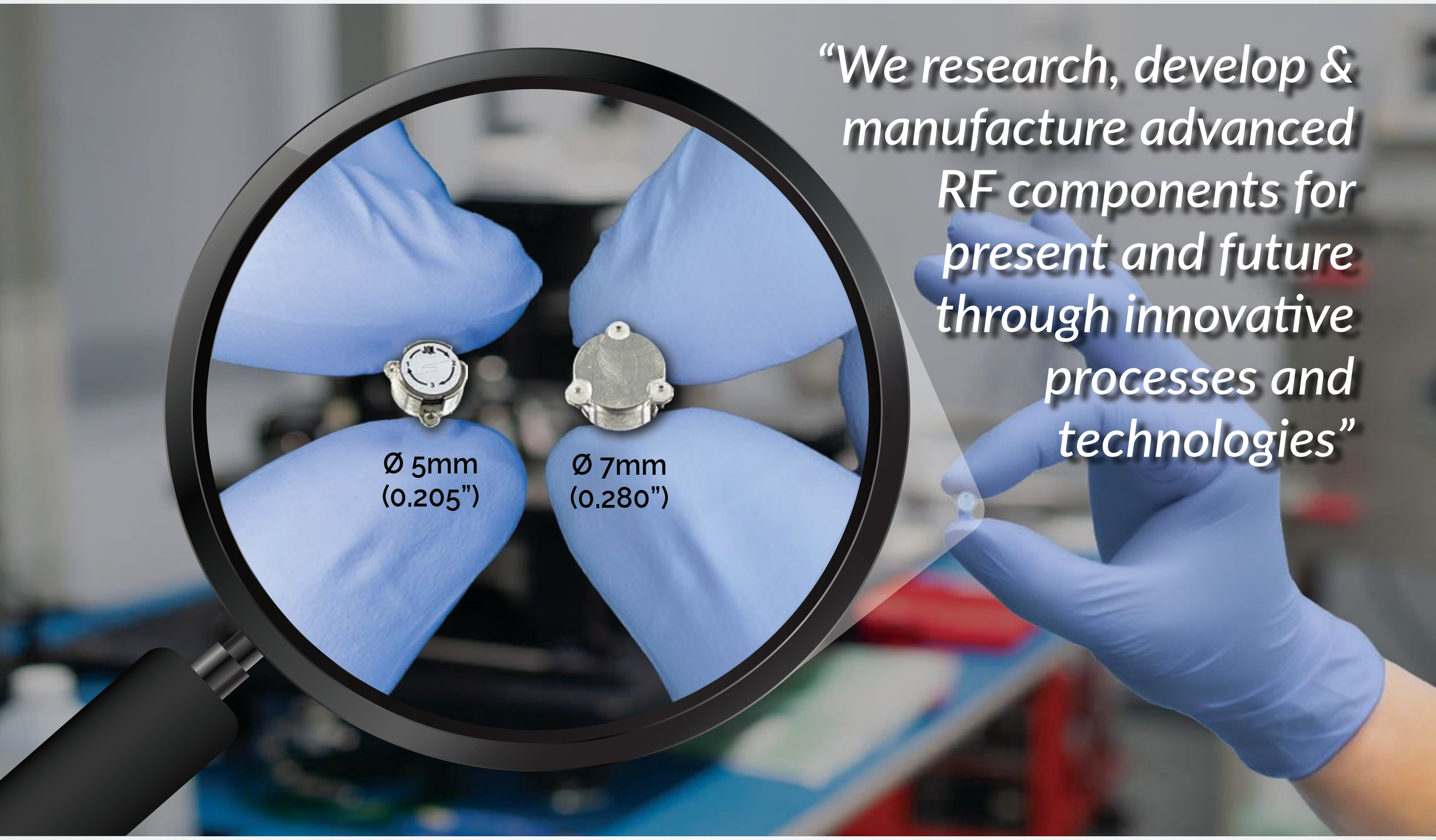

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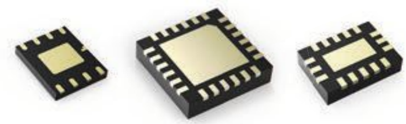

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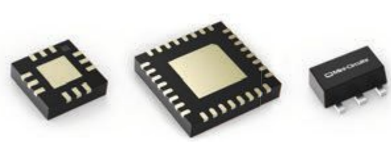

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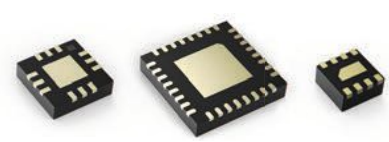

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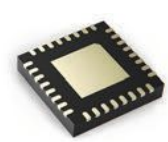

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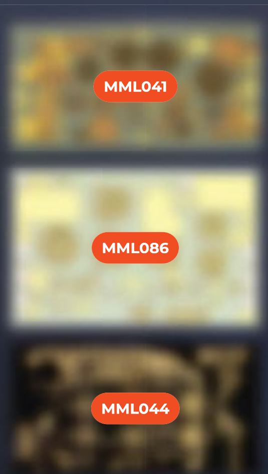

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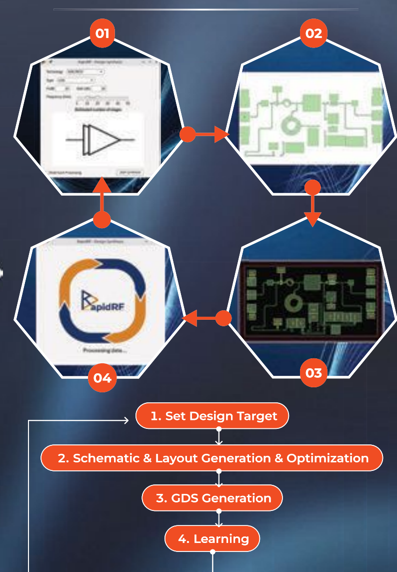

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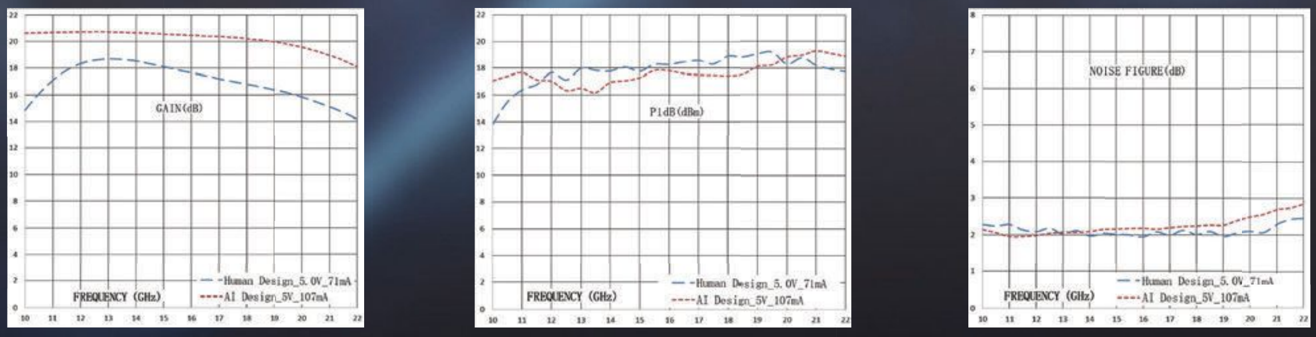

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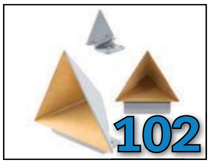

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TIME TRAVEL

By Stefano Selleri
University of Florence, Florence, Italy

Circling the Square: P.H. Smith and His Chart

Ancient Greek mathematicians unsuccessfully spent a long time trying to square the circle. Sadly, π is irrational, but one American went the other way around, "circling" a square.

While we are all familiar with Smith charts, which represent the circles of normalized impedances and admittances within a unitary circle on the reflection coefficient complex plane, few may know that the original Smith chart was square. The earliest Smith chart was devised by Philip Hagar Smith in 1931 while trying to find a quick graphical way to compute the matching network for a large transatlantic communications antenna.[1-3] The first draft was square and drawn on the normalized impedance plane, with circumferences showing the impedance transport along the line. Distances from the load are given by the radial curves emerging from the central matched impedance point and marked in wavelengths from 0 to 0.5, as shown in **Figure 1**.

This was far from perfect because the reflection coefficient could not be displayed graphically and impedances might very well be outside the chart. The second try in 1936 was better. In polar coordinates, the plane had VSWR as a radial coordinate and the distance in wavelengths from the VSWR minimum as an angular coordinate. This was nice since VSWR was directly measured on the line, but it was a nightmare to draw lines at the constant real and imaginary parts of the normalized impedance, which were not circles, as shown in **Figure 2**.

The third time was the charm. Using the reflection coefficient (modulus and phase) to define the plane, the curves at constant real and imaginary parts of the normalized impedance become circles with an easy analytic formula.[4] This chart, developed in 1939, is still in use today. It is worth noting that Tosaku Mizuhashi independently obtained the same chart as evidenced by a Japanese paper, but this did not reach Western researchers until too late.[2,5]

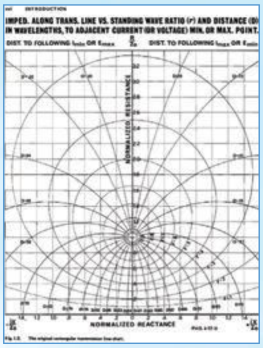

Fig. 1 The 1931 square Smith chart.[1]

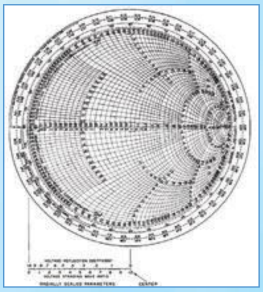

Fig. 2 The 1936 circular Smith chart.[1]

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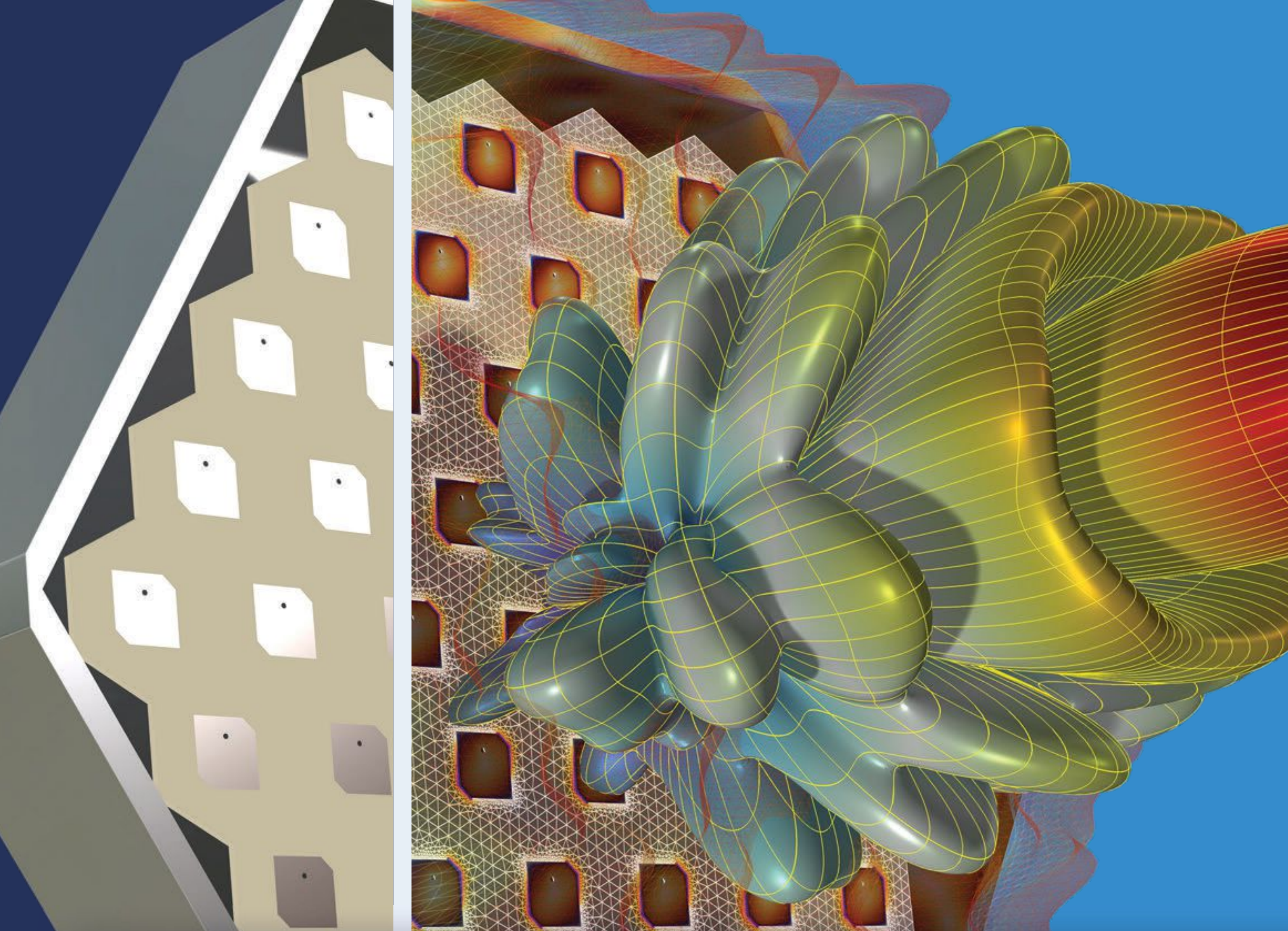


COVER FEATURE
INVITED PAPER

MEMS-Inside-CMOS Technology Makes RF MEMS a Reality for RF Front-Ends

Marc Llamas
Nanusens, Devon, UK

Despite superior performance to solid-state technologies, RF MEMS devices have had almost no penetration in the RF front-end (RFFE) market during the last two decades. This is primarily because of direct or indirect mechanical challenges. These challenges give rise to reliability and packaging issues for the semiconductor industry. There are several solutions for RF MEMS packaging, but the consumer RF market is driven strongly by cost and these solutions are expensive compared to standard packaging techniques. Using nonstandard solutions leads to higher costs and hinders the volume production capability required for the consumer market.

Nanusens has focused on circumventing the challenges preventing RF MEMS technology RFFE adoption by the consumer market by implementing the technology on the back end of a standard complementary metal-oxide semiconductor (CMOS) process. This article introduces the Nanusens MEMS-inside-CMOS technology and subsequently presents an RF MEMS capacitive switch used as a digital tunable capacitor (DTC) building block. Electrical performance and reliability data will be presented to demonstrate a complete DTC prototype and its performance. An aperture antenna simulation compares the Nanusens MEMS-inside-CMOS DTC to a silicon on insulator (SOI) solution currently in the RFFE of some of today's smartphones.

MEMS-INSIDE-CMOS TECHNOLOGY

Nanusens' RF MEMS capacitive switches are implemented on the back-end-of-line (BEOL) of the CMOS process. The switches use the routing metal layers as structural components for the mechanical part and the inter-metal dielectric layers as the sacrificial material. Nanusens' MEMS-inside-CMOS technology requires only one additional maskless step added to

Fig. 1 BEOL of the CMOS wafer after passivation opening (a). After post-processing etching (b). After sealing (c).

the standard CMOS fabrication process. This step, the inter-metal dielectric etching, allows the mechanical structure to move. The top metal acts as the lid of the MEMS cavity, with release holes distributed across the MEMS area. That allows the device to be sealed by standard re-passivation techniques on wafer-level chip scale packages. This method ensures low cost and the volume production capability of standard CMOS devices. These steps are shown in ***Figure 1***.

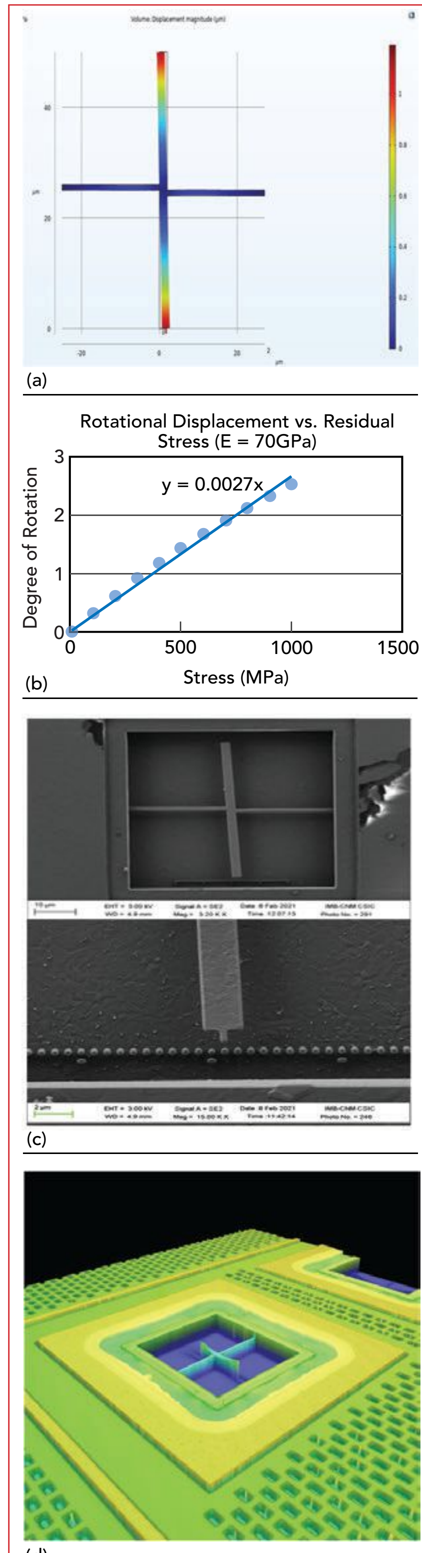
While the CMOS foundry can supply the electrical parameters of the BEOL layers, this is not the case for mechanical properties that are not applicable during ASIC circuit design. Nanusens has developed and implemented several test structures to obtain the necessary mechanical parameters like gradient and residual stresses and Young's modulus to design these devices properly. Examples of these results are shown in ***Figures 2a*** to ***2d***.

However, the CMOS process is not intended as a MEMS process, so different design strategies and techniques were developed to overcome the limitations. RF MEMS capacitive switches have already been implemented and characterized in two different CMOS foundries (TSMC and SMIC) with similar performance. This demonstrates that the technology is compatible with mainstream CMOS foundries.

CAPACITIVE SWITCH DESCRIPTION AND PRINCIPLE OF ACTUATION

The capacitive switch implemented with MEMS-inside-CMOS technology is a varactor that switches between ON and OFF capacitance states. It can be visualized as a binary capacitor with the ON state corresponding to a large capacitance value, while the OFF state corresponds to a low value. The device is implemented with an interdigitated structure shown in the ANSYS-HFSS© models of ***Figure 3***. Figure 3a shows a 3D view of the capacitive switch model with stator fingers in orange and rotor fingers in green. Figure 3b shows the reduced stator/rotator gap in the ON state and Figure 3c shows the gap during the OFF state.

The device is enclosed in a MEMS cavity. It comprises of two parts not shown in Figure 3: the actuation section containing the actuation electrodes and the RF section containing the electrodes which exhibit the capacitance change between the two states. The DC circuitry is isolated from the RF components, ensuring no RF signal coupling to the DC. The actuation section generates electrostatic force by applying a control voltage between the movable and fixed electrodes to "pull in" the RF electrode, creating the ON state capacitance and "pull off" to



▲ Fig. 2 **(a) COMSOL CMOS BEOL model to extract its residual stress. (b) Correlation between rotational displacement and residual stress. (c) SEM image of the residual stress test structure. (d) Confocal image of the residual stress test structure.**

achieve the OFF state capacitance. Pull-off electrodes ensure no self-actuation caused by large RF voltages when the device is OFF.

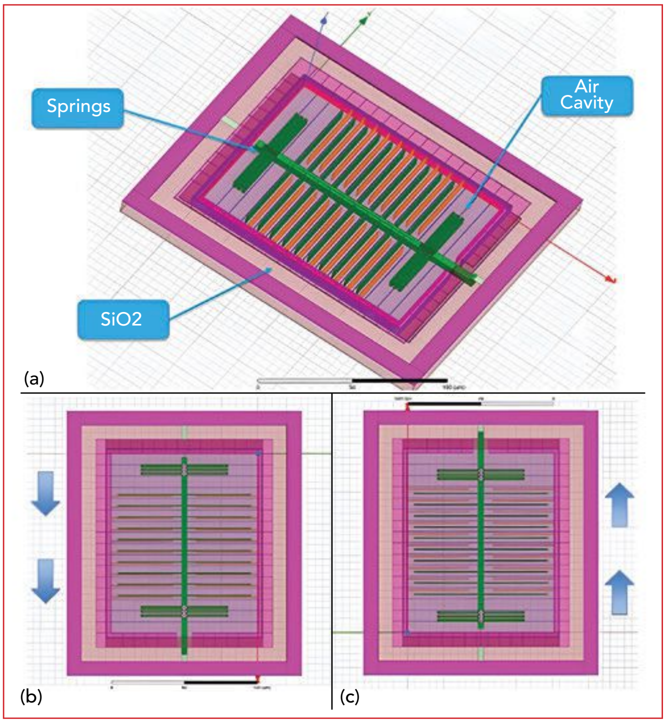


Fig. 3 **3D view of the capacitive switch model (a). ON-state gap (b). OFF-state gap (c).**

CAPACITIVE SWITCH RELIABILITY

The main failure mechanism of RF MEMS capacitive switches is dielectric charging due to charge trapping in the dielectric. This charge accumulation tends to generate an electrostatic force that can hold the device in the ON or the OFF state after removing the control voltage. Nanusens' RF MEMS capacitive switches have no dielectric, ensuring that dielectric charging cannot cause failure. Taking advantage of the small gaps achievable with CMOS processes, the displacement of the movable part has been minimized to prevent failure due to the mechanical fatigue of the materials. ON/OFF state cycle testing has been performed by applying a 1 kHz square wave with a 50 percent duty cycle and the appropriate control voltage amplitude. Nanusens' RF MEMS capacitive switches have survived more than 3 billion cycles without significant changes in their mechanical or electrical performance, demonstrating their suitability for antenna applications. ***Figure 4*** shows the C-V curve with 11 V bias voltage.

These switches have been tested from -20°C to 150°C without noticeable performance degradation during operation. The switches have also been subjected to shock tests up to 6000 g and 50 Hz vibration tests for 30 minutes in each direction without performance degradation. They have also passed a preconditioning test, including 24 hours of baking at 150°C, seven days at 70°C/70 percent RH and six reflows up to 260°C for 15 minutes.

Currently, the main driver for yield is the etching post-processing step required to free the devices so they can move. Standard semiconductor equipment at the equipment manufacturer's facilities does the etching step. Yield figures of 85 to 95 percent are constantly being achieved and the belief is that these will exceed 95 percent in production.

CAPACITIVE SWITCH PERFORMANCE

While dielectric-less capacitive switches prevent dielectric charging failure, the lack of a dielectric makes it more difficult to achieve large capacitance ratios. However, capacitance ratios from 2 to 4 are sufficient for aperture antenna applications in all bands from 0.5

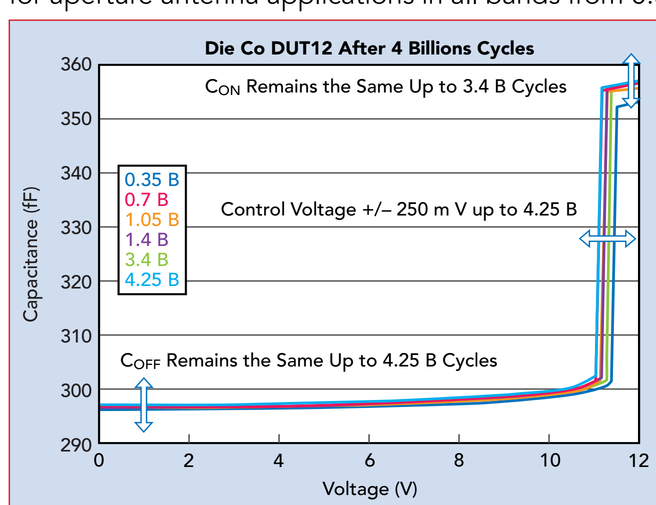


Fig. 4 **Switch C-V curve.**


Has Amplifier Performance or
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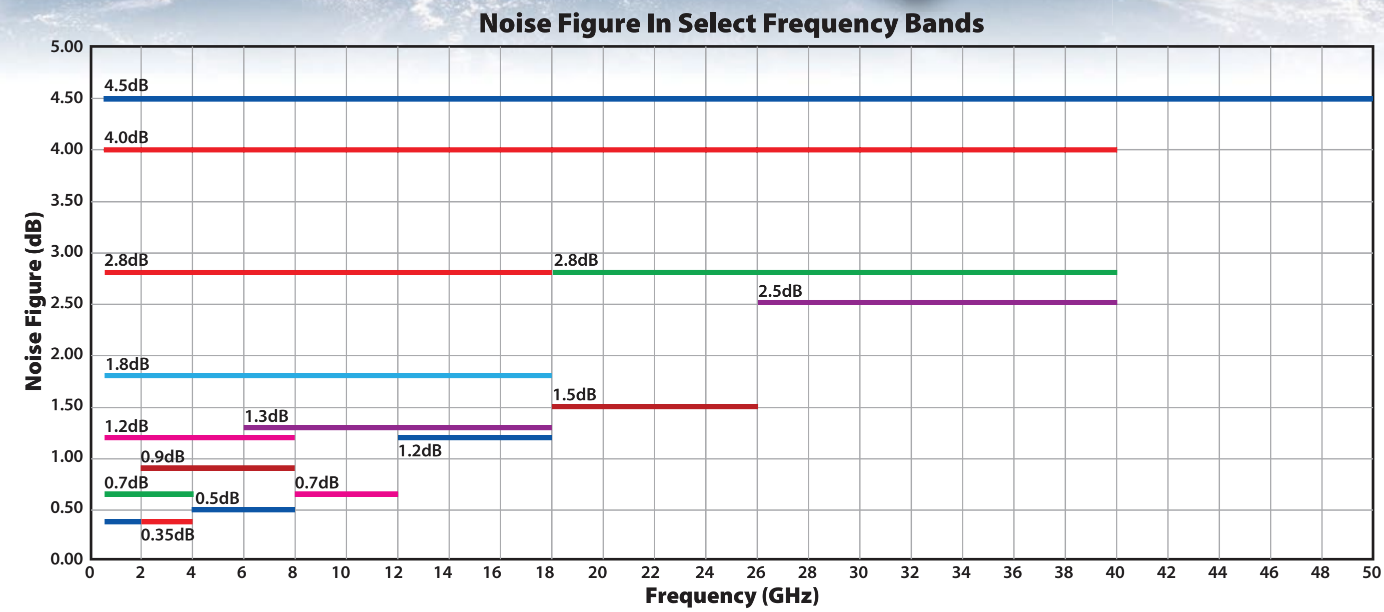
Noise Figure In Select Frequency Bands
Noise Figure (dB)
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4.0dB
2.8dB
2.8dB
2.5dB
1.8dB
1.5dB
1.3dB
1.2dB
1.2dB
0.9dB
0.7dB
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0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50

to 6 GHz. These capacitive switches have capacitance ratios to 3.5, with the next generation of devices targeting a capacitance ratio of 5.

One of the main advantages of MEMS technology compared with solid-state technologies is the quality factor (Q). Some DTCs are currently implemented as SOI switches and off-chip capacitors. The ON state resistance of SOI switches is mainly determined by the channel resistance of the transistors (R_{on}). As the transistor channel length decreases, R_{on} decreases. While this increases the Q factor, it also reduces the breakdown voltage. This means stacking more SOI transistors to sustain the large peak voltage across the DTC, especially in aperture antenna applications. The series resistance of the transistor stack dominates the equivalent series resistance (ESR) of the SOI-based solution. There is a trade-off for SOI-based solutions among Q, power handling and area. The Nanusens switches have a Q of 190 at 1 GHz and 97 at 2 GHz, as shown in ***Figure 5***. This is despite being implemented on a 10 Ω.cm resistivity standard CMOS silicon substrate. This is because the MEMS are enclosed in a grounded Faraday cage that prevents the coupling of the electromagnetic (EM) field into the lossy substrate. The maximum peak voltage the MEMS switches can currently withstand is 65 V in the OFF state and 50 V in the ON state. The next generation of capacitive switches will target 80 V peak voltage by improving the electrode robustness without degrading Q or increasing the area for a given capacitance.

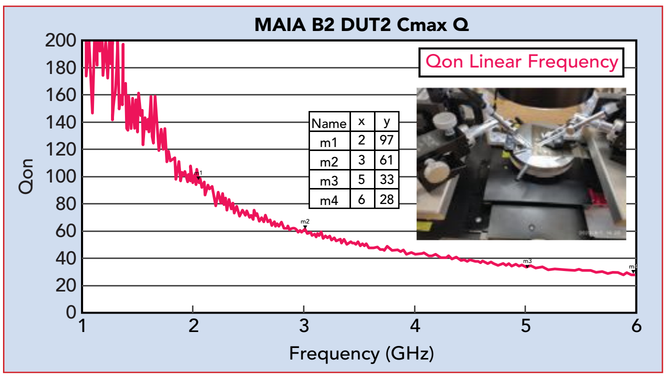

Fig. 5 Switch Q.

Nanusens capacitive switches have high linearity. Measuring intermodulation distortion with tones at 875 MHz and 915 MHz gives an IIP3 value of 85 dBm, equal to the IIP3 of the unconnected setup. This indicates the IIP3 of the devices is greater than 85 dBm. The second-order harmonic distortion is also better than the setup, which measures -118 dBc. This linearity is due to the mechanical nature of the RF MEMS devices and the absence of dielectrics and semiconductor materials. The RF MEMS switch mechanical resonant frequency, which acts like a lowpass filter, is well below the RFFE RF frequency. Nanusens switches are also robust in front of low-frequency intermodulation distortion (IMD) products that can fall inside the mechanical bandwidth of the MEMS for some digital modulation schemes.[1] This is because the switches are always in a well-defined position and held in place by large electrostatic forces. This prevents the device from responding to these signals within its mechanical bandwidth.

Current Nanusens RF MEMS capacitive switches have demonstrated that they can function up to 35 dBm without degradation. The in-house power handling setup is being improved to characterize the switches to 40 dBm.

Switching time depends on the stiffness and the actuation voltage of the switches. Depending on the application, the actuation voltage for Nanusens capacitive switches can be tailored to be from 5 to 100 V. Current variants with actuation voltages of 24 V have a switching time of less than 10 µs, which is sufficient for antenna tuning.

RF MEMS DTC

The RF MEMS capacitive switches can be arranged in an array to construct a DTC. ***Figure 6a*** shows the first prototype, which comprises an array of eight capacitive switches forming a four-bit DTC. ***Figure 6b*** details the capacitive switches used to implement the bits and their location in the DTC layout. Bit 1 comprises a single capacitive switch with one RF electrode. Bit 2 is also a single capacitive switch but contains two RF electrodes, doubling the capacitance. Bit 3 comprises two capacitive switches of the same type as Bit 2, while Bit 4 is implemented with four capacitive switches.

The dimensions of the DTC MEMS area are 360 µm × 400 µm for a maximum capacitance of 1.97 pF. The pad in the center part of the four-bit DTC shown in Figure 6a is the RF input signal with ground pads on either side for a shunt connection of the DTC. This cre-

ates a ground-signal-ground configuration with a 500 µm pitch. This prototype does not yet include the control electronics, so the capacitive switch control voltages must be applied through the pads around the die perimeter to switch the different bits to their respective ON and OFF state positions.

DTC PERFORMANCE

The prototype has been characterized to 20 GHz by measuring S-parameters. The capacitance ratio and Q have been extracted from the S_{11} measurements. The device has a capacitance ratio of nearly 2.2, from 0.9 pF when all switches are OFF to 1.97 pF when all are ON. The self-resonant frequency for the ON state is close to 13 GHz, demonstrating that the switch can be used for sub-6 GHz bands. The extracted Q is 50 at 2 GHz for the maximum capacitance state. These results are shown in ***Figure 7***. The Q of the DTC prototype is less than the Q of the single capacitive switch. This is due to the routing parasitic resistance and requires optimization. FEM simulations with ANSYS-HFSS have shown that the routing resistance can be optimized to get a Q close to 100.

The DTC IMD has also been measured for the minimum (state 0) and the maximum (state 15) capacitance state using the same setup as for the capacitive switches. The DTC has shown an IIP3 better than 85 dBm for both states, corresponding to the unconnected IIP3 of the characterization setup. Furthermore, the second harmonic distortion of the 980 MHz fundamental tone has been measured at better than -118 dBc for both states at 40 V bias. This measured harmonic distortion corresponds to the unconnected characterization setup value.

The DTC prototype has been measured from -20°C to 100°C. It shows a 0.4 percent capacitance variation in the ON state and 0.1 percent in the OFF state. After device etch post-processing, the DTC shows a yield of over 85 percent.

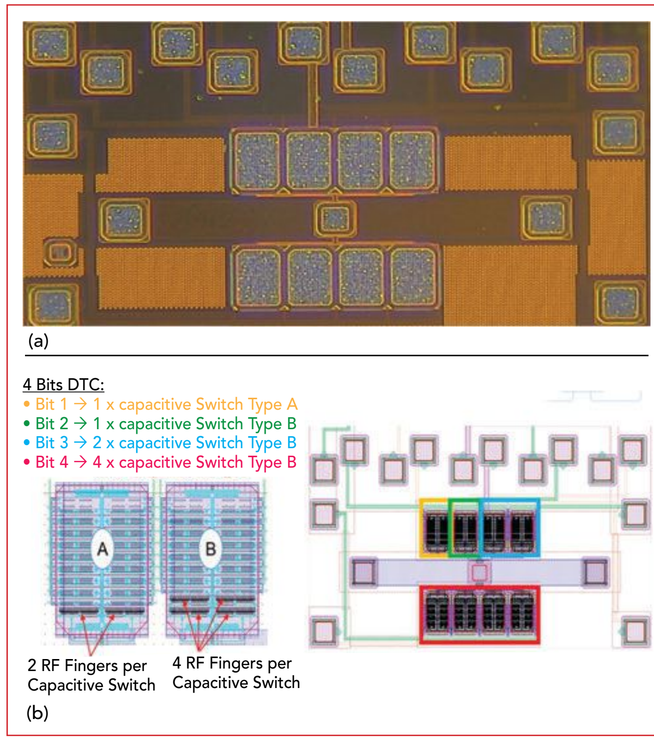

Fig. 6 **(a) Four-bit CMOS DTC prototype. (b) Capacitive switches used to implement the DTC.**

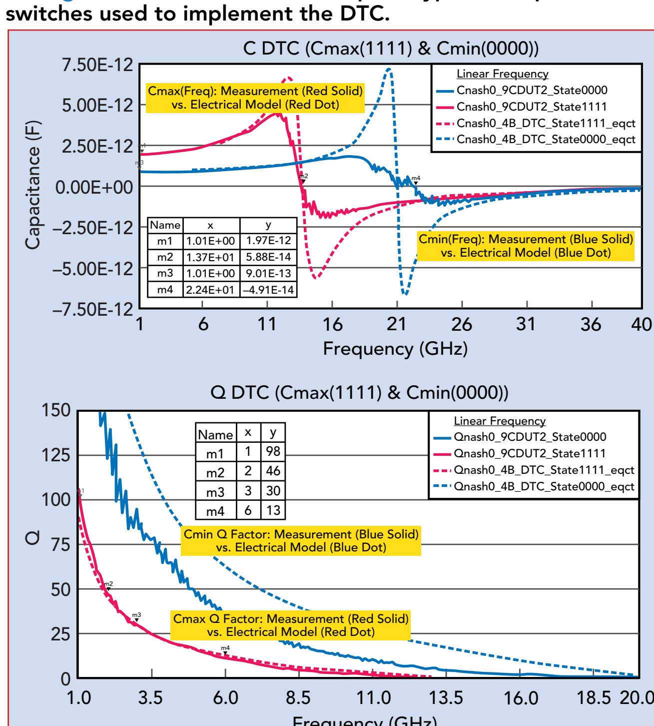

Fig. 7 **Measured and modeled capacitance and Q for 1111 and 0000 states.**

APERTURE ANTENNA SIMULATIONS

Currently, DTCs for aperture antenna tuning are implemented with SOI xPxT/SPxT switches that require two to four off-chip components. These off-chip components increase the bill of material, cost and board footprint area. The off-chip components also increase parasitics, which could lead to unwanted resonances and increase design complexity. These solutions are limited by available off-chip component values and the tolerances for small values can be quite large, limiting the DTC resolution. MEMS-inside-CMOS DTCs are a single-die solution that reduces the board footprint by up to 30 percent compared to current solutions. They also minimize PCB parasitics, reduce design complexity and enable resolution to a few femtofarads.

To demonstrate the RF MEMS-inside-CMOS DTC performance advantages versus current SOI-based solutions, a tunable dual-band aperture antenna, based on the planar inverted-F antenna (PIFA) of a smartphone, was modeled using ANSYS-HFSS. Two different DTCs have been attached to the antenna to address low band (LB) 690 to 960 MHz and low mid band (LMB) 1420 to 1520 MHz frequencies. Simulations were performed using RLC values extracted from models and measurements of the MEMS DTCs and SOI 4P4T switches. S-parameters of off-chip capacitors have been obtained from vendor websites and board trace parasitics were not considered for the SOI-based solution.

A DTC with a capacitance ratio of 4 covers LB, as shown in ***Figure 8a***. A capacitance ratio of 2 is enough to cover the LMB, as shown in ***Figure 8b***. ***Figure 8c*** shows the antenna efficiency for the lower LMB frequency range and ***Figure 8d*** for the upper LMB frequency range. The antenna efficiency plots show results for both solutions and without DTCs. Antenna efficiency is improved in the LMB upper and lower ranges by 17 percent and 30 percent, respectively, using the MEMS DTC versus the SOI solution. Results for the LB, not shown, have antenna efficiency improving by 10 percent for the upper and lower parts of the band. This exercise has been repeated for the high

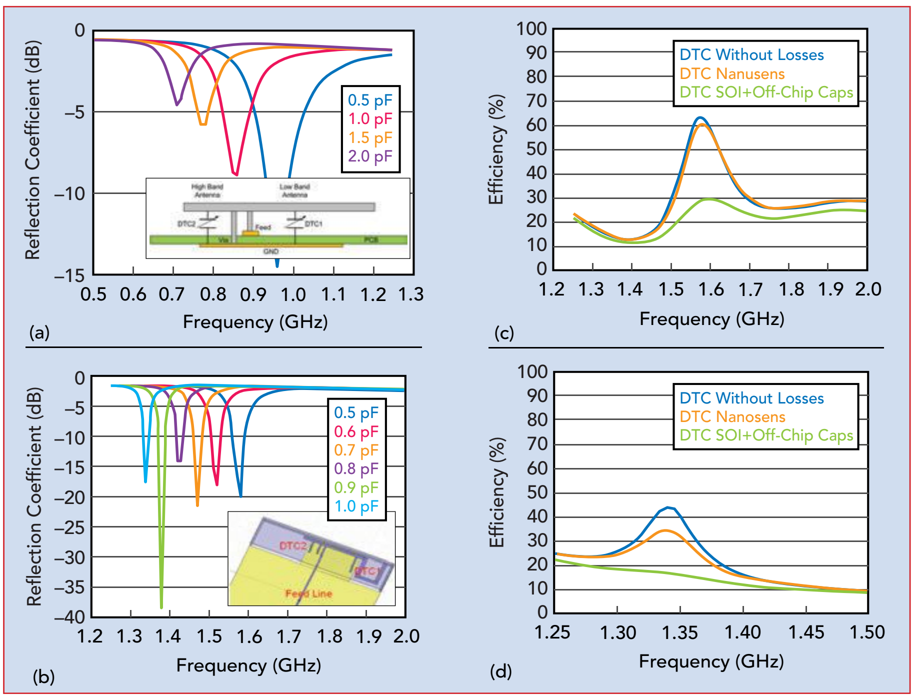

Fig. 8 (a) LB performance. (b) LMB performance. (c) Antenna efficiency for the low-frequency range of LMB. (d) Antenna efficiency for the high-frequency range of LMB.

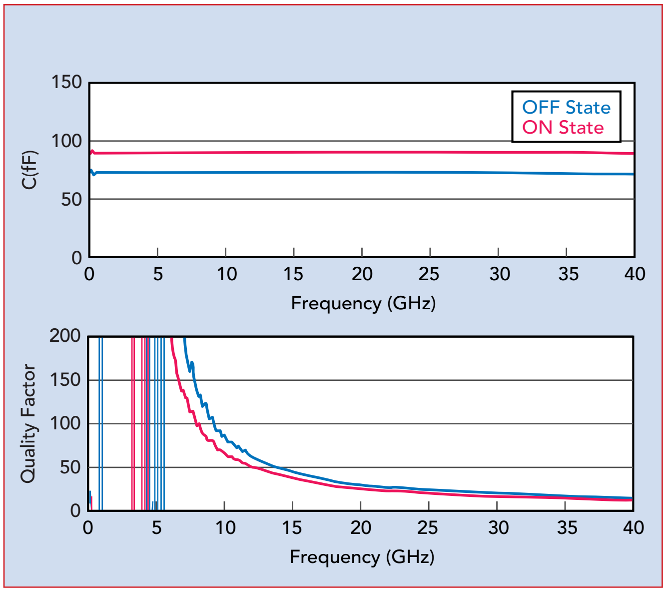

Fig. 9 Capacitive switch capacitance and Q for the ON and OFF states.

mid band (HMB) in the 1710 to 2200 MHz range. In this case, the antenna efficiency improvement resulting from the RF MEMS DTC is 15 percent for the lower part of the band and 25 percent for the upper part. The antenna efficiency improvement is mainly due to the higher Q of the RF MEMS DTCs compared to SOI-based solutions. Further improvement in antenna efficiency of RF MEMS-based solutions could also improve ACPR due to increased linearity, especially using the high voltages that can be present on the DTC in aperture antenna applications.

Nanusens has recently demonstrated that its metal-air-metal (MAM) RF MEMS capacitive switch achieves a very high Q factor up to 40 GHz with a capacitance ratio of 2.5. This performance is shown in ***Figure 9***. It should be noted that switch capacitance results are without de-embedding the pad capacitance estimated to be 60 fF and for frequencies less than 5 GHz, the resistance is close to zero.

CONCLUSION

Despite its superior performance, RF MEMS technology adoption in the RFFE market has been very slow compared to solid-state technologies. After many years of development, Nanusens has solved many challenges that have slowed adoption. Nanusens' RF MEMS-inside-CMOS technology permits mass production and maintains production costs well below those of other MEMS solutions. The costs of these solutions can be below those of SOI switches while offering improved performance.

Nanusens DTCs can be easily implemented in antenna tuners, aperture antennas and reconfigurable matching networks on smartphone RFFEs for better and faster voice and data transmission. The technology's advantages will also help reduce dropped calls and improve battery life by increasing antenna efficiency. The DTCs will be available as a 9-pin WLSCP with a 350 µm profile and expected dimensions of 1.5 mm x 1.5 mm.

The Nanusens RF MEMS-inside-CMOS DTC can be integrated with control electronics and ESD protection at the die level. This allows area and cost savings compared to system on chip and multi-component solutions. The DTC will be fully compatible with 2G/3G/4G/5G power handling and linearity requirements and it provides a MIPI RFFE interface for configuration and control. It enables a viable choice for future 6G solutions, especially in microwave bands. ■

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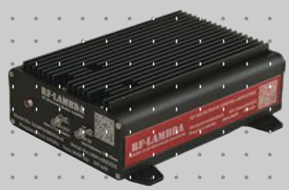

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INVITED PAPER

Direct-to-Device: Satellite's Breakout Second Act

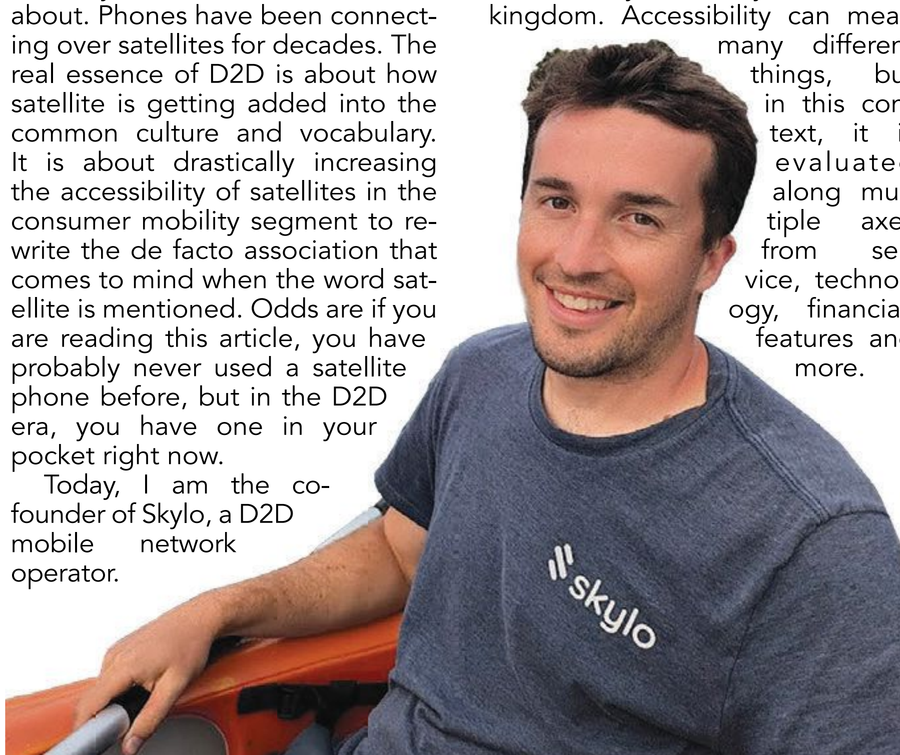
Andrew Nuttall
Skylo Technologies, Mountain View, Calif.

I grew up in the Upper Peninsula of Michigan. We lived in a remote part of the state and only received a few fuzzy TV news channels over the air when we pointed the big antenna on the roof of our house south, toward Wisconsin. This was certainly nothing to capture the attention of a young person. Then, one day, a Dish Network truck pulled up to our house and installed a satellite TV dish in the front yard and my siblings' and my collective minds were forever blown away by the cornucopia of different cartoons that were now suddenly at our disposal. For the next 30 years, when anyone mentioned satellite to me, my first thought was always that big two-foot-wide cartoon-delivering parabolic dish in our front yard. Satellite, to me, meant TV. A scan of the roofline of any residential neighborhood would suggest that this is a commonly held association.

As we enter the era of direct-to-device (D2D) communications, the word satellite is being injected into the common vocabulary again, but this time to mean not satellite TV, but the delivery of cellular connectivity over a satellite directly to the phone in your pocket. As an engineer, it is easy to get excited about the engineering challenges of connecting a phone over satellite, but candidly, that is not what D2D is about. Phones have been connecting over satellites for decades. The real essence of D2D is about how satellite is getting added into the common culture and vocabulary. It is about drastically increasing the accessibility of satellites in the consumer mobility segment to rewrite the de facto association that comes to mind when the word satellite is mentioned. Odds are if you are reading this article, you have probably never used a satellite phone before, but in the D2D era, you have one in your pocket right now.

Today, I am the co-founder of Skylo, a D2D mobile network operator.

Skylo delivers services over satellite to phones, watches, asset trackers and other cellular devices all over the world, guided by the principle of increasing accessibility. Accessibility is the key to the D2D kingdom. Accessibility can mean many different things, but in this context, it is evaluated along multiple axes from service, technology, financial, features and more.



Skylo works with partners in each domain to systematically remove barriers from access to satellite to create a world where every consumer and enterprise has access to hybrid (terrestrial + satellite) connectivity by default, where their device seamlessly roams onto satellite when terrestrial connectivity is unavailable.

The journey of ultimate accessibility starts with the hardware and devices. Historically speaking, if you wanted a satellite-enabled phone, you had to buy a specialized satellite phone. This was not the phone you already had, it was a new one, an extra step, a barrier. To eliminate that hurdle, Skylo has worked with major chipset manufacturers such as Qualcomm, MediaTek, Sony, Samsung LSI and others to enable and certify the cellular modems that go into your favorite devices for native support for Skylo and satellite. Now, the popular consumer phones already in your pocket, like the Google Pixel 9, come natively equipped for satellite, with no extra motions. Eliminating the need for special hardware is just the first step.

The incumbent mobile network operators bring cellular network connectivity to the market today. To make satellite connectivity as accessible as possible, that should not change. Skylo partners with popular mobile network operators, such as Verizon, to enable them to provide hybrid connectivity services for their customers. Skylo integrates its network with the terrestrial networks to enable roaming in the exact same way that your phone may roam across different network operators as you travel. The result is a consumer experience where satellite is enabled without a consumer having to change their carrier, sign up for a new bill plan or get a new SIM. The second you leave cellular connectivity; your device automatically roams onto satellite. It just works.

A D2D service works with your existing phone, your existing service operator and most importantly, it works anywhere and everywhere. If you can see the sky, it works. Skylo is realizing that vision with operations across multiple satellite constellations today to deliver a global, best-in-class and robust D2D satellite service. Skylo currently has commercial deployments across North America, Europe, Australia, Asia and Central America, with upcoming deployments in South America and Africa. Skylo has the largest geographic footprint of any 3GPP cellular technology network operator, ensuring the highest degree of accessibility. Whether in the middle of the desert, on the top of a mountain, fishing 10 miles offshore or in downtown Chicago, Skylo has you covered.

An often-unsung hero of enabling this service is the RF spectrum over which this Skylo D2D service operates. Skylo, with its satellite partners, runs this service across the Mobile Satellite Service (MSS) spectrum. This special spectrum is specifically allocated for satellite use and is globally harmonized across borders. This contrasts with other D2D approaches that reuse the cellular operator's terrestrial spectrum. Using the MSS spectrum as the backbone for service delivery ensures the service remains affordable and global.

As the world continues to shrink, offering strong and compelling wireless services to people and devices as they travel is becoming increasingly important. Personally, traveling internationally can be a stressful experience and the last thing you want is to have your primary mode of communication severed by the act of traveling. Service delivery over the MSS spectrum ensures that whether you are in the U.S. or on the other side of the planet, you can have access to the same services. There are no country-by-country regulatory battles required to enable D2D, as we see playing out at the FCC in the U.S. now. An existing framework exists for the rapid globalization of D2D services over the MSS spectrum.

Network connectivity over satellite, using the same device you already have, with the same service provider you already have and network access wherever you are on the planet has to have a catch. Is it expensive? Delivering this service over MSS spectrum, which does not compete with terrestrial MNO spectrum revenue requirements and by delivering it as an additional capability of your existing service plan, Skylo ensures that service is also extremely financially accessible.

Network connectivity is just a means to an end and what you do with that connectivity matters the most. Skylo's deep technological development expertise is the foundation for the rollout of key features and functions. Skylo has enabled core IP and non-IP data services, which are used for applications like asset tracking, pipeline monitoring, location sharing, financial transactions and many more. Skylo has enabled core communication services, like SMS, so that when you roam on satellite, you can send and receive SMS messages the same way you do now. Skylo has partnered with key ecosystem players, such as Google Android, to put all these features and others, like SOS services, directly at your fingertips.

This experience of bringing D2D services to market at Skylo has changed my perception of satellite. It is no longer just the big TV dish on the roof; it is about being able to communicate. All this work integrating satellites seamlessly into the cellular ecosystem is now blended into my broader view of Wi-Fi, cellular and network connectivity, in general. It no longer has that distinct parabolic shape in my mind; it has been absorbed by the ethereal construct of connectivity that we all have, which is kind of the point. Satellite does not have to be this special niche technology; it can always be with you and go everywhere.

Now satellite is just simply a farmer in Australia keeping track of cattle. It is texting your friend that you will be late for dinner because you decided to extend your hike. It is that call in the dead of winter when the snow and ice have brought down the power grid and you need emergency help now. It is peace and comfort knowing that whatever life throws at you, you will always be connected. The best part is that it is delivered directly into your pocket without you having to do anything; you can even take it for granted. ■

Anduril Collaborates with Microsoft to Bring Lattice to the U.S. Army's IVAS Program

Anduril Industries announced a new collaboration with Microsoft aimed at advancing the U.S. Army's Integrated Visual Augmentation System (IVAS) Program. This partnership includes initial integration of Anduril's Lattice platform into the IVAS ecosystem, leveraging Anduril's software and systems integration expertise to enhance the capabilities fielded to soldiers through IVAS.

Anduril successfully integrated Lattice into Microsoft's IVAS hardware and software platform, enabling soldiers to see real-time threats across the battlespace. This integration demonstrates the interoperability and extensibility of the Lattice software and IVAS platform. Soldiers wearing Lattice-enabled IVAS headsets are rapidly warned of incoming autonomously detected airborne threats, enhancing survivability in complex, contested environments. The integration of Anduril's systems, alongside third-party technologies, is set to propel the IVAS mission capabilities forward.

Palmer Luckey, founder of Anduril Industries and Oculus VR, is spearheading this strategic initiative for Anduril. Pairing Luckey's commercial expertise in VR/AR systems with Anduril's technology creates expansive additive value for the Army, soldiers and the IVAS program. "This project is my top priority at Anduril, and it has been for some time now. It is one of the Army's most critical programs being fielded in the near future, with the goal of getting the right data to the right people at the right time," said Luckey. "This is Anduril's bread and butter, and we have been building the backbone for this for years. I can't wait to show our customers what's next — I'm incredibly excited about what's to come."

IVAS (Source: Anduril Industries)

Robin Seiler, corporate vice president of mixed reality at Microsoft, added, "IVAS is more than the sum of its parts. Through integration across existing and new software and sensors, IVAS brings a full picture of the battlefield to every soldier, enabling safer and more effective operations. Our collaboration with Anduril to integrate their suite of critical sensors, along with their groundbreaking Lattice system into IVAS, demonstrates the transformative capability of this fighting goggle and will allow us to further expand the impact IVAS will have for every U.S. soldier."

IVAS is a platform designed to ingest data from a host of sensors, including those integrated on the headset, attached to weapon systems and via third-party devices and software, giving soldiers unprecedented visibility on the battlefield. With the integration of Anduril's Lattice system, soldiers will have a significantly enhanced capacity to detect, track and respond to threats in real time while rapidly expanding the mission capabilities available to soldiers around the world.

NGC Completes Hybrid Satcom Demo, Connecting to Commercial Space Internet

Northrop Grumman Corporation (NGC) successfully completed its first over-the-air demonstration of a hybrid satellite communications (satcom) solution, providing seamless connection with Viasat and a commercial proliferated low Earth orbit (PLEO) communications provider. The demonstration validated resilient, uninterrupted connectivity while rapidly switching between constellations and orbits.

- As a prime systems integrator, Northrop Grumman's hybrid satcom solution enhances communication for pilots and operators between space, air and ground.
- This capability increases mission effectiveness by making it exceedingly difficult for adversarial threats to disrupt U.S. communications across multiple orbits, providers and frequency bands.
- Demonstrated for the Air Force Research Laboratory, this technology is an integral part of the Defense Experimentation Using Commercial Space Internet program, also known as Global Lightning.

The Northrop Grumman hybrid satcom terminal is capable of hosting nine modems with network routing, security and encryption for mission networks. The terminal alternates among the modems if network failures occur to maintain resilient connectivity for the user.

The demonstration proved communications diversity with a connection to a commercial PLEO communications provider at Ku-Band frequencies in low Earth orbit and Viasat at Ka-Band frequencies through its Viasat-3 F1 satellite in geosynchronous orbit. The hybrid satcom terminal includes a Northrop Grumman radio outfitted with an antenna provided by GetSat.

Satcom Demo (Source: Northrop Grumman Corporation)

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On-the-Move Capabilities Demonstrated by Elbit America's MATR-X Radar in U.S. Navy Experiments

Smaller than a suitcase and mounted to a 55 ft. government vessel traveling at 15 knots, a specialized radar sped through the waters of Lake Huron in mid-July. Despite a barrage of inputs — information collected and processed on-the-move — the radar identified all potential threats in the environment, tracked them and could link the most appropriate countermeasure for a fictional interdiction.

The radar was Elbit System of America's (Elbit America) Multi-Mission AESA Tactical Radar — X-Band, or simply, MATR-X and it was put to the test during a recent series of experimental events in Alpena, Mich., called "Silent Swarm." Sponsored by the Office of the Under Secretary of Defense for Research and Engineering, Integrated Sensing and Cyber and led by the Naval Surface Warfare Center — Crane Division, Silent Swarm wrapped after two weeks, involving numerous capabilities and innovators. Silent Swarm is an experimentation event designed to drive advancements in electromagnetic warfare capabilities. It provided Elbit America the opportunity to test the MATR-X radar's utility in an operationally relevant environment. This event was also the first time that MATR-X was mounted aboard a ship and provided essential testing data for successful integration on future vessels.

MATR-X (Source: Elbit America)

Elbit America's MATR-X has a 360-degree field of regard and can track up to 10,000 targets simultaneously. The system is lightweight, easy to set-up and nearly inescapable when it comes to detecting threats. The system's active electronically scanned array radiates multiple beams of radio waves at various frequencies in every direction, picking up the signatures of people and non-biological threats such as unmanned aerial vehicles, uncrewed surface vessels and other vehicles. In the congested modern battlefield, MATR-X offers the sensing, tracking and targeting needed for users to see the big picture and respond accordingly.

With MATR-X's utility, size and minimal power requirements, applications for the radar abound. The system can be used to cut through the clutter of a congested battlefield, providing exceptional situational awareness to rapidly engage hostile threats, ideal for counter-unmanned systems applications.

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Cliff Drubin, Associate Technical Editor

Telecom Capex Down 10 Percent in 1H24

According to the September 2024 Telecom Capex report from Dell'Oro Group, telecom operators are now scaling back their investments in 5G and fixed broadband technologies. Preliminary findings show that the more challenging conditions that shaped the second half of 2023 extended into the first half of 2024. Worldwide telecom capex, the sum of wireless and wireline/other telecom carrier investments, declined 10 percent year-over-year in the first half of 2024, partly due to built-up inventory, weaker demand in China, India and the U.S., challenging 5G comparisons, excess capacity and elevated uncertainty.

"The high-level message is clear. The flattish revenue trajectory and the difficulties with monetizing new technologies and opportunities are impacting the risk appetite and willingness to raise the capital intensity levels for extended periods," said Stefan Pongratz, vice president for RAN and telecom capex research at Dell'Oro Group.

The telecom capex report provides in-depth coverage of around 50 telecom operators, highlighting carrier revenue, capital expenditure and capital intensity trends. The report provides actual and three-year forecast details by carrier, by region by country (U.S., Canada, China, India, Japan and South Korea) and by technology (wireless/wireline).

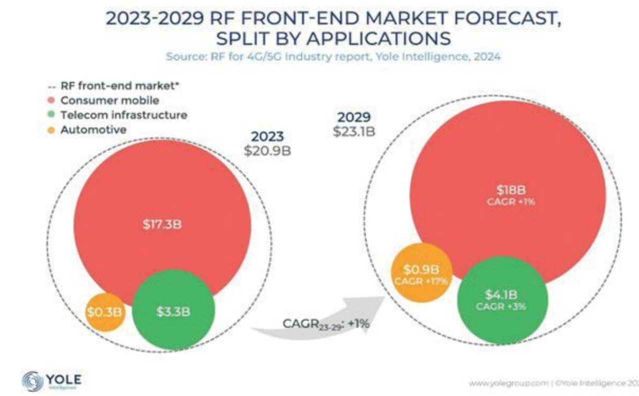
Additional highlights from the September 2024 Telecom Capex report include:

- Global carrier revenues are expected to increase at a 1 percent CAGR over the next three years
- Worldwide telecom capex is projected to decline at a mid-single-digit rate in 2024 and at a negative 2 percent CAGR by 2026
- The mix between wireless and wireline remains largely unchanged, reflecting challenging times still ahead for wireless. Wireless-related capex will decline at a 3 percent CAGR by 2026
- Capital intensity ratios are modeled to approach 15 percent by 2026, down from 17 percent in 2023.

RF Front-End Technologies Driving Innovation in the Automotive Industry

The US$21 billion RF front-end (RFFE) industry, initially driven by mobile and infrastructure, is now evolving to embrace growth in the automotive market. Each segment within the industry presents unique dynamics and growth opportunities.

After a difficult 2022, the smartphone market is showing signs of recovery, with expected year-over-year growth of 4 percent, projected to reach 1.2 billion units by 2024. The mobile RFFE market is predicted to hit US$18 billion by the end of 2024, though it may face stagnation due to market saturation and pricing pressures.



Front-End Market Forecast (Source: Yole Group)

In parallel, despite a recent deceleration, the telecom infrastructure market is projected to recover by 2026, with the RFFE market expected to reach US$4 billion by 2029, spurred by the adoption of massive MIMO technology and radio unit enhancements. Additionally, the small cell market, bolstered by private networks, has contributed approximately US$300 million in RFFE content in 2023.

In this regard, Yole Group released its report: RF for 4G/5G Industry 2024, which analyzes the latest and emerging RFFE technologies for 4G and 5G while also assessing the semiconductor advancements driving performance. It provides a comprehensive market overview, examining demand and growth forecasts across verticals like smartphones, telecom infrastructure and automotive. Additionally, the report evaluates market dynamics, competitive landscape and key technological trends such as carrier aggregation and massive MIMO, offering insights into region-specific factors and opportunities for RFFE development.

The RFFE ecosystem is a vital and evolving part of the telecommunications industry, providing the essential devices and technologies for various wireless communication systems. The supply chain spans a broad range of devices and technologies and is following the growing trend of miniaturization and integration into multifunctional modules to reduce space and costs in mobile and infrastructure systems. The RF component market for 4G/5G is highly fragmented, resulting in a complex technological landscape made more intricate by the number of players involved. The industry's latest technological shift, spurred by 5G, has begun to consolidate the fragmented market around a few major players.

The ecosystem is led by a small number of key companies, including Qualcomm, Broadcom, Skyworks, Qorvo, Murata and NXP, alongside newer companies like Maxscend, Vanchip and Smarter Micro, which recently emerged from the dynamic Chinese market. These eight companies account for over 80 percent of the RFFE devices targeting the 4G/5G economy, with a

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total value of $16 billion.

In this overall RF industry, Qualcomm primarily dominates the automotive segment. This company uses its end-to-end approach to provide complete RF bundles, from modem to RFFE, to its clients. Qualcomm also holds a significant share in the fixed wireless access CPE market. Meanwhile, Qorvo and Skyworks are expanding into the infrastructure and automotive markets. These emerging sectors are particularly profitable, although the volume of end systems remains relatively small.

5G Americas Studies 6G Vision Outlined by ITU Framework

The strategic vision for developing 6G mobile telecommunications systems is outlined by the International Telecommunication Union (ITU) IMT-2030 Framework, which sets the foundation for innovation, performance standards and global cooperation. 5G Americas recently published the white paper, "ITU's IMT 2030 Vision: Navigating Towards 6G in the Americas," which studies the ITU IMT-2030 vision and its implications for the Americas.

The ITU IMT-2030 vision framework emphasizes enhanced capabilities and new usage scenarios that extend the boundaries of current 5G technologies, providing a blueprint for the future of global mobile communication. These advancements aim to expand connectivity, integrate artificial intelligence (AI) and support emerging technologies such as integrated sensing and communications, among other technologies.

"ITU's IMT 2030 Vision: Navigating Towards 6G in the Americas" covers the following key highlights:

- Enhanced Performance: significant improvements in data rates, latency and reliability, focusing on delivering high speed, ultra-reliable low latency communications for industries and consumers alike.
- New Usage Scenarios: advanced use cases, including immersive multimedia, smart industrial applications, digital twin, ubiquitous connectivity and the integration of AI to create intelligent, self-learning systems.
- Global Harmonization: emphasis on alignment of global standards, spectrum policies and regulatory frameworks to ensure interoperability and a unified approach to 6G development.
- Strategic 6G Initiatives: U.S. and other American governments have initiated several research and policy activities to drive 6G innovation.
- Sustainability and Security: promotion of energy-efficient technologies and robust security measures to safeguard data integrity, privacy and national security.

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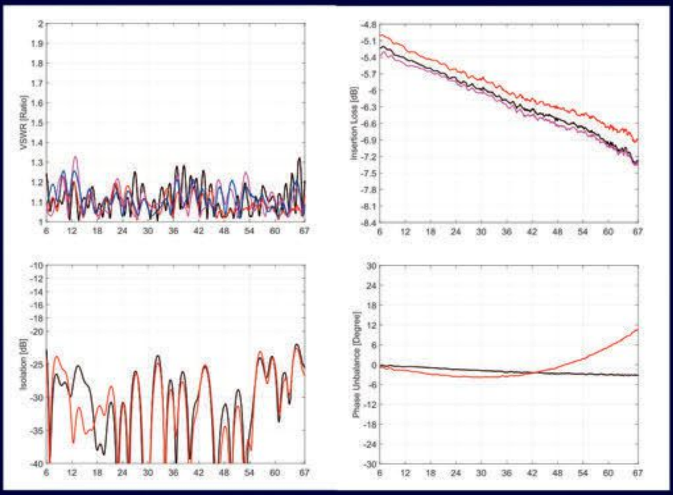
Distri. VSWR	1.9:1(Max.)
Insertion Loss*	3.1 dB(Max.)
Amplitude Unbal.	±1 dB(Max.)
Phase Unbal.	±13 Deg.(Max.)
Isolation	16 dB(Min.)
Dimension	38.1×43.2×12.7(mm)

* Above Theoretical Loss 4.8dB

Test Curve
(P03N060670)



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Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

BAE Systems has acquired **Kirintec**, an innovative U.K. cyber and electromagnetic activities (CEMA) company, which specializes in counter-improvised explosive devices, counter-uncrewed air systems and electronic warfare products and solutions. Kirintec's battle-proven technology protects military platforms and personnel from cyber and electromagnetic attacks. The open architecture of the products enables them to work together across all domains and a range of military platforms. The acquisition brings together complementary capabilities in CEMA and multi-domain integration will enable BAE Systems to support growing customer requirements and address increasing demand for these capabilities.

Synopsys Inc. announced it has entered into a definitive agreement for the sale of its **Optical Solutions Group** (OSG) to **Keysight Technologies Inc.**, a leading provider of design, emulation and test solutions. The transaction is subject to customary closing conditions, including review by regulatory authorities, and the closing of Synopsys' proposed acquisition of Ansys, which is pending regulatory approvals and expected to close in the first half of 2025. The sale of OSG was determined to be a necessary step towards obtaining regulatory approval of and successfully closing Synopsys' proposed acquisition of Ansys.

Honeywell announced the completion of its acquisition of **CAES Systems Holdings LLC** from private equity firm Advent International for approximately $1.9 billion in an all-cash transaction. The acquisition enhances Honeywell's defense technology solutions across land, sea, air and space and is also expected to create favorable tailwinds for growth across Honeywell's Aerospace Technologies business. CAES expands Honeywell's current defense and space portfolio with scalable offerings that enable Honeywell to both increase production and upgrade positions on critical platforms that include F-35, EA-18G, AMRAAM and GMLRS. Honeywell will also benefit from the ability to introduce its existing offerings on new platforms, such as the Navy Radar (SPY-6), unmanned aerial system (UAS) and counter-UAS technologies.

COLLABORATIONS

Rohde & Schwarz has been a strategic partner of **fiveD** since the end of July. The Radar Simulation Suite created by fiveD takes radar simulations to the next level, closing the gap between reality and virtual worlds. This expertise will help Rohde & Schwarz to further expand its market leadership in the field of contactless security checks. As a future-oriented company, Rohde & Schwarz collaborates with many national and international universities. The group has a particularly long-standing and successful collaborative partnership with the Friedrich-Alexander-Universität Erlangen–Nürnberg and its Institute of Microwaves and Photonics (LHFT), where the founders of fiveD worked as doctoral candidates.

Siemens Digital Industries Software announced that **GlobalFoundries** (GF) has certified Siemens' industry leading Analog FastSPICE (AFS) platform for GF's 22FDX®, 22FDX+, 12LP and 12LP+ Process Design Kits. With these certifications, mutual customers using Siemens' AFS tool can now leverage the exceptional performance and power efficiency of these GF processes. AFS is a key part of Siemens' Solido™ Simulation Suite software. It provides leading-edge circuit verification for nanometer analog, RF, mixed-signal, memory and custom digital circuits. This proven Siemens EDA solution provides a unified platform for the broader integrated circuit (IC) design industry to develop mixed-signal and variation-aware verification capabilities with SPICE accuracy, high performance, high capacity and ease of use.

ACHIEVEMENTS

The **FCC** took a significant step to promote competition in the wireless market by granting **EchoStar's** 5G network buildout framework. The updated framework enables EchoStar to optimize and enhance its coast-to-coast buildout of the world's first cloud-native Open RAN 5G Boost Mobile Network, while more efficiently deploying the network in new areas of the country. The pricing and innovation improvements from EchoStar's continued presence in the wireless market is a win for all American consumers. EchoStar has already achieved deploying a next-generation cloud-native Open RAN network that supports 21st century innovations, including artificial intelligence and the many more advancements yet to come.

Reticulate Micro Inc. announced it successfully demonstrated what the company believes to be the first-ever real-time video streaming over the mobile user objective system (MUOS) tactical satellite network for a U.S. Special Operations organization. The joint U.S. Army live training exercise included Reticulate and its partners, **NanTenna LLC** and **Curtiss-Wright**. The teams integrated Reticulate Micro's VAST video encoder and Curtiss-Wright Defense Solutions' PacStar® Modular Radio Center to deliver live video for the first time over unbonded but Type 1 encrypted MUOS narrowband channels.

Sivers Semiconductors announced receiving first-year funding of $6 million from the **Northeast Microelectronics Coalition Hub** through U.S. CHIPS and Science Act under the Microelectronics Commons Program, executed through the Naval Surface Warfare Center Crane Division and the National Security Technology Accelerator. The award funds collaboration between Sivers Semiconductors and partners **Ericsson**, **Ray-**

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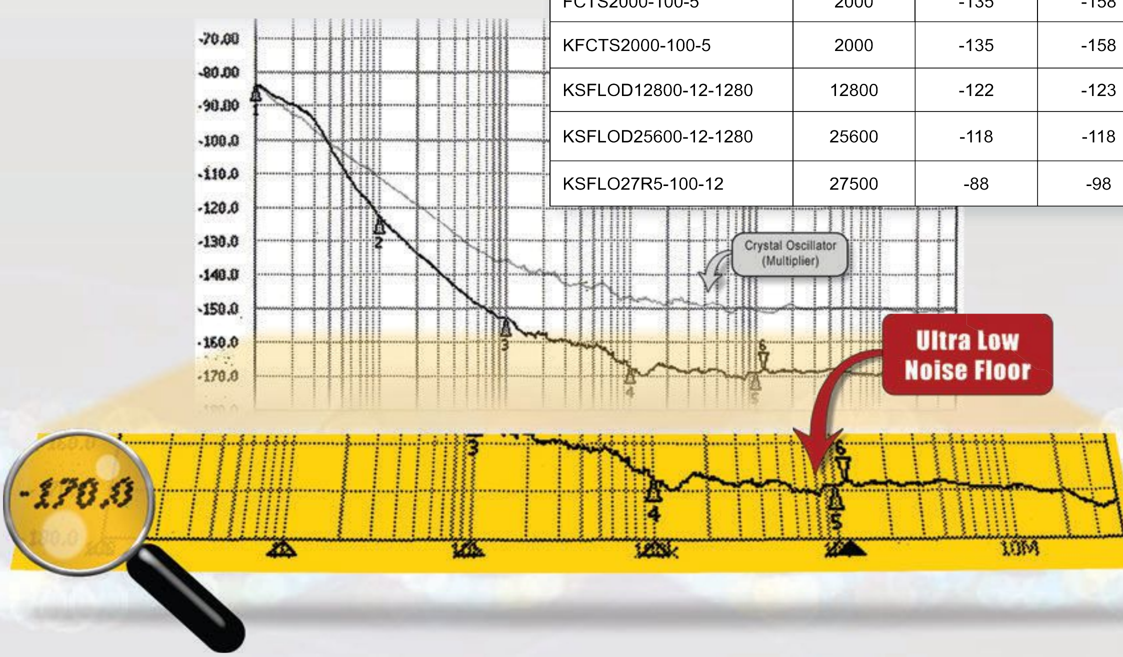
VFCTS120-10	120	-156	-165	
VFCTS125-10	125	-156	-165	
VFCTS128-10	128	-155	-160	
FCTS800-10-5	800	-144	-158	
FCTS1000-10-5	1000	-141	-158	
FCTS1000-100-5	1000	-141	-158	
FSA1000-100	1000	-145	-160	
FXLNS-1000	1000	-149	-154	
KFCTS1000-10-5	1000	-141	-158	
KFCTS1000-100-5	1000	-141	-158	
KFSA1000-100	1000	-145	-160	
KFXLNS-1000	1000	-149	-154	
FCTS2000-10-5	2000	-135	-158	
FCTS2000-100-5	2000	-135	-158	
KFCTS2000-100-5	2000	-135	-158	
KSFLOD12800-12-1280	12800	-122	-123	
KSFLOD25600-12-1280	25600	-118	-118	
KSFLO27R5-100-12	27500	-88	-98	



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theon, **MIT**, **Boston University** and **Northeastern University** to accelerate domestic prototyping and expand the nation's global leadership in microelectronics. This is one of six projects awarded to the NEMC Hub, led by Massachusetts Technology Collaborative, under the Microelectronics Commons Program.

CONTRACTS

L3Harris Technologies has received an indefinite delivery, indefinite quantity contract worth up to $182 million from the **U.S. Air Force** to deliver advanced situational awareness capabilities. Partnering with the Air Force Life Cycle Management Center, this contract will enable L3Harris to provide economies of scale for the U.S. Department of Defense and allied nations when procuring critical video data link technology, including the ROVER® 6S and Tactical Network ROVER® 2 wideband ISR handheld transceivers. Designed for air, surface and maritime use, the ROVER 6S provides real-time, full-motion video and other data for situational awareness, surveillance, convey overwatch operations and other situations where eyes-on-target are required.

Infineon Technologies AG and its technology partner **Oxford Ionics Ltd.** have been selected to build a mobile quantum computer as one of three consortia by **Agentur für Innovation in der Cybersicherheit GmbH**, "Innovation for Cybersecurity" (Cyberagentur). The Cyberagentur, supported by the German Federal Ministries of the Interior and Defence, aims to obtain three functioning mobile quantum computers within three years, of which one system will be selected for further development for practical use. It is investing a total of 35 million euros in the research and development project. The competition is intended to help strengthen the technological sovereignty of Germany and Europe in the field of quantum technologies.

Epirus announced the introduction of Leonidas Expeditionary, developed as part of a $5.5 million contract award from the **U.S. Navy's Office of Naval Research (ONR)**. The high-power microwave system, with the program name: Expeditionary Directed Energy Counter-Swarm (ExDECS) is being developed by ONR, Marine Corps Warfighting Lab and the Joint Counter-small Unmanned Aircraft Systems Office. The program's future will involve initial integration with the U.S. Marine Corps' (USMC's) Common Aviation Command and Control System, along with field experimentation and multi-platform testing in expeditionary scenarios to enhance USMC's ground-based air defense capabilities. Epirus developed ExDECS, a solid-state, software-defined, long-pulse high power microwave system to support USMC's Expeditionary Advanced Base Operations and counter-unmanned systems missions.

Raytheon, an RTX business, has been awarded a three-year, two-phase contract from **DARPA** to develop foundational ultra-wide bandgap semiconductors (UWBGS). Based on diamond and aluminum nitride technology, UWBGS will revolutionize semiconductor electronics with increased power delivery and thermal management in sensors and other electronic applications. During phase one of the contract, the Raytheon Advanced Technology team will develop diamond and aluminum nitride semiconductor films and their integration onto electronic devices. Phase two will focus on optimizing and maturing the diamond and aluminum nitride technology onto larger diameter wafers for sensor applications.

The Norwegian Defence Materiel Agency exercised a contract option to procure three additional TPY-4 radars from **Lockheed Martin** (LM), bringing the new total to 11 of the ground-based multi-mission radars. The TPY-4, which has been coined "NATO's eyes in the north," also recently completed the Critical Design Review confirming the radar design is meeting the program requirements. The relationship with Norwegian industry has been a critical element to the development of TPY-4. LM leveraged an extensive Norwegian supplier base making this program and other active international opportunities for TPY-4 a true U.S./Norwegian industry partnership.

ICEYE, the global leader in synthetic aperture radar (SAR) satellite operations for earth observation, persistent monitoring and natural catastrophe solutions, has announced signing the contract for the Greek National Satellite Space Project Axis 1.2 (radar program) for the **Greek Space Agency** and **Greek Ministry of Digital Governance**, together with the **European Space Agency**. Axis 1.2 covers the Greek SAR Space Segment and includes both radar imagery and the development of a greek observation System with two ICEYE SAR satellites and their launches. In addition to sovereign satellites, Greece will also have access to ICEYE's existing SAR satellite constellation, the largest in the world, and can start monitoring its areas of interest already while building its space capabilities.

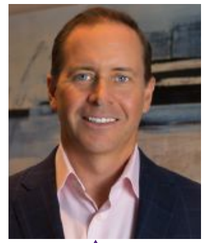
PEOPLE

Fractal Antenna Systems announced that its CEO and founder, **Nathan Cohen**, will be honored with the first Arno Penzias Award by the Radio Club of America in recognition of his groundbreaking basic science contributions to the field of radio science. This prestigious award is named after Nobel Laureate Arno Penzias, whose discovery of cosmic microwave background radiation revolutionized our understanding of the universe. Cohen, a visionary in fractal antenna technology and metamaterials, is known for reshaping modern science with innovations that have had far-reaching impacts across defense, aerospace, telecommunications and more.

▲ *Nathan Cohen*

TagoreTech Inc., a pioneer of high-power GaN-based RF switches and front-end solutions, announced the appointment of **Paul Hart** as chief executive officer. Hart will succeed Chae Lee, who will be leaving the

Around the **Circuit**


▲ *Paul Hart*

company following the successful sale of its Power GaN-on-Si business to GlobalFoundries. Hart brings more than 25 years of experience to TagoreTech. Before joining TagoreTech, Hart was executive vice president and general manager of the Radio Power Business at NXP Semiconductor. In this role, Hart was responsible for establishing NXP's leadership position in 5G and identifying new market opportunities to drive growth with best-in-class technologies, product offerings, and system solutions spanning the entire range of 5G frequencies.


▲ *Keith Barclay*

Stellant Systems Inc. announced the appointment of **Keith Barclay** as its chief executive officer and to the board of directors. With more than 30 years of experience in the aerospace and defense, medical, industrial and optical networking industries, Barclay brings both executive leadership and extensive entrepreneurial experience to Stellant, positioning the company for accelerated growth and success. Prior to joining Stellant, Barclay led the development, expansion and significant growth of Hermetic Solutions Group, Inc. in his roles as executive vice president of sales and business development and, most recently, president and CEO.

REP APPOINTMENTS

ANYFIELDS announced a new partnership for distribution in France with **MATECH**, a top distributor in microwave and optoelectronic components. This collaboration significantly expands ANYFIELDS' reach and services. MATECH has 40 years' experience in the design, manufacture and distribution of RF, microwave and optoelectronic components and systems. MATECH offers an exclusive French and international selection of partners and suppliers for the highest performance and reliability.

Richardson Electronics Ltd., a global leader in engineered solutions, announced a global distribution agreement with **Quantic® Electronics**, a portfolio company of Arcline Investment Management. This strategic partnership encompasses Quantic's premier U.S.-based capacitor businesses: Quantic™ Evans, Quantic™ Eulex, Quantic™ Paktron and Quantic™ UTC. This collaboration brings together Richardson's unparalleled distribution network and Quantic's state-of-the-art capacitor technologies, significantly expanding access to mission-critical capacitors for defense, aerospace, space, communications and industrial applications worldwide. This diverse portfolio empowers designers to push the boundaries of electronic performance across critical sectors, from next-generation defense systems to cutting-edge space exploration and counter-UAS technologies.

INVITED PAPER

RF GaN-on-Si Technology Powers the Future of Wireless

Johannes Schulze and Peter Singerl
Infineon, Neubiberg, Germany

Mobile data traffic continues to grow. Constant video streaming is on the rise in applications like TikTok, Netflix and Instagram, but also increasingly LinkedIn and even simple websites. Ericsson estimates that mobile data traffic, excluding fixed wireless access, is going to increase by a factor of 3x by 2029.[1]

While mobile traffic is expected to increase by multiples, revenues at mobile network operators are expected to stay flat. This is because the so-called "killer app" for 5G that helps to monetize new capabilities has not been found yet. This means customers continue paying the same for their 5G contract as they did for 4G.

This challenges network operators and radio manufacturers to manage a much higher data capability at the same total cost, which calls for a significant reduction in the cost per bit. This can be achieved by optimizing a multitude of levers. Combining frequency bands in one radio unit and employing wider frequency bands will reduce the number of required radios. Reducing the size and weight of radios will lower tower rental costs and reducing the consumed energy per radio will lower operators' energy bills. Higher frequency bands need to be utilized, especially in high-density urban areas. To do this in a cost-efficient way, the grid of the radio base station ought not to be changed.[2] This results in radios operating at 6 to 10 GHz, covering the same area as those operating at half that frequency. Finally, the cost of radio components is under pressure to lower initial capital expenditures.

Breaking these requirements down for 5G radios, the RF PAs need to support higher frequencies, significantly wider instantaneous bandwidths and high efficiency over a wide back-off range. These radios must also be capable of being linearized at levels below -50 dBc with digital predistortion (DPD). The semiconductor technologies capable of delivering those targets at a commercially viable price position are RF GaN-on-SiC and RF GaN-on-Si.

RF GAN-ON-SIC

Since the late 2010s, when the first 5G radios came on the market, GaN-on-SiC has increasingly been the semiconductor technology of choice for RF power amplifiers (PAs), increasing its market share to 51 percent of the current telecom market.[3] First used for military and space applications where performance is the key driver, GaN-on-SiC has delivered the gain, power density and high transit frequency needed to power radar and communications from S-Band to Ka-Band. Wide telecommunications adoption has increased demand and volume. Many wafer fabs updated from 3 in. to 4 in. and, in some cases, 6 in. wafer manufacturing, driving down the initially high product cost of GaN-on-SiC wafers to levels more palatable for commercial applications.

New transistor concepts, like a graded AlGaN channel, were recently shown to improve power-added efficiency (PAE) and the linearity of GaN-on-SiC transistors at mmWave frequencies.[4] A study[5] used a sunken field plate to achieve higher voltage capability and gain while improving PAE. A paper[6] introduced 0.25 µm RF GaN-on-SiC technology, reaching a maximum stable gain of 22 dB at 3.5 GHz and an f_T of 23 GHz. The authors of that paper presented a Doherty demonstrator with greater than 16 dB gain that reaches between 49 and 55 percent efficiency for a W-CDMA signal between 3.4 and 3.8 GHz.

While the performance of RF GaN-on-SiC technologies will continue to improve, it is unclear how product prices will be significantly reduced. This price reduction is necessary to pave the way for fully integrated MMIC PAs to enable the best performance and commercial viability for massive MIMO (mMIMO) radios at 6 GHz and beyond. To focus the radio beam and create the same coverage range as a 3.5 GHz radio may require more than 500 antenna elements and 128 Tx channels in a 7 GHz radio.[7] This means that the average PA price needs to come down.

RF GAN-ON-SI DEVICE-LEVEL PERFORMANCE

In November 2021, Infineon introduced its first generation of 28 V RF GaN-on-Si.[8] The technology is used in RF PAs for 5G mMIMO base transceiver stations (BTS) and operates reliably in the field. Infineon introduced the second generation three years later. This new process is a fully MMIC-capable, 28 V, 0.25 μm RF GaN-on-Si technology manufactured on 8 in. wafers in an Infineon silicon fab.

RF GaN-on-Si uses a less expensive silicon substrate that is easier to procure than SiC substrates. Using 8 in. wafers drives the per-area cost down even more. This lower cost is expected to enable integrated RF PA architectures for frequencies greater than 6 GHz at a commercially viable price. RF GaN-on-Si can be produced in a silicon fab and does not need the separate manufacturing line typically required for RF GaN-on-SiC processes. The manufacturing equipment can be shared with other processes, allowing a more dynamic volume scaling. This helps reduce the volume dependency of manufacturing costs, enabling a reliable and sustainable manufacturing process throughout the market cycle. Manufacturing in a silicon fab involves the same tight process controls applied to other silicon processes, resulting in high process stability and low tolerances.

Infineon's next-generation RF GaN-on-Si technology enables significant performance improvements, especially in gain. These improvements are made possible mainly by implementing a disruptive concept of advanced field-plate structures for the active devices. Compared to first-generation devices, this concept reduces parasitic feedback capacitances,

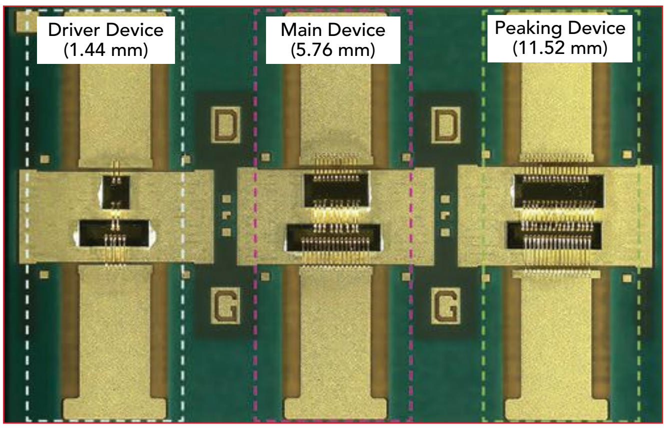


Fig. 1 GaN-on-Si test cell.

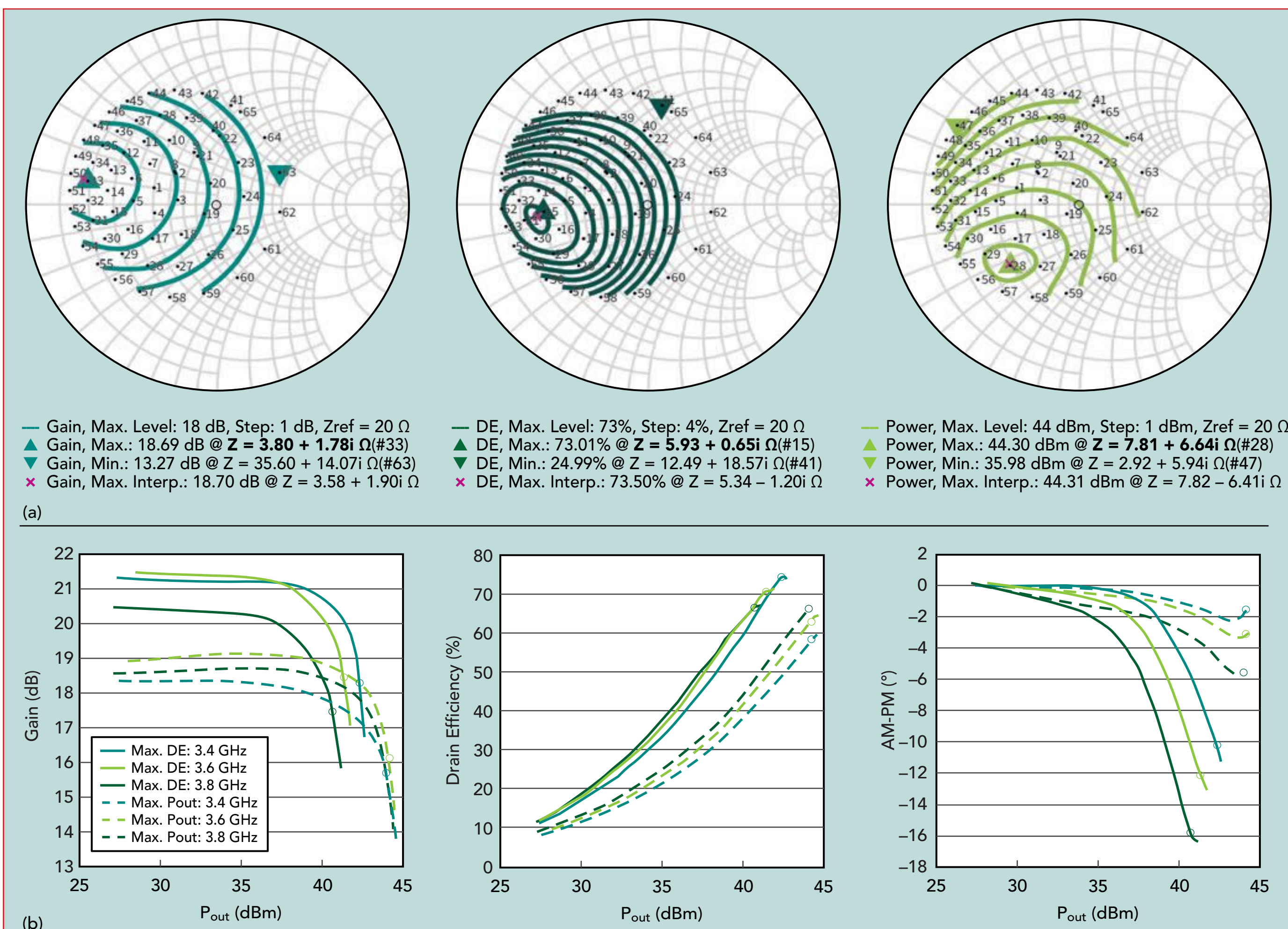


Fig. 2 (a) Load-pull contours at 3 dB gain compression for the main amplifier at 3.6 GHz. (b) Power sweeps for the 5.76 mm main PA device.

Miniature Thin Film Band Pass Filters

For 5G Technology

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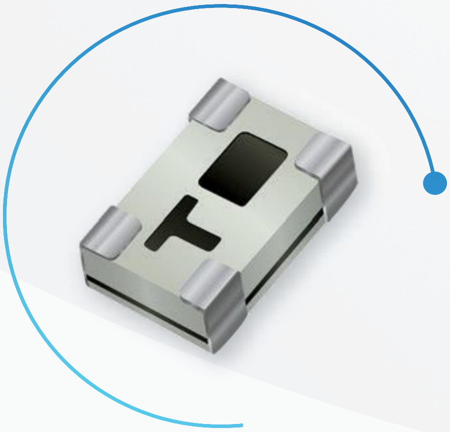
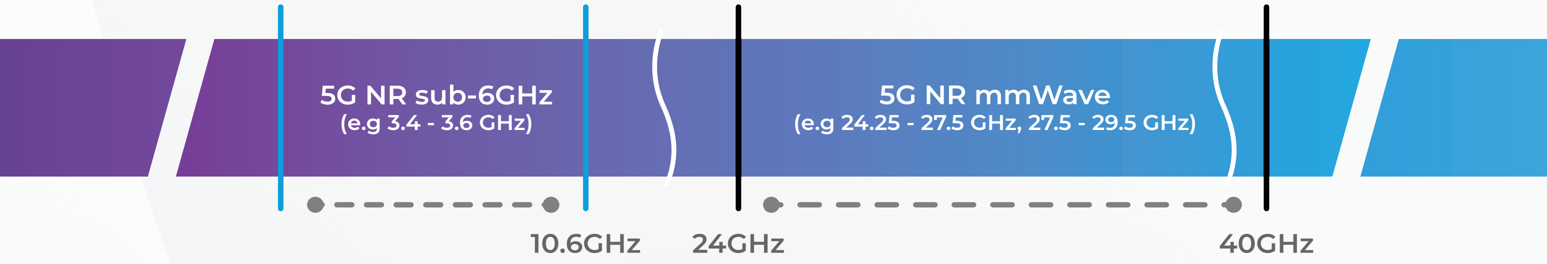


5G technology (3.1-10.6 GHz , 24 - 40 GHz) uses a very low energy level for short-range, high-bandwidth communications over a large portion of the radio spectrum.

Most recent applications target sensor data collection, precision locating and tracking applications and vehicle to everything communication.

During the coming years, the number of wireless sensor and communication systems will increase significantly, due to the expected low costs of these systems and their technical advantages.



KYOCERA AVX Thin Film Band Pass Filter Advantages

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- **Quick Adjustment of RF Parameters**
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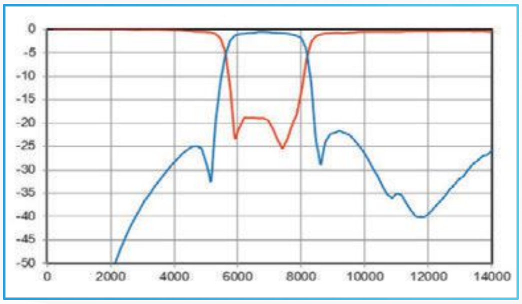
- **Short Lead Time: 8 - 16 Weeks ARO**



1206 Size, Central Frequency: 6.67 GHz
Passband: 1.55 GHz

Applications

Military | Base Stations | Test Equipment | Handheld Radios | Consumer | Active Antenna Systems | Automotive | Emergency Services

C_{dg}. These transistors show better stability, 3 to 4 dB higher gain, lower frequency dispersion and more "Doherty-friendly" behavior, which is important to fulfill bandwidth and efficiency requirements for next-generation BTS deployments.

Figure 1 shows a test cell that will demonstrate the new technology's device-level RF performance. The test cell contains different GaN-on-Si transistors with gate peripheries of 1.44 mm for a driver device, 5.76 mm for a main device and 11.52 mm for a peaking device. The gate pads of the transistors are wire-bonded to high Q metal-oxide-semiconductor capacitors (MOS caps) to provide low ohmic impedances for the second harmonics on the transistor input sides. The test cell is implemented on an 8 mm × 12 mm multi-layer laminate with identical dimensions, material and laminate layer stack-up to the one used for the Doherty PA module implementation described later. For this Doherty PA, only the main and peaking devices shown in Figure 1 are used; the driver device is prepared for future PA designs.

Figure 2a shows the measured Smith chart load-pull contours for the 5.76 mm main PA device in Figure 1, with the 20 Ω taper de-embedded at 3.6 GHz for 3 dB transducer gain compression, drain efficiency and P_{out}, with 20 Ω reference impedances. The triangular markers in the plots show the load impedances and the corresponding minimum and maximum performance values. The load-pull measurements were performed at 28 V drain voltage and a quiescent current of 115 mA (20 mA/mm gate periphery), which was chosen to ensure a flat gain in power back-off. This performance is summarized in ***Table 1***.

The solid curves of ***Figure 2b*** show the power sweeps for the $Z_{Lmax.DE}$ = (5.3 - j1.2) Ω maximum drain efficiency load. The dashed curves show the sweeps for $Z_{Lmax.Pout}$ = (7.8 - j6.4) Ω maximum output power load. These values have been optimized for 3.6 GHz, but the plots show 3.4, 3.6 and 3.8 GHz values.

Figure 3 depicts the load-pull measurement data in a "nose plot," which shows the drain efficiency versus P_{out} for all the applied load impedances in 3 dB gain compression at 3.6 GHz.

The performance of the driver and peaking devices of the test cells shown in Figure 1 is not explicitly shown in this article. However, it is close to the performance of the main device. The P_{out} performance scales according to the gate periphery of the device as compared to the 5.76 mm main transistor.

RF GAN-ON-SI DOHERTY PA MODULE

An 8 W (average) Doherty PA was designed with the main and peaking devices from the test cell shown in Figure 1 to operate over the 3.5 to 3.9 GHz frequency range. The PA, including an Infineon smart bias and control IC, was fabricated

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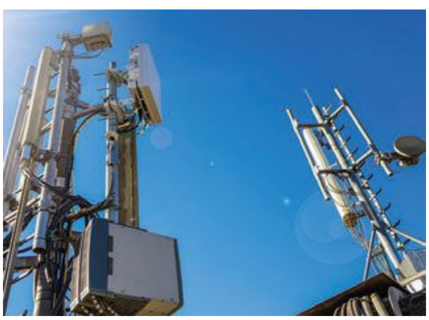
SKYFR-001982	Single-Junction Robust Lead Circulator	1.200 to 1.400
SKY16603-632LF	High Linearity Limiter Module	0.600 to 6.000



Cellular Infrastructure

For applications including 5G and 4G LTE systems, small cells, massive MIMO, active antenna arrays, micro and macro base stations.

Part Number	Description	Freq. Range (GHz)
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SKY67189-396LF	Ultra Broadband Low-Noise Amplifier	0.400 to 6.000
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SKY66318-11	High Efficiency Wideband 5G n78 Small Cell Amplifier	3.300 to 3.600

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SKY66430-11	5G Massive IoT System-in-Package	0.698 to 2.200
SKY66420/21/23	Sub-1 GHz RF FEMs for LoRa, SigFox, Wireless MBUS Applications	0.860 to 0.930

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SKY55501-11	5 GHz LNA with LAA Support Front-end Module	5.150 to 5.925
SKY55242-11	Dual 2.4 GHz, 802.11ax High-Linearity, High-Efficiency Sky5® Front-end Module	2.400 to 2.500

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to be the same 8 mm × 12 mm size with the same multi-layer laminate as the device test cell. This enables using measured load-pull data and device models in the design and subsequent PA tuning. The peripheries for the main and peaking devices were chosen with a 1:2 ratio for optimum efficiency and linearity performance for 5G NR signals with 7.5 dB PAPR at 39 dBm P_{out}. The device output matching for the fundamental and second harmonics and the power combining network is accomplished with transmission lines on the laminate and high-quality SMD caps. The RF input signal separation for the main and peaking devices is implemented with a lumped-element 3 dB Wilkinson splitter. A smart bias and control IC is integrated into the module to control the biasing and TDD switching of the Doherty PA. This module is programmable with a digital I2C interface during the production cycle. This PA module is shown in ***Figure 4***.

TABLE 1

ACTUAL VALUES FROM LOAD-PULL CONTOUR PLOTS IN FIG. 2A

	P_{out} (dBm)	Gain (dB)	Drain Efficiency (%)	Z_L (Ω)
At Max. P_{out}	44.3	16.2	64.1	7.8 - j6.4
At Max. Gain	39.1	18.7	67	3.6 + j1.9
At Max. Drain Efficiency	42.4	18.0	73	5.3 - j1.2

Figure 5a shows the gain performance, ***Figure 5b*** shows the drain efficiency and ***Figure 5c*** shows the measured AM-PM versus output power performance of the Doherty PA module shown in Figure 4. These results are measured with RF pulses having a pulse width of 200 µs and a duty cycle of 10 percent.

The gain of approximately 14.5 dB at 39 dBm average P_{out}, shown in Figure 5a, is close to the best values that have been published for GaN-on-SiC-based Doherty PAs with the drain voltage increased from 28 V to 50 V.[6] The efficiency shown in Figure 5b is more than 55 percent at 39 dBm output power over 400 MHz bandwidth. Secondary research shows this is the same level as the best GaN-on-SiC Doherty PAs.[6,9] The peak output power at 4 dB gain compression is greater than 47 dBm with a maximum AM-PM of 23 degrees, with about 6 degrees of phase variation over frequency at the average and peak power levels. The smooth gain and AM-PM behaviors shown in Figure 5a and Figure 5c are im-

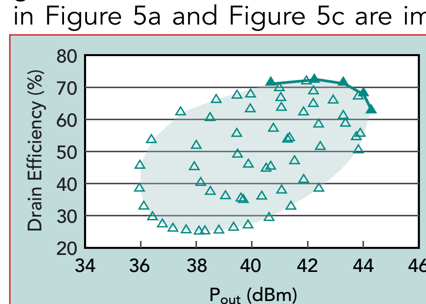

Fig. 3 "Nose-plot" load-pull measurement results for the main device.

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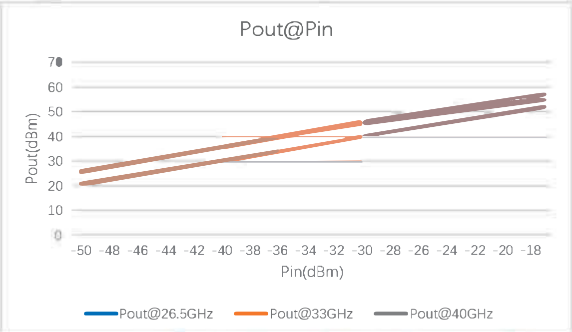

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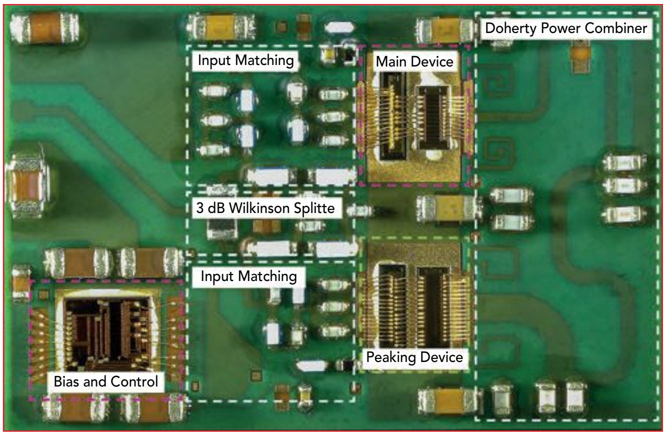


Fig. 4 Doherty PA module with Infineon GaN-on-Si devices and bias and control IC.

portant for efficient wideband DPD linearization.

Figure 6 shows the measured modulated PAE versus output power for a 5G NR FDD signal with 256-QAM modulation, 1 × 100 MHz signal bandwidth, a signal carrier spacing of 30 kHz and PAPR = 7.5 dB for three different carrier frequencies. The dashed lines depict the non-linearized PAE curves and the solid lines show linearized performance with the DPD. At the average P_{out} of 39 dBm, the PAE value is greater than 50 percent.

The linearization performance in the frequency domain is evaluated with the adjacent channel power ratio as ADJ_{max} = max [ADJ_{left}, ADJ_{right}]. The results are shown in ***Figure 7*** for different average power levels. At the 39 dBm Doherty PA average P_{out}, the linearized ADJ_{max} is less than -51 dBc for a 100 MHz 5G NR signal with a PAPR of 7.5 dB. To assess the linearized performance in the time domain, the maximum symbol EVM versus output power must be considered for a 5G NR TDD test signal (NR-TM3.1) with 1 × 20 MHz signal bandwidth, a signal carrier spacing of 60 kHz and a PAPR of 8.4 dB. The measurement results in ***Figure 8*** show an almost flat maximum symbol EVM of less than 1 percent over the PA linearized P_{out}.

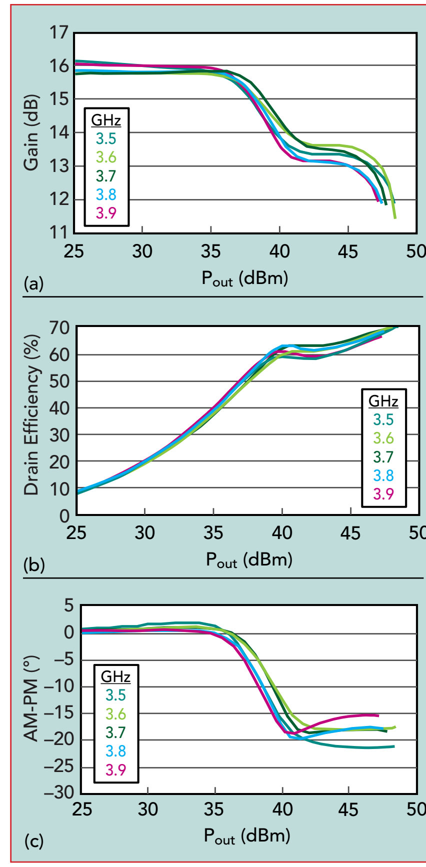


Fig. 5 (a) Pulsed gain versus output power. (b) Pulsed drain efficiency versus output power. (c) Pulsed CW AM-PM versus output power.

RELIABILITY

Reliable device operation is a given. Devices in telecom infrastructure applications must typically operate for at least 10 years under harsh conditions. If devices can sustain higher temperatures, base station cooling facilities can be smaller and lighter, reducing operating costs for network providers. ***Figure 9*** shows the MTTF of this new GaN-on-Si technology. For temperatures below 200°C, electromigration is the dominant failure mechanism. This failure is purely defined by the metallization layers of the process and the width of the connections and can be scaled independently of the intrinsic transistor. Above 200°C, intrinsic failure mechanisms of the transistors start to dominate. For a typical 150°C transistor operating temperature, the MTTF is 10^8 hours or 11,000 years, meeting lifetime requirements.

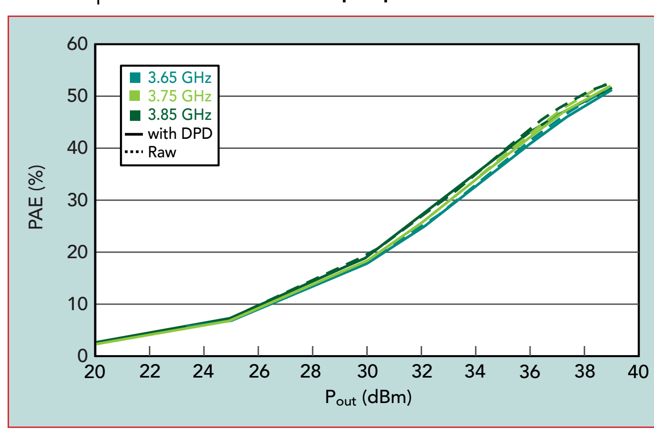


Fig. 6 PAE versus average P_{out}.

While there is no field data available yet for this second-generation technology, Infineon's first generation of RF GaN-on-Si devices have been operating in the field in mil-

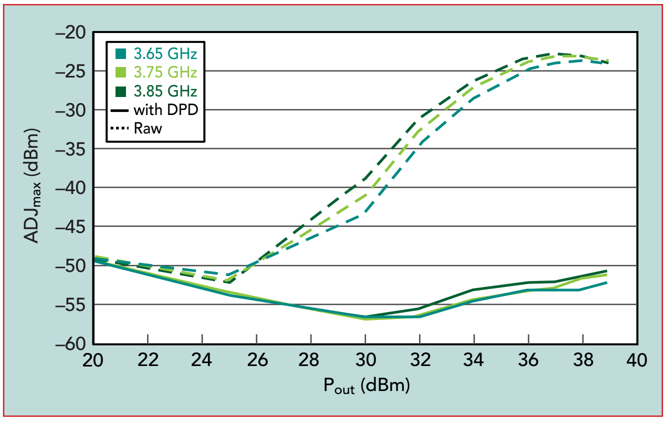


Fig. 7 ADJ_{max} versus average output power.

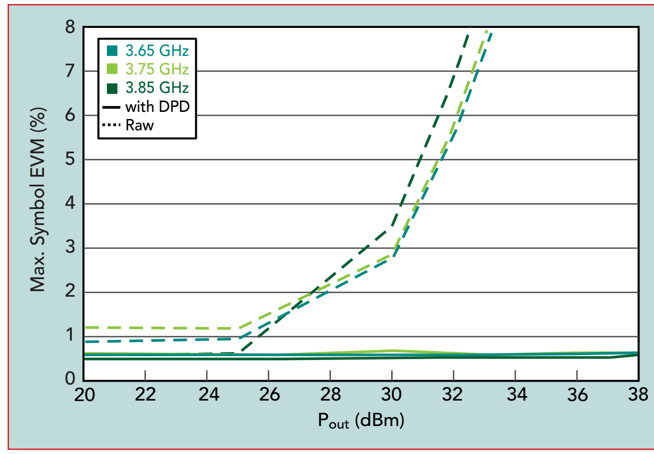


Fig. 8 Maximum symbol EVM versus average P_{out} for 5G NR-TM3.1 test conditions.

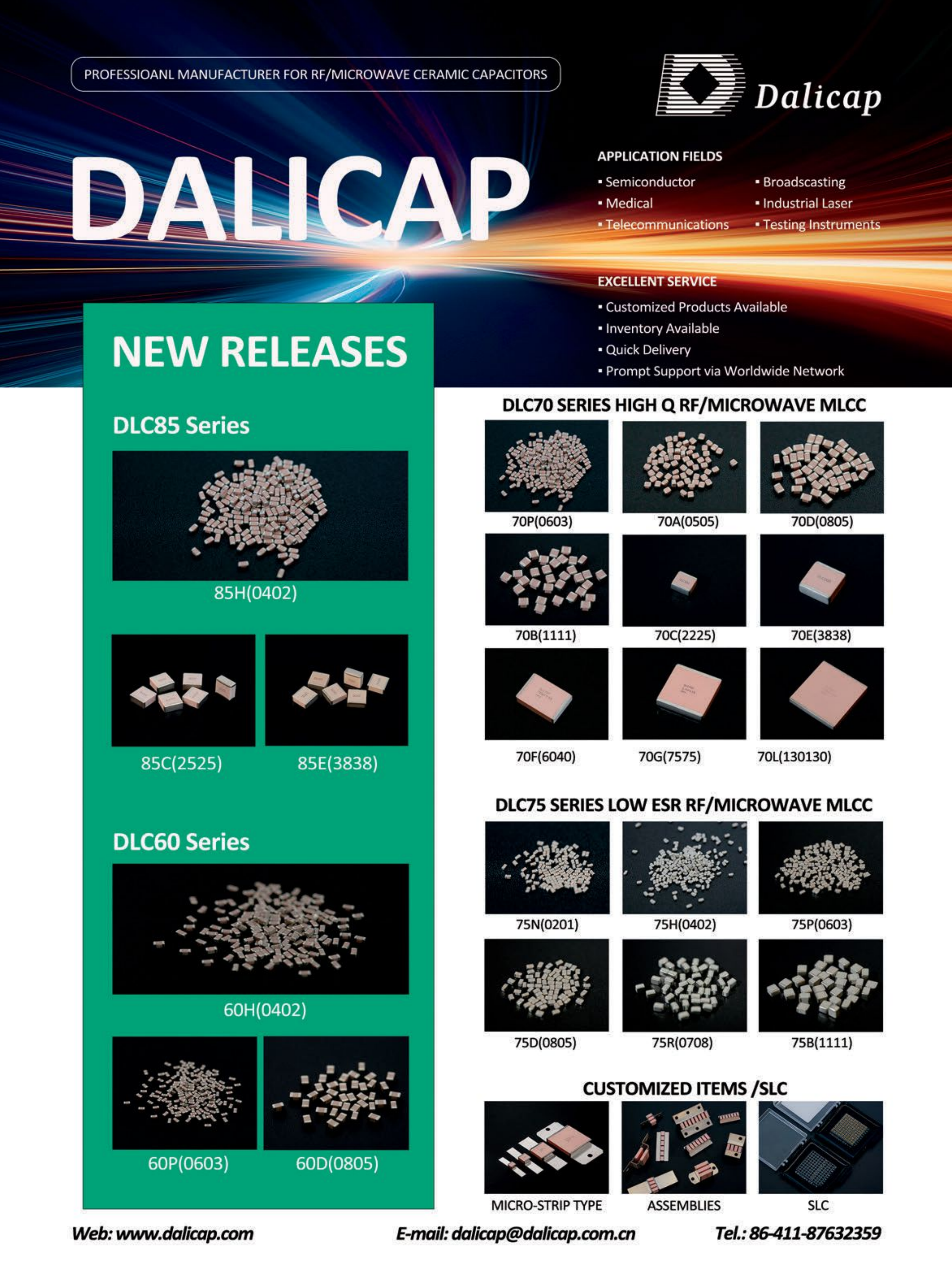
lions of PAs without any field returns, showing that RF GaN-on-Si is a suitable technology choice for harsh telecom applications.

SUPPLY VOLTAGE

The Infineon RF GaN-on-Si processes are developed for a supply voltage of 28 V and qualified up to 32 V. While the 8 to 12 W PAs commonly used in 5G mMIMO BTS can be designed with a 50 V supply, the slightly larger 28 V periphery and the lower output impedance allows for easier output matching. As base stations move toward frequencies above 6 GHz and the number of transmit channels increases, the average P_{out} of the PA will decrease. If the transformation ratio becomes too large, the impedance transformation networks and associated losses in the RF PAs become challenging and 28 V emerges as the sweet spot. For base stations operating at 10 GHz, with radios having 256 or more transmit channels, the industry is discussing even lower, 12 V, supply voltages. This will improve the competitiveness of GaN-on-Si even further.

CONCLUSION

The economic drivers of the BTS market that define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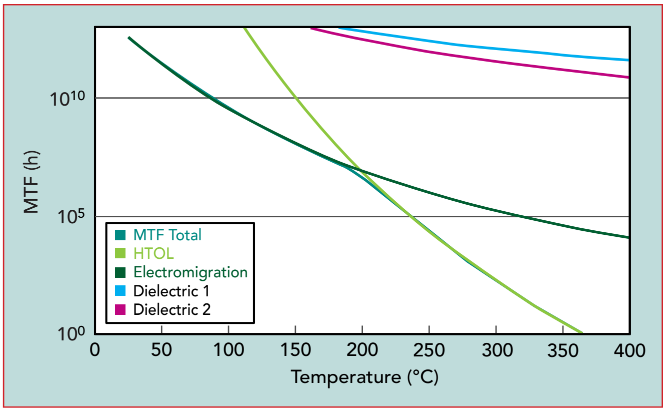

Fig. 9 **MTTF versus temperature for RF GaN-on-Si technology.**

current and future RF PA technical requirements are higher frequencies, wider instantaneous bandwidths and higher efficiency. Infineon's second-generation RF GaN-on-Si technology provides a disruptive low feedback capacitance concept that significantly improves gain and "Doherty-friendly" PA behavior. The resulting Doherty PA has a PAE greater than 50 percent for a 100 MHz 5G NR signal at 39 dBm average output power. These results show the promise of this technology. The Doherty PA has been linearized to EVM values of less than 1 percent across the output power range from 3.6 to 3.8 GHz. With 8 in. silicon manufacturing and fabrication capabilities, the advantages of PA designs on RF GaN-on-Si technology will be apparent as higher frequencies for 5G Advanced and 6G emerge, requiring a commercially viable solution for MMIC integration. ■

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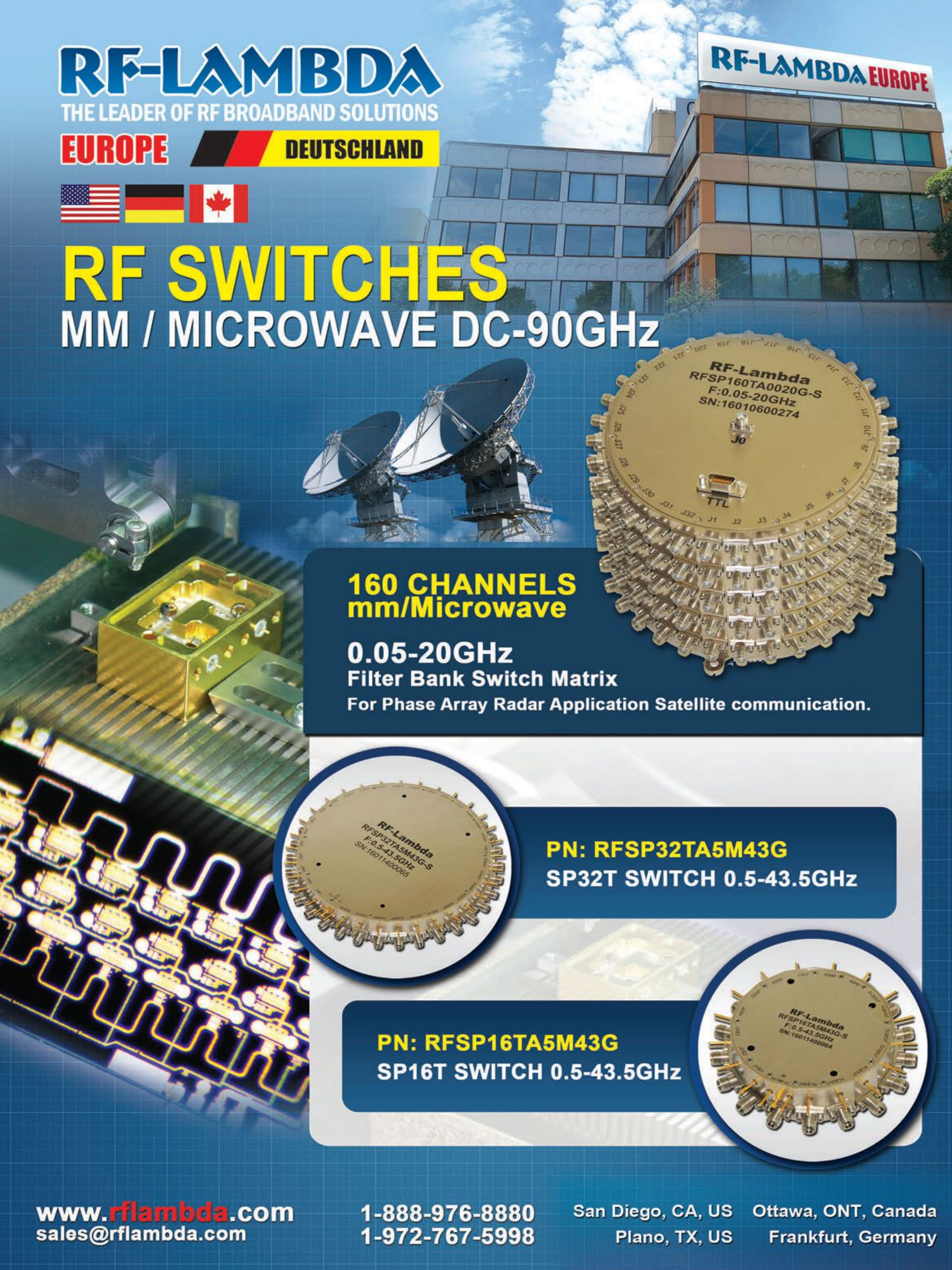
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INVITED PAPER

Enabling Simultaneous Multi-User Access to a Single Vector Network Analyzer

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Soonchunhyang University, Asan 31538, Republic of Korea

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This article presents a new network analyzer sharing (NAS) system that enables four users to simultaneously access a two-port vector network analyzer (VNA) operating up to 8.5 GHz. To enable four simultaneous users, each port of the VNA is split using an SP4T RF switch. Each channel has two ports and performs high speed sequential switching. The VNA screen is divided into four and displayed synchronously on each user's monitor. Image processing techniques are utilized to set the optimal high speed switching time automatically.

With the telecommunications industry rapidly advancing, there is a notable increase in demand for devices and components. This is leading to a greater need for measurement instruments and the demand for high performance VNAs is increasing significantly. The VNA is an expensive piece of equipment that analyzes the electrical characteristics of electronic devices. It sends and receives electrical signals to measure and analyze the response of the device under test (DUT). This allows for the examination of parameters such as frequency response, reflection and insertion loss. The VNA is widely used in the design and testing of wireless communications, radar, antennas, high frequency circuits and more.

Typically, these VNAs are designed to measure a single DUT and there are limitations when measuring multiple DUTs or having multiple simultaneous users. To address this issue, advances now enable multiple measurement ports in a single VNA.[1] Currently, there are four-port, six-port, eight-port and other multiport VNAs available on the market. However, simply increasing the number of ports in one VNA increases the complexity of the system and increases the price. Alternatively, to improve price competitiveness, the number of ports can be increased with a switch matrix.[2,3] The primary objective of port expansion is to facilitate multiport device measurements or to analyze multiple S-parameters. Port expansion does not allow independent users to use one VNA at the same time.

Recently, several authors of this article proposed a NAS system that allows multiple users to access a VNA independently and simultaneously.[4] To demonstrate feasibility, the study implemented a switch matrix for port expansion and presented a de-embedding method to calibrate each channel. However, this study did not address high speed switching methods. In addition, the switch matrix was implemented with an SPDT switch operating up to 6 GHz. However, this was insufficient to achieve the performance of existing commercial VNAs. The article presents an efficient switching module and its optimal high speed switching method to enable four users to simultaneously access a commercial two-port VNA operating up to 8.5 GHz.

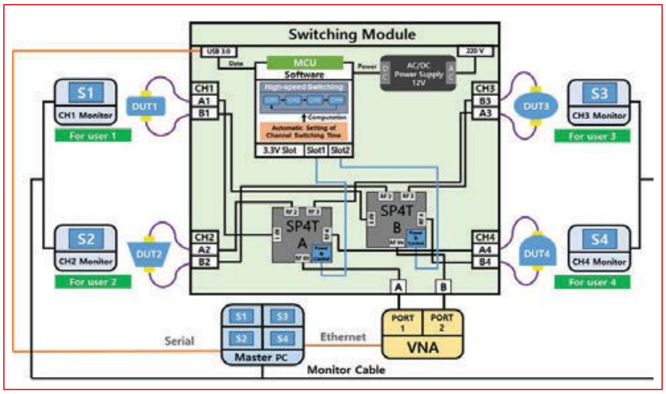

Fig. 1 **Overall schematic diagram of the NAS system.**

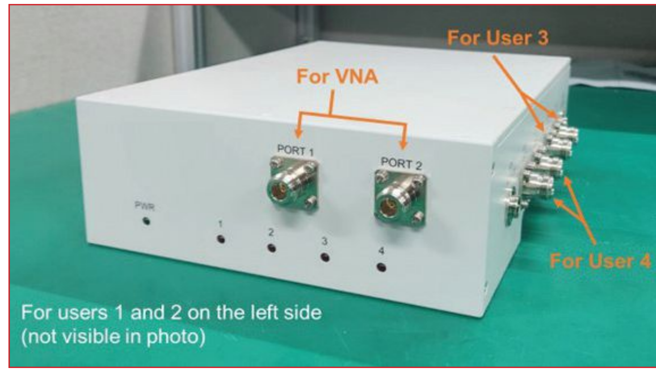

Fig. 2 **Switching module.**

OVERALL SYSTEM

The NAS system primarily consists of switching hardware to expand the VNA port, along with software that switches it rapidly and provides each measured screen to individual users. ***Figure 1*** shows the general schematic diagram of the proposed NAS system. Here, four users connect to a single two-port VNA through a switching module and measure the DUT while viewing their respective measurement screens.

The switching module includes two SP4T switches to split each VNA port into four. Port A of the VNA is split from A1 to A4, and Port B is split from B1 to B4, as shown in Figure 1. Each user is assigned two ports, for example, A1 and B1, for the first user. The SP4T switch operates up to 8.5 GHz to achieve the full performance of a typical commercial 8.5 GHz VNA. In addition, the switching module includes a microcontroller unit (MCU). This controls the high speed on/off switching of the SP4T switch, allowing all the users to access a single VNA simultaneously. With this technique, determining the switching time is a critical issue because incomplete measurements can lead to errors.

SWITCHING HARDWARE

The switching module schematic of Figure 1 expands each port of the VNA to four and the MCU turns the ports on and off sequentially according to the appropriate switching time. The fabricated switching module is shown in ***Figure 2***. It has two ports on

the front for connecting a VNA and four ports on each side to provide two ports per user.

In previous work,[4] 6 GHz SPDT switches were connected in two stages to achieve the 1:4 split of the VNA port. In this work, an 8.5 GHz SP4T switch is used to connect one input to any one of four outputs or vice versa. The use of an SP4T reduces the size of the switching module and the cable lengths between ports. These improvements are expected to decrease transmission losses. The operational frequency range of the SP4T switch extends to 8.5 GHz, ensuring full compatibility with commercial VNAs.

The manufactured switching module is interconnected with a semi-rigid RF cable to minimize cable loss and increase ease of assembly. Since the magnitude and phase of the transmitted signal will change with different RF cable lengths, it is recommended to match cable lengths to reduce electrical errors between channels. These errors make channel calibration difficult and can lead to measurement errors.[5]

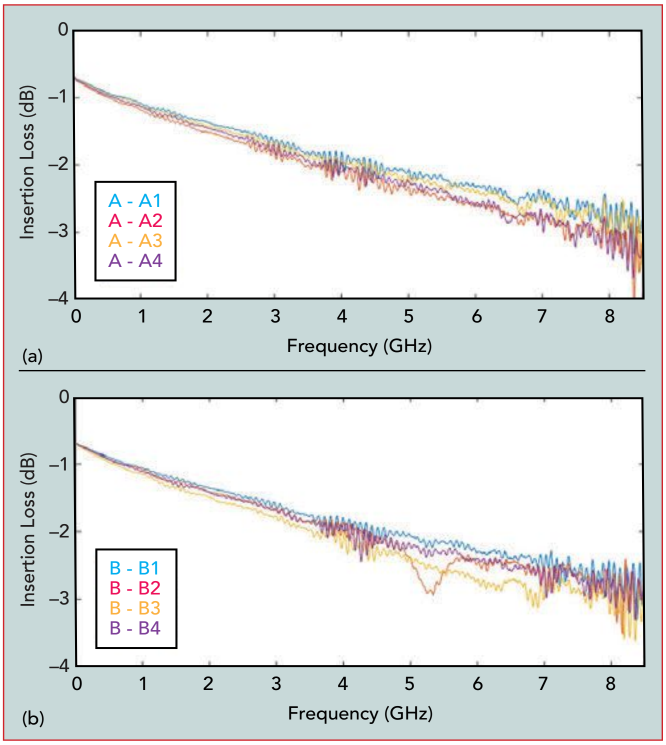

Fig. 3 Insertion loss characteristics of the switching module.

The S-parameters were measured to determine the channel characteristics of the manufactured switching module.[6] Performance assessment of the switching module involves measuring path-specific insertion loss, return loss and isolation. Insertion loss reduces the signal power that passes through the cables, connectors and switches of the switching module. Minimizing insertion loss is important in RF system design to ensure efficient signal transmission and reception. In the insertion loss measurement, only the specific path of the manufactured switching module is activated, while the others are turned off. S_{21} is measured on the activated path with a VNA. These results are shown in ***Figure 3a*** for Port A to all the associated output combinations and in ***Figure 3b*** for Port B to all the associated output combinations. These values are similar for all eight paths, decreasing from approximately -0.7 dB to -4 dB at the maximum operating frequency of 8.5 GHz.

Reflection loss measures the amount of signal power that is reflected toward the source due to impedance mismatches or discontinuities in the transmission path. When a signal encounters an impedance change, such as at the interface between two different transmission lines or at a connector, a portion of the signal is reflected rather than transmitted. These results are shown in ***Figure 4a*** for the Port A output paths and in ***Figure 4b*** for the Port B output paths. For the measurement, only one specific path was activated and S_{11} was measured at one end of the path. The characteristics of all paths are similar and the worst case is approximately -12 dB.

Isolation refers to the degree of mutual interference between two different paths in the switching


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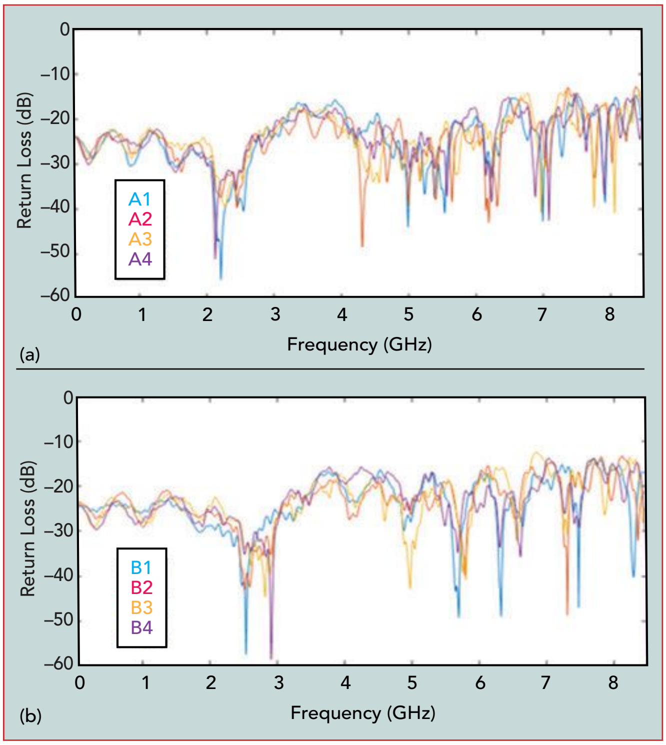

Fig. 4 **Return loss characteristics of the switching module.**

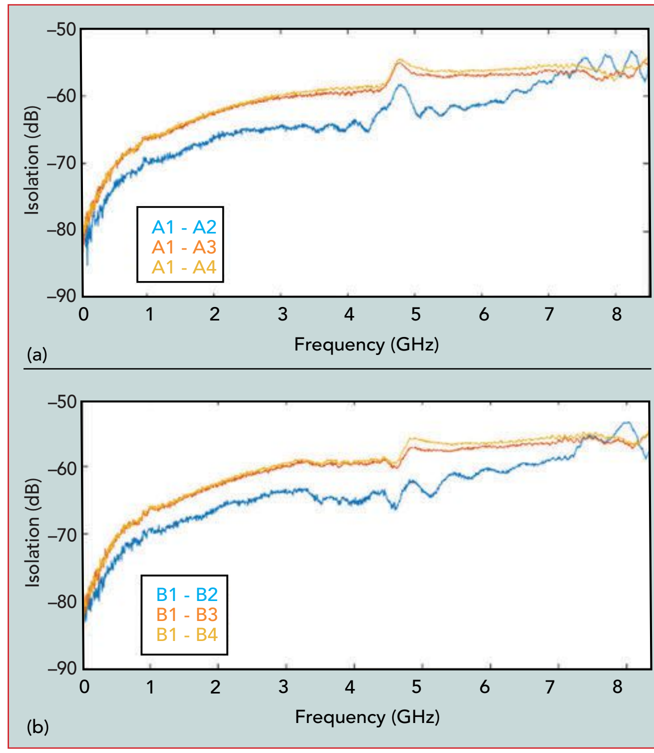

Fig. 5 **Isolation characteristics of the switching module.**

module. It indicates the extent to which a signal input to one path is transmitted to other paths as noise or external signals. Higher isolation minimizes unwanted signal interference within the system, improving the accuracy and reliability of the NAS system. The results shown in this section examine the amount of isolation between branched ports. For example, after activating the path between ports A and A1, S_{21} is measured between Ports A1 and A2, Ports A1 and A3 and Ports A1 and A4, respectively. The same is true for Port B. The results are shown in ***Figure 5a*** for the Port A combinations and ***Figure 5b*** for the Port B combinations. Not unexpectedly, the isolation performance deteriorates as the frequency increases, but the value is below approximately -55 dB at 8.5 GHz, showing excellent performance.

SWITCHING SOFTWARE

The software operating the NAS system allows four users to measure their respective DUTs simultaneously. This software controls the SP4T switches according to a series of switching schedules to activate four channels sequentially. In conjunction with this, the VNA measures the S-parameters of each activated channel and displays them on the primary screen. The primary screen is divided by channel and the measured S-parameters display is transmitted to each user monitor. Performing this operation repeatedly at a high speed allows four users to use one VNA simultaneously.

With this technique, it becomes very important to determine the appropriate switching timing to achieve the highest measurement speed. This must be done to ensure sufficient time for the VNA to measure each channel. A VNA's measurement time is variable depending on not only the measurement conditions (e.g., IF bandwidth, measurement points and the number of markers) but also the commercial VNA product used.

Figure 6 shows the operational timing of the overall NAS system. This includes the switching times between channels and the one-cycle time. When a switching command is issued, Channel 1 is activated and the VNA performs a measurement. When Channel 2 is activated, the VNA performs another measurement and this process is repeated to Channel 4. Then, the measurement results are displayed on the primary screen, divided and transmitted to each user screen. As mentioned, it is difficult to know the measurement time of a VNA. Suppose the switching time between channels is too short. In that case, the measurement data will be incomplete because the measurement of the new channel starts before the measurement of the previous channel is completed.

The measurement results screen for the case where the switching interval is too short is shown on the left side of ***Figure 7***. Conversely,

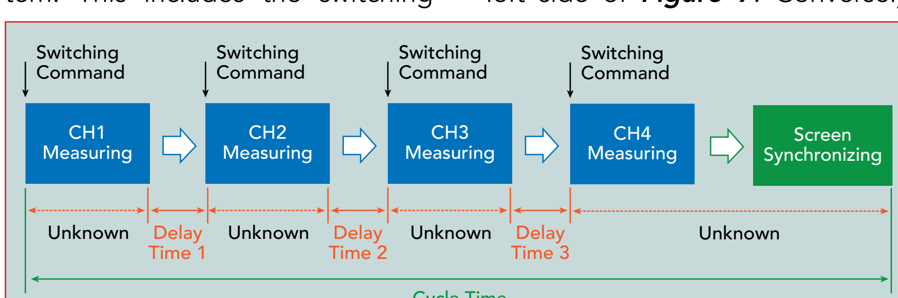

Fig. 6 **Switching schedule of NAS system.**

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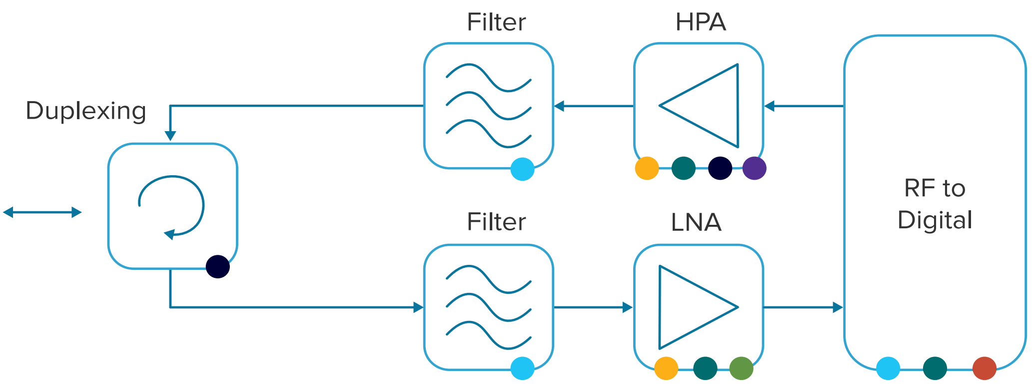

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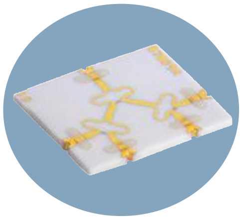

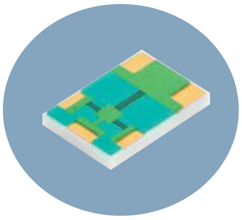

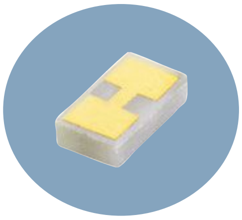

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Contact us today to explore a range of catalog and custom design options: **sales@rfmw.com** if the switching interval is too long, the user's screen refresh time will be inconveniently long. To eliminate these issues, this investigation developed a method to set the optimal switching time to achieve the highest switching speed. This technique relies on the fact that the measurement data image varies between channels when the switching time is not sufficient. The right side of Figure 7 shows the concept for setting optimal switching times based on differential images between channels.

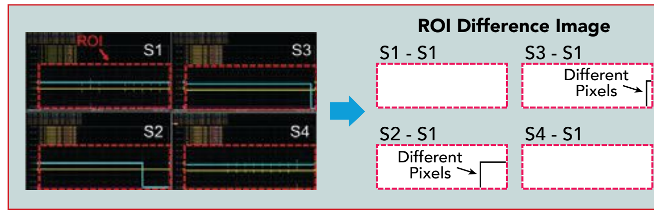

Fig. 7 Differential image processing concept for setting optimal switching time.

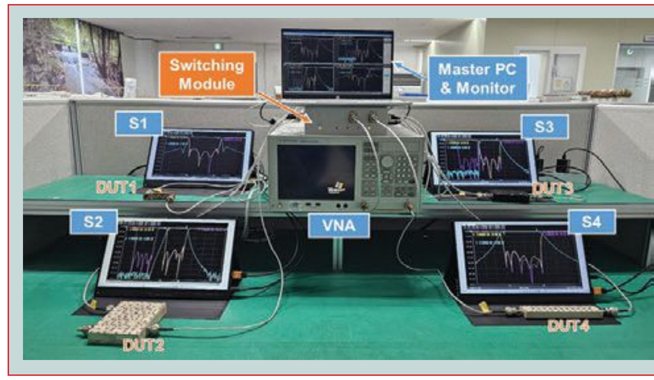

Fig. 8 NAS system setup.

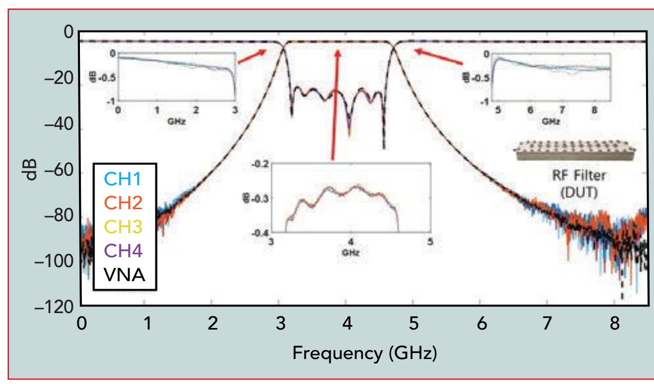

Fig. 9 Measurement results of DUT sample.

As an automatic setting environment, the two ports of each channel are directly connected by an RF cable without a DUT. Then, the same measurement data image can be obtained for all channels, thereby improving the accuracy of the difference image. In this work, the initial switching delay time was set to 10 ms to obtain the measurement data images shown on the left side of Figure 7. To obtain the significant differential images, regions of interest (ROI) were set instead of the entire measurement image.[7] Differential images are obtained by subtracting the ROI of each channel from the reference image of Channel 1. The resulting differential images are illustrated on the right side of Figure 7. The differential images for Channels 2 and 3 show a difference in the pixels. This difference arises because of the short switching time. Therefore, it is necessary to increase the switching delay time. The delay time is adjusted based on the number of pixels in each differential image. In this work, the threshold was set to 100 pixels. This value is obtained experimentally by setting the switching time to a sufficiently long value to ensure that the four measured images are almost the same. The delay time is then determined based on this threshold of 100 pixels. If the threshold is exceeded, an additional 1 ms is added to the initial delay time. This process is repeated until the number of different pixels becomes less than the threshold. Using this technique, the switching delay times between each channel in the manufactured NAS system were determined to be 16 ms, 17 ms and 17 ms.

Next, the cycle time needs to be determined. This is necessary to determine the timing for switching back to Channel 1. Without this determination, Channel 1 may be

switched before the measurement screen synchronization is complete, which will result in an error. This process is the same as determining the optimal switching time, as described earlier. This process yields a cycle time of 250 ms.

SYSTEM TEST RESULTS

Figure 8 shows a picture of the assembled NAS system. A different DUT is connected to each channel and its measurement data is displayed on each user's screen. Following the previously described method for determining high speed switching times, the cycle time was optimized to 250 ms. Therefore, the measurement data on each user's screen is refreshed four times every second.

It is also important to ensure consistency of measurement results for each channel. To verify this, the measurement results of a given DUT through the NAS system were compared with those measured by connecting it directly to the VNA. The comparisons are shown in ***Figure 9***. The DUT is a cavity filter with a passband between 3.1 and 4.8 GHz. The data measurements from the NAS system agree very well with the data measured directly from the VNA.

CONCLUSION

This article has presented a NAS system that allows four users to access a single VNA simultaneously. The system is designed to replicate the full performance of existing commercial VNAs operating up to 8.5 GHz. Measurements confirm that there is almost no difference in the characteristics between the channels. As an outcome of this technique, the optimal high speed switching time can be automatically set under any measurement conditions. The developed NAS system allows for simultaneous usage by four users, with a refresh time of 250 ms on each user's screen. This level of refresh is generally not inconvenient for measuring the characteristics of RF components or performing simple tuning tasks. Therefore, the NAS system alleviates the burden of using expensive VNAs and improves productivity. ■

ACKNOWLEDGMENTS

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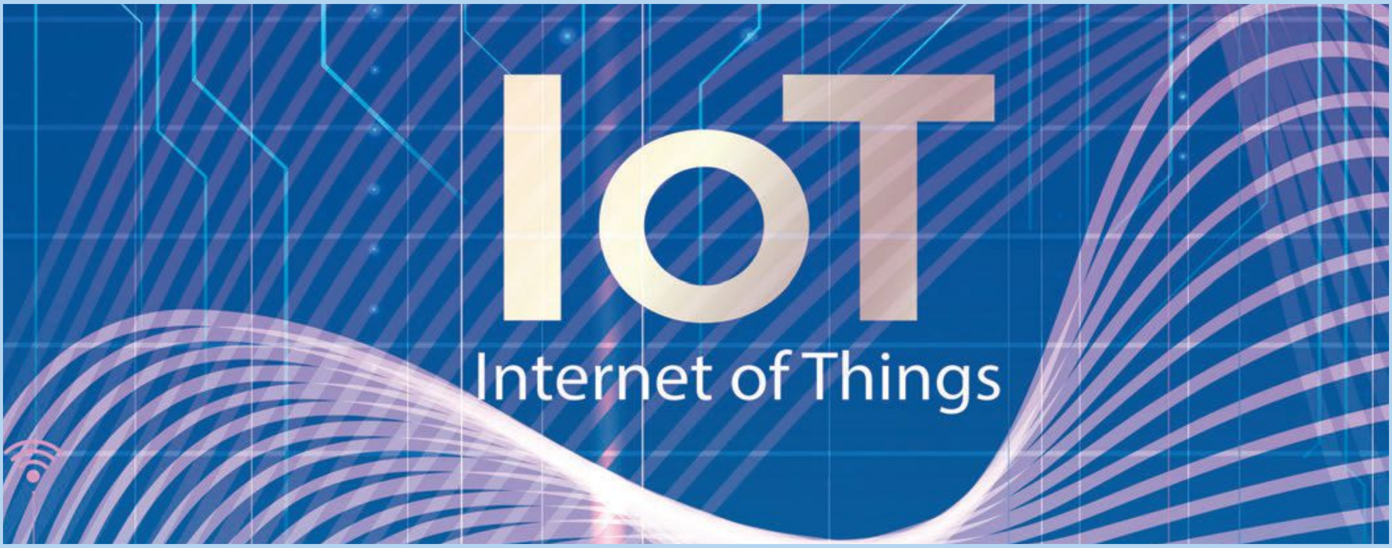

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Wireless Power Transfer: Waveform Efficiency, Interoperability and Technology Outlook

Eduardo Nunez van Eyl, Nikolas Athanasopoulos, Daniela Raddino and Rania Morsi
Rohde & Schwarz, Munich, Germany

With the growing prevalence of low-power sensor networks, simultaneously powering many devices is an increasingly important topic. The conventional way of powering devices (e.g., with cables or batteries) is becoming impractical with the increasing device density in smart buildings. Cables limit mobility, and batteries require additional maintenance because they must be periodically exchanged. Wireless power transfer (WPT) at a distance and energy harvesting (EH) enable low-power devices to operate indefinitely without requiring maintenance and allowing for greater mobility range.

While the physical concepts underlying WPT and EH have already been thoroughly studied, the use of RF waves to transmit energy has not been widely adopted due to challenges such as low end-to-end efficiency and a lack of coordinated effort to ensure interoperability. This article addresses these challenges by investigating the impact of the waveform on RF-to-DC conversion efficiency, confirming that high peak-to-average power ratio (PAPR) signals can increase efficiency in rectifier circuits. It also provides an overview of current standardization efforts and demonstrates how a prototype test setup from Rohde & Schwarz is contributing to the development of WPT technology. Furthermore, it discusses the potential of shifting to higher operating frequencies to enable smaller, more efficient devices and unlock the mass market potential of WPT. The reported findings offer valuable insights for researchers and industry stakeholders working to overcome the technical and practical hurdles in WPT and EH.

HISTORY OF WPT AND CURRENT CHALLENGES

The fundamental concept of WPT dates back to the 19th century. In 1888, Heinrich Hertz succeeded in experimentally verifying Maxwell's prediction of electromagnetic waves, confirming the possibility of transmitting power wirelessly from one point to another. In 1899, Nikola Tesla envisioned transferring considerable amounts of electric energy globally. To this end, he built the Wardenclyffe Tower, which had the goal of transatlantic wireless communications and power transfer.

No further progress was made in far-field WPT for several decades until advancements in microwave technology in the 1960s. William C. Brown pioneered the modern era of far-field WPT. He demonstrated the wireless powering of light bulbs and electric fans with a 5.5 m distant power transmitter (Tx). He also demonstrated the first microwave-powered helicopter. Another driving application for RF WPT was the solar-powered satellite. In this system, solar energy from the sun is captured by a geostationary satellite. The energy is converted in space into microwave power, which is beamed to Earth and converted to DC power. These experiments on far-field WPT focused on high-power RF transmissions over long distances using large antennas.

The recent proliferation and ubiquity of low-power communication devices, such as wireless sensors, IoT devices and wearable electronics, has drawn interest to using WPT for low-power delivery (e.g., microwatt to milliwatt) over short to moderate distances of a few meters. Despite the existing research on WPT, significant efforts are still required to model and optimize the receiving circuits to achieve the highest conversion efficiency possible. Another issue is coordinating development efforts and products to ensure coexistence and interoperability between WPT devices.

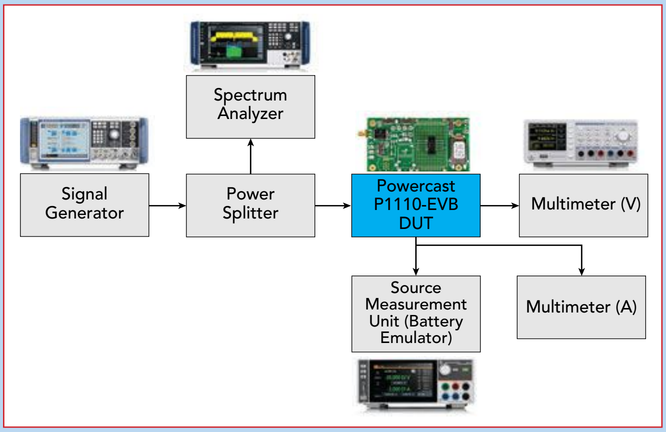

Fig. 1 Setup for waveform efficiency comparison.

TABLE 1

DEVICES USED TO COMPARE WAVEFORM EFFICIENCY

Device	Model
Voltmeter/Ammeter	R&S® HMC8012
Signal Generator	R&S SMW200A Vector Signal Generator
Spectrum Analyzer	R&S FSV3030
Source Measurement Unit (Battery Emulator)	R&S NGU201
WPT Prototype Board	Powercast P1110-EVB

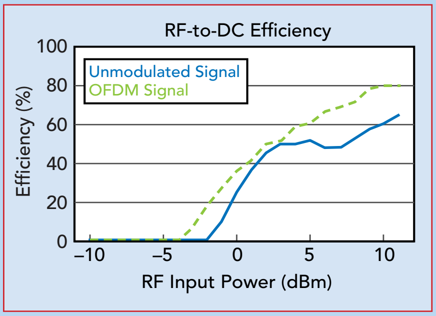

Fig. 2 RF-to-DC conversion efficiency of a prototype board.

TABLE 2

MEASUREMENT PARAMETERS AND CONFIGURATION TO COMPARE WAVEFORM EFFICIENCY

Parameter	Value
Storage Element Voltage	3.49 V
Center Frequency	915 MHz
OFDM Number of Subcarriers	64
OFDM Subcarrier Spacing	312.5 kHz
OFDM Occupied Subcarriers	6
Spectrum Analyzer Channel BW	20 MHz
Measured Samples Per Power Level	400

RF-to-DC Conversion Efficiency

At its core, the RF-to-DC conversion process is relatively simple; only two components are involved, namely the antenna and the rectifier, commonly grouped under the name "rectenna." The antenna receives the RF signal, and the rectifier converts it to DC. The rectifier typically contains diodes followed by a capacitor-based lowpass filter (LPF), making it a nonlinear circuit element.

A high RF-to-DC conversion efficiency has clear advantages. First, an efficient WPT means that less energy is wasted as heat. This improves the overall system performance, including the power transfer range and device charging times. Second, high efficiency allows for higher received power, expanding the possible areas where WPT can be deployed.

Theoretical Considerations

The rectifier component of an RF-to-DC converter is a nonlinear circuit element due to the relationship between the circuit's RF input power and DC output power. The waveform has an impact on the conversion efficiency.[1] Signals with high PAPR result in higher harvested DC power. This is because the peaks of a high PAPR signal are more likely to exceed the turn-on voltage of the diode compared to a constant envelope signal with the same average power but lower peak power. In addition, the peaks of a high PAPR signal can charge the capacitors to a higher voltage level. For an output LPF with a long time constant, the capacitor can maintain the charged voltage level until the next signal peak.

Waveform Efficiency Comparison

To compare the effect of high PAPR signals on the RF-to-DC conversion efficiency of a prototype board, a signal generator is connected to a power splitter, which equally divides the incoming power between the spectrum analyzer and the RF-to-DC receiver (Rx) board from Powercast. A battery emulator is connected to the DC output of the Rx. This eliminates the need for a physical battery by emulating the behavior of various battery types, including Li-Ion and NiCd. The states of charge, current and voltage at the battery terminals are also displayed. Precise measurements of both voltage and current are conducted using high precision multimeters. The setup is controlled remotely such that tests and other evaluations run automatically. ***Figure 1*** shows the setup diagram with the devices listed in ***Table 1***. The measurement parameters and configuration can be taken from ***Table 2***.

Figure 2 shows the RF-to-DC conversion efficiency for different RF power inputs to the Rx circuit. The OFDM signal generally outperforms the sinusoidal signal throughout the input power range. This confirms the hypothesis that high PAPR signals lead to better rectifier efficiency because of their nonlinear nature. Another interesting observation is that the higher efficiency of the high PAPR signals decreases the minimum input power required by the rectifier by about 2 to 3 dB. In other words, the RF-to-DC converter sensitivity improves with high PAPR signals. This translates to greater operational ranges, higher output power levels and a better user experience.

3GPP and Ambient IoT

Interoperability is a crucial factor in future WPT systems. It enables wireless device charging without compatibility issues. This leads to a more diverse ecosystem that promotes market growth and innovation, eventually making WPT technology more affordable.

The 3GPP, a global standards organization for telecommunications, has traditionally focused on communication standards for 3G to 5G networks. However, their ex-

isting standards did not previously address the specific needs of low-power, low-complexity devices that may operate without batteries and consume less than 10 mW of power. Recognizing this gap, 3GPP has introduced the concept of "Ambient IoT" in their recent studies, outlining requirements and air interface specifications in TR22.840 and TR38.848. The low-power nature of Ambient IoT devices makes them ideal candidates for RF-powered operation. In Release 19, the 3GPP Ambient IoT initiative tackles key aspects such as use cases, connectivity architectures, spectrum allocation, EH and coverage, paving the way for innovative IoT applications.

AirFuel Standardization Efforts and Testing

For a technology to be available for commercial use, it is essential to have a standard that can be applied to devices from different manufacturers. Moreover, it is necessary to define compliance testing requirements that must be met before a device can be deployed in the market. This is important for ensuring that a new technology like WPT has no negative impact on existing technologies. To this end, AirFuel Alliance (AFA) has defined a standard for RF WPT.

AFA is a global coalition of companies developing standards for wireless charging. AFA defined the AirFuel Resonant standard that uses magnetic resonance at 6.78 MHz in the industrial, scientific and medical (ISM) band to charge devices with powers up to 50 W at distances up to several centimeters. AFA also defined the AirFuel RF standard for using RF signals in the 900 MHz ISM band (865 to 868 MHz and 902 to 927 MHz, depending on the region) to deliver up to 1 W of wireless power over distances of several meters. This provides the Rx with motion freedom while it is being powered. AirFuel RF uses Bluetooth® Low Energy for the control channel signaling between the Tx and Rx. Receiving devices can establish a full Bluetooth connection to the Tx or exclusively broadcast Bluetooth advertisements to request that any Tx in range send them power.

The AirFuel RF standard Baseline System Specification (BSS) was released for AFA members in January 2023. The Interoperability (IOP) and Conformance Test Specification (CTS) were released for AFA members in April 2024. These standardization efforts aim to make RF signals for wireless charging as ubiquitous as Wi-Fi for communications.

As a member of the AFA, Rohde & Schwarz contributes to developing WPT. The Rohde & Schwarz WPT Project targets the emerging WPT market by leveraging the capabilities of its existing test and measurement equipment to provide a comprehensive test solution for wireless power Tx and Rx. The involvement of Rohde & Schwarz is key to refining the testing procedures of AirFuel RF.

The Rohde & Schwarz WPT Project created a test setup based on Figure 1 to deliver precise and actionable feedback during the AirFuel RF standard development process. A software framework complements the hardware, allowing precise control of individual devices. It also allows tests to be orchestrated through an API, command line interface and user-friendly web interface. Apart from testing the general capabilities of the device under test (DUT), the setup implements the AirFuel CTS for the Rx.

Figure 3 is a screenshot of the web interface showing one of the AirFuel RF CTS tests, namely the "Rx Frequency" test. This test case evaluates the DUT frequency range under various power levels. As shown in the black window in Figure 3, the signal generator feeds the input frequencies to the DUT at different power levels. It is verified whether the device charges for each frequency and power level combination. A test is successful if the device charges under the specified conditions; otherwise, the test is considered failed. The user can configure the test parameters, launch the test and monitor the progress within the interface.

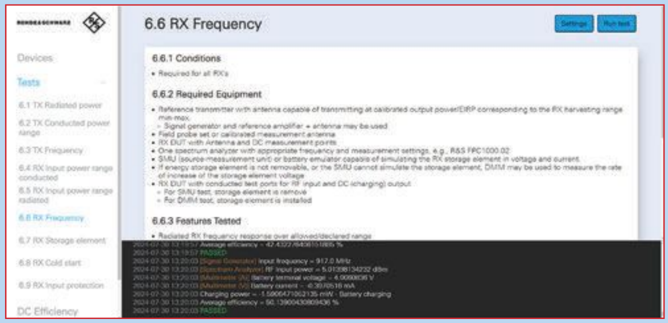

Fig. 3 Test setup web-UI including AirFuel Conformance Test Specification.

TECHNOLOGY OUTLOOK

Several technological developments are expected to shape the future of WPT and EH. One key trend is the shift toward higher frequencies, which promises advantages such as smaller form factors and higher power transfer rates. However, this development raises concerns about safety, cost and system complexity.

Higher Frequencies

Despite the associated higher path loss, there is an ongoing transition to higher operating frequencies.[2] Currently, some WPT efforts are focused on GSM bands and sub-GHz frequency ranges. The literature and latest market trends show a clear preference toward the ISM bands, especially in the 2.4 and 5 GHz ranges, but also ranging up to 60 GHz. To understand this interest, it is necessary to consider the numerous advantages that higher frequencies provide.

Smaller Antennas and Devices

It is well known that the size of an antenna is intrinsically related to the wavelength of the radio waves it transmits or receives, with $\lambda/2$ being the optimal antenna size for resonance and maximum efficiency. By increasing the frequency and, therefore, reducing the wavelength, antennas can be made smaller and more practical for mobile IoT devices. Early attempts at WPT required very large antennas because it was extremely difficult to generate higher frequencies then.[3] For example, utilizing DTV frequencies (470 to 770 MHz) for EH is difficult due to the impractical antenna size.[4]

Antenna components in the 2.4 GHz range, for example, are in the centimeter range. These can be developed based on well-known designs. For transmission at longer distances, this frequency range exhibits an excellent compromise between propagation attenuation at higher frequencies and the larger dimensions necessary for transmission at lower frequencies.[3]

Improved Beam Shaping Capabilities

Apart from their size, smaller antennas also offer beam shaping benefits. Precise beam shaping on higher frequencies while maintaining moderate antenna sizes is key to the widespread use of WPT.[3] A sharper beam is highly advantageous because it leads to higher antenna gain, which increases the power delivered to the Rx. This effectively increases the range and counteracts the higher path loss at higher frequencies. Extending the transmission distance proportionally is possible by utilizing transmit antenna arrays with more elements or operating at higher carrier frequencies. For example, transitioning from 2.4 to 60 GHz could theoretically increase the range by a factor of 25.[5] However, possible tradeoffs must be considered. Most importantly, the conversion efficiency decreases with increasing operating frequencies[6] because of some circuit topologies' lowpass characteristics. Addressing these challenges is crucial for the future of WPT, as large arrays of steerable antennas, capable of delivering narrow beams with high gain, have the potential to enable widespread adoption of WPT over long distances.[7]

Radiation Safety Concerns

Although traditional communication systems do not pose any radiation risk to the users, the higher power density of WPT systems must be closely studied. The narrower the transmission beam, the higher the power density, which can quickly surpass the radiation limits for humans,

as stated by organizations such as the FCC. This is especially true in the case of very narrow beams that are achievable at high frequencies and are necessary to achieve high antenna gain. This work[5] highlights the importance of considering the beamwidth to determine the unsafe beam interception distance. In addition, these calculations depend on local regulations applicable to the frequency ranges, exposure times and duty cycles of the signal.[8]

Increasing the operating frequencies of WPT devices makes more precise beamforming possible at the expense of higher radiation risks for humans and animals. This can be circumvented by implementing systems that steer the beam away from living organisms. However, such a system is a significant technical challenge. Another approach proposed by Ossia[9] is the use of retrodirectivity to identify all safe paths between Tx and Rx. This would be done using beacon signals before power transmission. For now, multiple open questions remain about the safety mechanisms for radiative WPT.

CONCLUSION

WPT and EH are not new concepts. However, there are significant challenges when it comes to implementing this technology. Key challenges are low end-to-end efficiency and industry coordination to ensure interoperability of these wireless systems. For the technology to advance, it is crucial to understand how to improve the RF-to-DC conversion efficiency by transmitting high PAPR signals. Ongoing standardization efforts, which Rohde & Schwarz actively supports with its prototype test setup, are paving the way for commercialization. A shift toward higher operating frequencies would enable narrower transmission beams and allow for smaller devices. This may play a decisive role in WPT technology entering the mass market. However, significant optimization is still required to overcome the decreasing efficiency of most rectifier circuits at higher frequency ranges. ■

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AWGs and Digitizers Offer 10 GSPS

Spectrum Instrumentation
Grosshansdorf, Germany

In March 2022, Spectrum Instrumentation launched the M5i series platform, the first PCIe digitizer to use the full 16 lanes (Gen 3) of the PCIe interface, leading to 12.8 GBytes/s data transfer rates. The M5i.33xx digitizer family was expanded the following year, with new models offering 10 GSPS sampling speed and 4.7 GHz bandwidth. Spectrum Instrumentation has used the M5i platform to design arbitrary waveform generators (AWGs) that offer up to 10 GSPS signal generation. The M5i.63xx series, launched in September, makes it possible to combine AWGs and digitizers with speeds up to 10 GSPS. This makes creating stimulus-response systems and closed-loop setups with cost-efficient COTS parts and PCs possible. ***Figure 1*** shows a new 16-bit, 10 GSPS AWG on the same M5i platform as the established 12-bit 10 GSPS digitizer series.

Fig. 1 **16-bit 10 GSPS AWG (front) and 12-bit 10 GSPS digitizer series (rear).**

NEW AWG CARD SERIES

Capable of producing waveforms with bandwidths up to 2.5 GHz, the new AWGs can turn any suitable PC into a powerful signal generation instrument. Four models make up the new M5i.63xx-series product line. Each one pairs exceptionally high bandwidth with matching DAC converter technology. The result is a family of AWGs offering 2.5 and 1.5 GHz bandwidths, that output waveforms at rates up to 10, 5 or 3.2 GSPS. All the units feature 16-bit vertical resolution and programmable full-scale output ranges of ±1 V (±500 mV into 50 Ω) – or double the range in differential mode. The combination of these features delivers new performance benchmarks for waveform speed, precision and quality.

Built on the M5i series platform, first developed for Spectrum's 33xx digitizer line, the AWGs exploit proven design technology. All the products come with 2 GSamples of onboard memory (8 GS optional) and high speed data transfer using a 16-lane, Gen 3, PCIe bus. This bus sends data to and from the cards at 10 GBytes/s. When needed, data can even be streamed directly to the AWG for replay in FIFO mode, a process that allows almost limitless

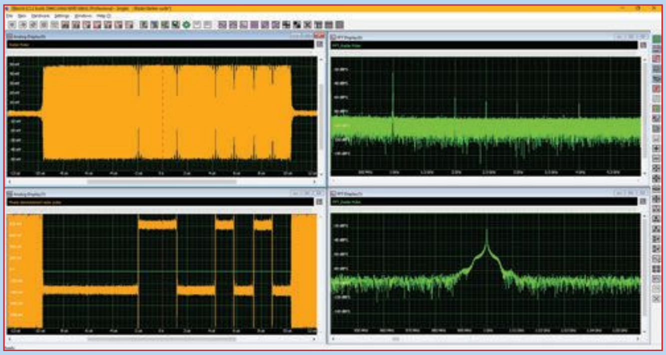


Fig. 2 Data generated by the M5i.63xx AWG.

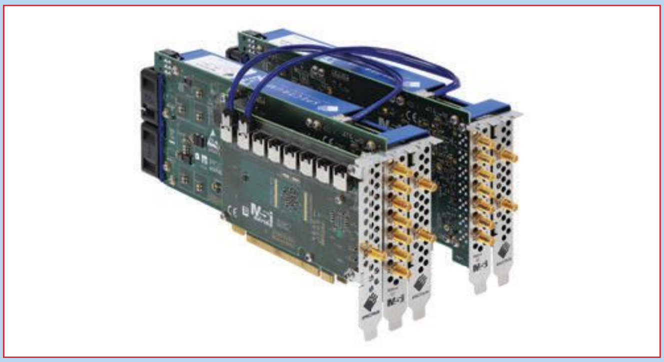


Fig. 3 M5i Star-Hub module on the left card.

waveform production.

The M5i series AWGs and digitizers can stream data directly to and from a GPU if Spectrum's SCAPP driver package is used. Waveforms can be replayed in a single-shot or repeated process, while multiple waveform segments can be output using the Multiple Replay mode, optimizing memory efficiency. The different replay modes can also be combined with FIFO streaming. A simple software command or trigger event can initiate waveform replay. Trigger signals can be input on two external trigger lines. ***Figure 2*** shows a simulated 1 GHz phase-modulated radar pulse (upper left) generated with a new M5i.63xx AWG. The demodulated phase information (lower left), a pulse frequency spectrum (upper right) and a horizontally-expanded view of the spectrum (lower right) are also visible.

GETTING 16 CHANNELS

Individual cards offer one or two output channels. If more channels are needed, connecting multiple cards using the company's proprietary Star-Hub clock and trigger synchronization module is possible. Star-Hub allows up to eight M5i.63xx AWG cards to be connected, to create systems with up to 16 fully synchronized channels. A common clock then drives each channel and shares the same trigger. Using Star-Hub synchronized M5i.63xx AWGs, the user can build synchronous systems with output rates up to 16 × 5 GSPS or 8 × 10 GSPS. ***Figure 3*** shows the M5i Star-Hub module that synchronizes up to eight AWGs or eight digitizers by sharing a common sampling clock and trigger source.

COMBINING AWGS AND DIGITIZERS

For applications like stimulus-response or closed-loop test systems that require AWGs and digitizer connections, M5i.63xx AWGs and M5i.33xx digitizers can be synchronized using direct clock and trigger connections. Digitizers and AWGs are available with matching speed grades of 3.2 GSPS, 5 GSPS and 10 GSPS for easy integration. With two Star-Hubs, one can combine up to eight AWGs, while the other links up to eight digitizers for 16T16R MIMO systems having channels of 5 GSPS. The AWG-plus-digitizer combination can be utilized for several dynamic test applications, like determining the frequency characteristics of wideband amplifiers or filters or testing the response of electronic components and subassemblies under various conditions.

SIMPLE SIGNAL GENERATION AND CONTROL

Fully programmable, the M5i cards can run under Windows or LINUX operating systems using today's most popular and powerful software languages. The M5i products are shipped with SDKs for C++, Python, VB.NET, C#, Julia, Java and IVI. Drivers are also provided for the third-party software products LabVIEW and MATLAB.

TEST SYSTEM INTEGRATION AND MIXED MODE OPERATION

A high level of connectivity allows the cards to be integrated easily into almost any automated test system. Signal outputs, as well as clock and trigger inputs, are accessible via front-panel SMA connectors. The front panel has four SMA connectors for multi-function I/O, which can be used for tasks like asynchronous digital I/O, timestamp reference clock input, synchronous digital out, trigger output, run and arm status flags or the system clock.

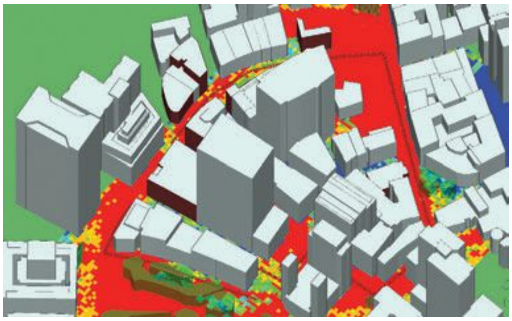
Switching the multi-purpose I/O lines to digital outputs adds four more synchronous output channels to the AWG. This allows a single AWG card to generate up to two analog and four digital outputs in parallel at full speed, which is helpful when interfacing with other equipment for experiment control or in OEM projects.

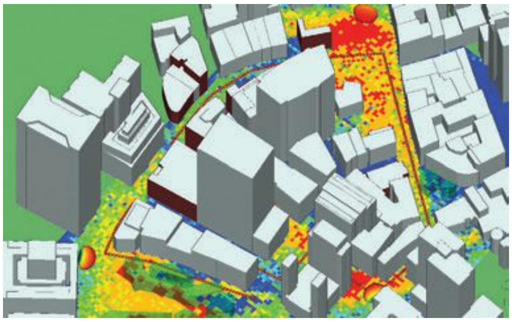
DIGITAL PULSE GENERATOR OPTION

The M5i.63xx AWG cards and the M5i.33xx digitizer cards offer a built-in digital pulse generator (DPG) capability. This firmware option uses the multi-purpose output connectors to provide four internal, independent digital pulse generators. Each DPG can be programmed for duty cycle, output frequency, delay and number of loops. The DPGs can be triggered by software or hardware and can trigger each other, allowing complex pulse schemes to be created to drive external equipment or experiments. Model-dependent, the fastest cards can produce digital pulses at rates up to 312.5 MSPS or every 3.2 ns.

VENDORVIEW

Spectrum Instrumentation
Grosshansdorf, Germany
www.spectrum-instrumentation.com





Beamforming with massive MIMO (top) shows significant improvement to throughput over links between single antennas (bottom)

Reimagining a Stacked Patch

Taoglas
San Diego, Calif.

Taoglas' Inception HP5354.A "patch-in-a-patch" antenna exemplifies a forward-thinking approach to antenna design. The HP5354.A is a passive GNSS L1/L5 antenna offering dual-band stacked patch performance in a standard 35 × 35 × 4 mm form factor. By recessing the second antenna within the first, Inception reduces antenna height by 50 percent and decreases weight, making it an ideal solution for the demanding precision and accuracy of GNSS applications with limited space. ***Figure 1*** illustrates a standard stacked patch antenna as compared to the HP5354.A.

The patent-pending HP5354.A is a drop-in replacement for single-band surface-mount patches, improving the IoT device's positioning accuracy from over 3 meters to 1.5 meters without compromising the dual-band L1/L5 performance.

Fig. 1 **Standard stacked patch antenna compared to the Taoglas Inception HP5354.A.**

ANTENNA PERFORMANCE AND KEY SPECIFICATIONS

The HP5354.A has a passive peak gain of 2.61 dBi optimized for GPS L1/ L5, BeiDou B1, Galileo E1 and GLONASS G1 operation with the next generation of dual-band GNSS receivers on the market. ***Figure 2*** displays the peak gain for L1-B1-E1-G1 and L5.

Key product specifications include:

- Band coverage: GPS L1/L5, GLONASS G1, Galileo E1/E5a, BeiDou B1/B2a
- Frequency range: 1160 to 1610 MHz
- Maximum gain: 2.61 dBi
- Tight phase center variation (PCV): < 0.02 cm
- Polarization: right hand circularly polarized (RHCP)
- Material: ceramic
- Dimensions: 35 x 35 x 4 mm
- Weight: 16 g.

Figure 3 shows a Taoglas anechoic chamber used to test the radiation patterns on a 70 mm × 70 mm ground plane. ***Figure 4***

shows the radiation patterns at 1176 MHz. The radiation patterns at 1561 MHz, 1575 MHz and 1602 MHz can be found in the product datasheet.

SUPPORTS INDUSTRY'S TRANSITION FROM L1 TO L5

Applications such as asset tracking, smart agriculture, industrial tracking, commercial drones and autonomous vehicles require better stability, resilience and precision. For decades, the industry has used single-band GPS, but emerging bands such as L2, L5, L6 and L-Band offer system designers a path to cleaner signals, improved gain and cm-level accuracy. The same trend applies to global GNSS technologies, including GPS, GLONASS, Galileo, BeiDou, QZSS, IRNSS and SBAS. The L5 band utilized by the HP5354.A has a higher signal strength that is less susceptible to interference and ionospheric distortion, so when combined with the L1 signal, it allows for better error correction, which leads to more precise positional accuracy.

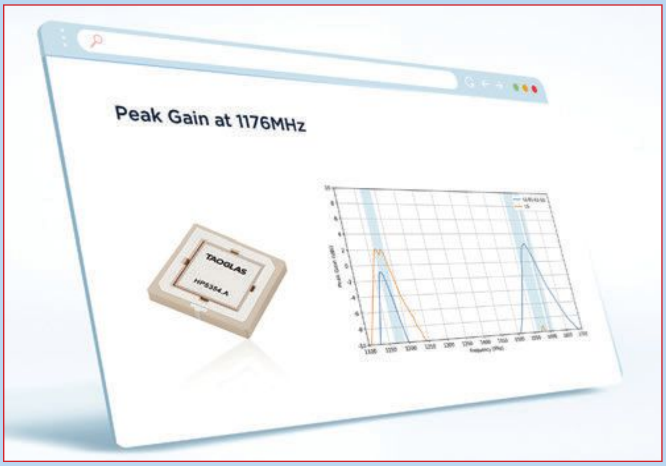


Fig. 2 Peak gain for L1-B1-E1-G1 and L5.

Fig. 3 Anechoic chamber test setup.

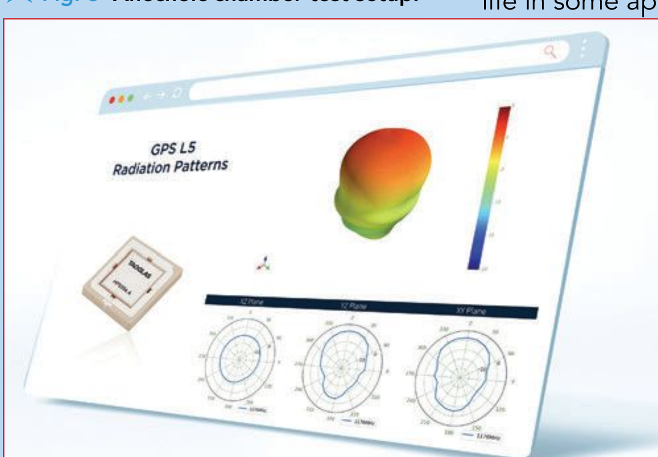


Fig. 4 Radiation patterns at 1176 MHz.

Inception's unique design allows customers to integrate a multi-band L1/L5 GNSS patch into devices where this would not have been possible before due to height constraints. Instead of using two patch antennas, a single HP5354.A antenna can be used. At only 4 mm in height, the HP5354.A can be used in various applications where typical stacked patch designs are too tall. Weighing only 16 g, the HP5354.A can reduce the overall system weight, which may increase battery life in some applications.

For applications with stringent system-level requirements, like automotive and space, Taoglas meets various customer surface-mount reflow profiles, resulting in very secure mounting on customer printed circuit boards (PCBs). This secure mounting helps minimize shock and vibration issues. Additionally, the dual-feed design helps maintain circular polarization gain in cases where the antenna has been detuned and/or needs to be tuned in situ. This improves multipath rejection over the entire antenna bandwidth for improved timing and cleaner signals. It also improves axial ratio bandwidth, helping reject multipath signals and enhancing navigation accuracy.

USES A CUSTOM ELECTROCERAMICS FORMULA

The Taoglas surface-mount antenna technology is designed using a custom electroceramics formula. This ensures high-quality performance and seamless integration into devices requiring high-precision GNSS. Instead of using off-the-shelf formulas, Taoglas uses its in-house design and manufacturing capabilities to optimize its electroceramic mix, delivering robust performance for high-reliability applications.

ANTENNA INTEGRATION WITH SUPPORTING PRODUCTS

The HP5354.A has three feeds. Two feeds are used for the L1 band and the other for the L5 band. The Taoglas HC125A hybrid coupler can combine the dual feeds for the L1 patch, offering high RHCP gain and optimal axial ratio for upper constellations, including GPS L1, BeiDou B1, Galileo E1 and GLONASS G1.

Active circuitry needs to be upgraded to L1/L5 along with the antenna. The Taoglas TFM.100B L1/L5 front-end module can be designed onto the device PCB alongside the antenna to reclaim valuable real estate and save designers up to two years of complex design. The module features a SAW/LNA/SAW/LNA topology in both the low- and high-band signal paths to prevent unwanted out-of-band interference from overdriving the GNSS LNAs or receiver. The SAW filters have been carefully selected and placed to provide excellent out-of-band rejection while maintaining a low noise figure.

Taoglas
San Diego, Calif.
www.taoglas.com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Since 1961, Greenray Industries has been a preferred provider of precision, high performance reference sources to many of the world's leading military, defense and industrial manufacturers.
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Radar + Portable Communications + GPS + Detection & Identification

OMNIDIRECTIONAL ANTENNA OPERATES AT 300 GHZ

VENDORVIEW

Model SAO-2943040345-03-S1 is an omnidirectional antenna that operates from 297 to 303 GHz. The vertically polarized antenna offers 360 degrees of azimuth coverage with 3 dBi typical gain and ±2 dBi angular gain flatness. The vertical beam width is 45 degrees. The antenna feed is WR-03 waveguide with a UG-387/U-M anti-cocking flange.

Eravant
www.eravant.com

SURFACE-MOUNT 90° HYBRID

VENDORVIEW

MIcable released the new 0.8 to 2.7 GHz high power surface-mount 90-degree hybrid. It has low insertion loss (0.5 dB maximum), excellent VSWR (1.35:1 maximum), extremely good amplitude unbalance (±0.65 dB maximum) and phase unbalance (±5 degrees maximum), high isolation (17 dB minimum) and 200 W power handling capability with excellent stability and heat dissipation ability in a small package. It is suitable for power amplifier, power combining network, antenna feed network, modulator and phase shifter applications.

MIcable Inc.
www.micable.cn

WAVEGUIDE STANDARD GAIN HORNS

VENDORVIEW

Fairview Microwave has announced the launch of its new low frequency waveguide standard gain horns, designed specifically for test and measurement applications. The new line is well suited for characterizing antennas and wireless systems. Models are available in WR-510, WR-650 and WR-770 sizes, both 10 dBi and 15 dBi gain options, and type-N female connectors. The waveguide standard gain horns support frequency ranges down to 320 MHz, addressing a significant gap in the market for low frequency testing solutions.

Fairview Microwave
www.fairviewmicrowave.com

WIRELESS INSITE®

VENDORVIEW

Non-terrestrial wireless networks play a critical role in providing service to locations not covered by terrestrial 5G networks. Wireless InSite® models satellite coverage, simulating the satcom channel to capture important effects such as terrain masking, shadowing due to foliage and multipath fading, which are essential to a proper evaluation of the link budget. Ray-tracing models can be used to identify cases where terrestrial coverage needs to be supplemented with a LEO satellite overlay to improve NB-IoT coverage in rural areas.

Remcom
www.remcom.com

MiCable

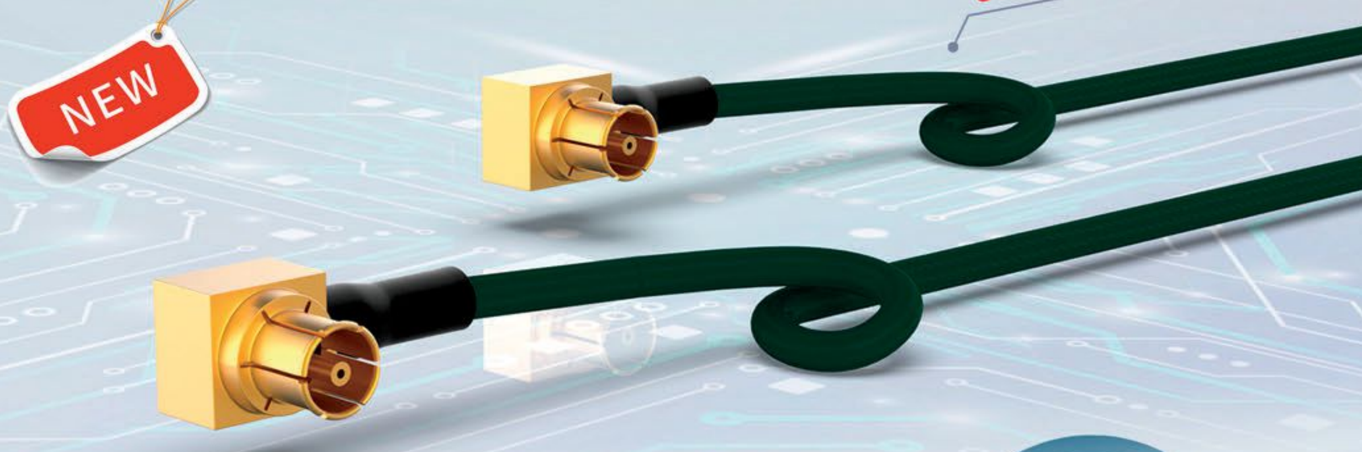
SSMP 40GHz Female Right Angle

C25F Series MILLIMETER WAVE CABLE ASSEMBLY

Ideal for connection and jumper requiring extremely limited installation space and high reliability

NEW

3mm Min. Bend Radius



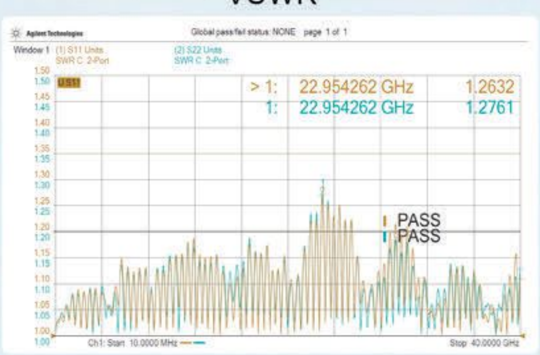
Excellent Phase Stability vs. Temp.

Excellent Mechanical/Temp. Stability

High Freq. **Low** Loss **Low** VSWR

Small Size for **High** Density Arrangement

VSWR



Cable Diameter	1.42mm
Frequency	DC~40GHz
Cable Attenuation	7.69dB/m@40GHz
VSWR	<1.40@40GHz
Shielding Effectiveness	<-90dB
Phase Stability vs. Flex.	<±4°@40GHz
Phase Stability vs. Temp.	<200ppm@-15°C~+35°C <400ppm@-40°C~+70°C
Amplitude Stability vs. Flex.	<±0.1dB/m@40GHz

More Information-
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MIcable Inc.

www.micable.cn sales@micable.cn +86-591-87382856

Trihedral Corner Reflectors Enhance Testing

Pasternack, an Infinite Electronics brand and a leading provider of RF, microwave and mmWave products, has launched its new trihedral corner reflectors. These reflectors have three flat surfaces meeting at right angles to form a corner structure. This innovative design ensures the efficient reflection of incoming signals back toward the source, making them indispensable in various testing and measurement scenarios. These trihedral reflectors are poised to revolutionize radar and antenna testing applications by optimizing signal reflection and measurement accuracy.

One of the primary applications of Pasternack's trihedral corner reflectors is radar cross-section (RCS) measurements. Placed strategically within a controlled environment, these reflectors simulate radar echoes, enabling precise assessment and calibration of radar systems. Moreover, they find extensive use in antenna testing, helping evaluate and optimize antenna performance.

Key features of the corner reflectors include their compact size, ranging from 1.4 to 13 in., which caters to different radar target sizes. With a high RCS, these reflectors ensure optimal signal reflectivity for accurate measurements. Their rugged configuration, complemented by a durable gray powder-coat finish, allows them to withstand diverse environmental conditions.

Operating in the 10 to 100 GHz frequency range, these reflectors are suitable for a wide array of applications. Precision machined and tripod mountable, they offer convenient and secure mounting options for seamless integration into testing setups.

Pasternack's new trihedral corner reflectors are in stock and available for same-day shipping.

A leader in RF products since 1972, Pasternack is an ISO 9001:2015-certified manufacturer and supplier offering the industry's largest selection of active and passive RF, microwave and mmWave products available for same-day shipping. Pasternack is an Infinite Electronics brand.

VENDORVIEW

Pasternack
Irvine, Calif.
www.pasternack.com
For inquiries, please call +1 (949) 261-1920

Vector Signal Generators Operate to 40 GHz

AnaPico Switzerland has been delivering the APVSG series of single- and multi-channel vector signal generators (VSGs) for the past three years. A notable new feature has recently been added: the capability to generate radar and electronic warfare (EW) signals based on pulse descriptor words (PDWs). Each PDW can describe a single pulse with sophisticated intra-pulse modulation. Users can compile a list of PDWs offline, following an AnaPico-specific PDW data structure and upload it into the APVSG's internal memory for playback and radar signal generation at frequencies up to 40 GHz. The multi-channel, highly phase-coherent APVSG also supports the generation of multi-stream signals, accurately feeding radar antenna arrays with precise beam angles and power information. Additional features like low phase noise and fast switching further demonstrate the APVSG's suitability for these applications.

Moreover, AnaPico has developed specialized firmware that supports system-level power and phase calibration in a significantly shorter time. The associated algorithm reduces the required number of calibration points while achieving the desired calibration precision. The APVSG is a cost-effective platform offering a modulation bandwidth of 400 MHz and a radar pulse repetition rate of up to 500,000 pulses per second.

AnaPico is an ISO9001:2015 certified technology leader developing, manufacturing and supplying RF and microwave test and measurement instruments for a wide range of civil and governmental applications. AnaPico strives to be the independent developer and global supplier of high-quality RF and microwave test and measurement instruments with unique features and outstanding performance, combining "Swissness" and cost-efficiency. All of our products are 100 percent developed and manufactured in Switzerland.

VENDORVIEW

AnaPico AG
Glattbrugg, Switzerland
anapico.com

Ka Band Electronically Steerable Phased Array Demonstrating Active Beam Steering

Watch as ADI's ADIS1648 iSensor device works hand-in-hand with ADI's beamformer, the ADAR3002 and ADI's Wilkinson splitter/combiner, the ADAR5000.

Analog Devices Inc.

www.analog.com/en/resources/media-center/videos/6331955114112.html

Leading Mobile Device Remanufacture and Repair Company Operations Using Anritsu Custom Solution

A main company in the 5G UE repair space relied on Anritsu to develop an easy-to-operate and dependable RF test system to efficiently verify 5G mobile devices. Learn more in this case study.

Anritsu Company

bit.ly/4475PkV

Current Sense Transformers for Switched-mode Power Supplies

Current sensors are frequently used to measure and control the load current in power supplies, safety circuits and a variety of control circuits. This application note discusses the parameters for selecting current sensors, as well as the limitations of alternative technologies such as current sense resistors.

Coilcraft

bit.ly/3zw2X68

Fairview Unveils New Enhanced Website

Fairview Microwave introduced an enhanced e-commerce website aimed at optimizing customer experience. This upgraded platform facilitates easier product discovery and improves access to resources for Fairview's customers.

Fairview Microwave

www.fairviewmicrowave.com

Microwave Switch Design Tool Update

Pickering Interfaces' Microwave Switch Design Tool, a free online tool for configuring application-specific PXI and LXI RF and microwave switching subsystems with just a few clicks, has been updated to include schematic design and simulation capabilities.

Pickering Interface

bit.ly/4ezjx3Z

The Evolution of Broadband, Delivering Entertainment and Data

In this two-part series, RFMW explores how we receive entertainment programming and connect to the world via the internet. Part 1 will focus on the evolution of cable television (CATV) and geosynchronous satellites to deliver television and internet access.

RFMW

bit.ly/3Bl3U1J

IEEE

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MTT-S MHz to THz Community | IEEE AP-S Antennas and Propagation Society 75th Anniversary

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December 09-13, 2024 | Hyderabad International Convention Centre, Hyderabad

IEEE Microwaves, Antennas and Propagation Conference, MAPCON-2024 will be held from December 09 – 13, 2024 at the Hyderabad International Convention Centre (HICC), Hyderabad, India. This is the third edition of the MAPCON, which is a joint flagship conference of IEEE MTT and IEEE AP societies in India. The conference will be held in-person (physical mode).

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EMI,/EMC fundamentals, testing and challenges

Millimetre wave imaging

Microwave based non-destructive and non-invasive testing

Quantum Bootcamp

Antenna & RF Front End Design for Monopulse Tracking System using MATLAB

PLENARY AND KEYNOTE TALKS

Dr. Satish Sharma, "Design and Development of Flat Panel Phased Array Antennas for Wireless and Satellite Communication Applications," San Diego State University.

Maurizio Bozzi, “Novel Microwave sensors and technologies”, University of Pavia, Italy

Dirk I. L. de Villiers, “An Optimal 18 m Shaped Offset Gregorian Reflector for the ngVLA Radio Telescope,” University of Stellenbosch, Stellenbosch, South Africa.

George Shaker, “Radars for UAV classification,” University of Waterloo, California, USA.

Luciano Tarricone, Electromagnetics for healthcare/ biomedical applications, University of Salento, Italy.

Ahmed Kishk, Efficient antenna array design for mm-wave applications, Concordia University, Montreal

SPECIAL SESSIONS

THz devices, circuits and systems for remote sensing, astronomy and secure communications

Radar Seeker technology

Intelligent surfaces and their applications in smart reflections, absorption and energy harvesting

Reconfigurable metasurfaces for non-terrestrial networks

III-V semiconductor technologies for defence and

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DEVICES/ COMPONENTS/MODULES

2-Way RF Splitter Combiner

VENDORVIEW

The ADAR5001 is a wideband Wilkinson splitter that is ideal for signal distribution applications, requiring low time skew between channels. The ADAR5001 can also be used as a combiner, combining input signals at the P1 and P2 ports to an output at the S1 port; all within the smallest package on the market.

Analog Devices
www.analog.com

Band Reject Filters

New production release of the 120 Series of band reject filters 80 dB notch covering 6 to 18 GHz, 8 to 20 GHz and 6 to 20 GHz. Applications include wideband receivers, automated test systems, telecom, satcom, UAVs and drones and a variety of military and commercial test applications.

Micro Lambda Wireless
www.microlambdawireless.com

MMIC I/Q Mixer

VENDORVIEW

Mini-Circuits' model SMIQ-134H+ is a passive in-phase/ quadrature (I/Q) mixer that translates RF and LO signals from 10 to 30 GHz to intermediate-frequency signals from DC to 7 GHz. It has 7.5 dB conversion loss when operating with +18 dBm LO power and features at least 38 dB LO-RF isolation. Ideal for 5G as well as electronic warfare and radar systems, the 50 Ω GaAs HBT MMIC mixer is supplied in a 24-lead, QFN-style 4 ×4 mm surface-mount package.

Mini-Circuits
www.minicircuits.com

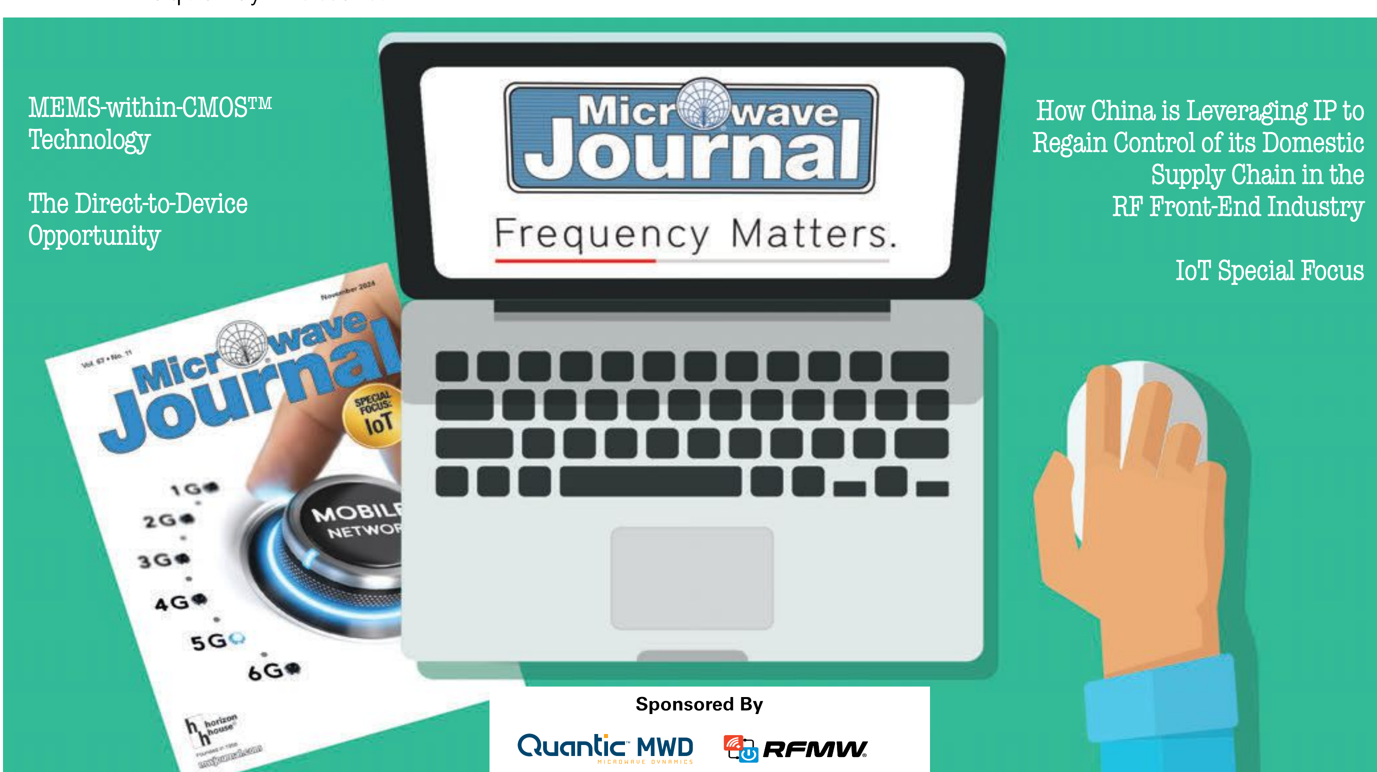
CABLES & CONNECTORS

High Frequency Connectors

VENDORVIEW

Pasternack, an Infinite Electronics brand, announced the launch of its new high frequency connectors for semi-rigid coax cables sized 0.034 and 0.047. The high performance connectors are available in 2.92 mm, SMA, SMPM and 3.5 mm interface types, catering to the growing demands of high frequency applications. They ensure versatile application across various setups. The connectors support frequencies from DC up to 18 GHz or 40 GHz, making them ideal for a wide range of high frequency applications.

Pasternack
www.pasternack.com



AMPLIFIERS

2 KW Solid-State C-Band Pulse Amplifier

VENDORVIEW

Exodus Advanced Communications' AMP2083P-2KW pulse amplifier is designed for pulse/HIRF, EMC/EMI Mil-Std 461/464 and radar applications. Providing superb pulse fidelity and up to 100 usec pulse widths. Duty cycles to 6 percent with a minimum 63 dB gain. Available monitoring parameters for forward/reflected power in watts and dBm, VSWR, voltage, current and temperature sensing for outstanding reliability and ruggedness in a compact 7U chassis.

Exodus Advanced Communications
www.exoduscomm.com

SDLVA

VENDORVIEW

Quantic PMI Model SDLVA-2G18G-50MV-100-NRF is a successive detection logarithmic amplifier (SDLVA) designed to operate over the 2 to 18 GHz frequency range with a frequency flatness of 1.64 dB; TSS of -75 dBm; VSWR: 2.0:1; power input +17 dBm; log range of -67 to +5 dBm with a 50 mV/dB log slope and log linearity of 1.04 dB. This model is designed for ultra-high speed applications while maintaining flatness and accuracy. Housing size is 3.20 × 1.80 × 0.40 in. with SMA female connectors.

Quantic PMI
www.quanticpmi.com

ISM-Band Linear Power Amplifier

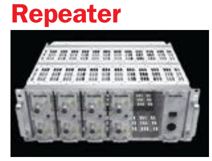
VENDORVIEW

The CML CMX90A006 is a 2 W, 900 MHz ISM-band linear power amplifier. This two-stage, input matched MMIC PA delivers +32.9 dBm of power at 1 dB compression for use in the 860 to 930 MHz range and is applicable to license-free bands. The use of InGaP HBT process technology provides excellent reliability and balance between efficiency, gain and linearity. CMX90A006 is intended as a final stage ISM-band PA in wireless applications. Now available at RFMW.

RFMW
www.rfmw.com

SYSTEMS

Repeater



Advanced RF Technologies, Inc. announced the SDRC Series, its first Part 20 repeater to bring instant wireless connectivity to small and mid-sized buildings. The repeater makes it easier, faster and more cost-effective than ever to provide cellular coverage by streamlining the lengthy and cumbersome process typically involved with establishing in-building wireless networks. The SDRC is sold in a turnkey solution with four 4G/LTE RF bands (e.g. 700 MHz, 850 MHz, PCS, AWS), coaxial cable, donor and server antenna.

Advanced RF Technologies, Inc.
www.adrftech.com

Radio Module

VENDORVIEW

The compact Ophelia-III radio module is offered as part of Würth Elektronik's "Build Your Own Firmware" concept. The manufacturer enables custom radio solutions in the 2402 to 2480 MHz frequency range to be developed with this module, which comes without firmware and a software development kit. Applications range from the widely used Bluetooth®LE for specific use to proprietary, highly customized radio protocols. Ophelia-III is based on the nRF52840 chipset from Nordic Semiconductor, a 32-bit ARM Cortex M4F CPU.

Würth Elektronik
www.we-online.com

SOURCES

Solid-State Magnetron Weather Radar Transmitters

Pulse Systems has developed a unique weather radar system. This engineering accomplishment has been possible due to the recent development of SiC high-power FET switching devices. The XM3 series is the new FET design by Wolfspeed. This design over the CAS series is far superior in performance efficiency and cost. The high-power switching capability of these devices and their high efficiency make them unique and ideal for our application to be used in our weather radar systems.

Pulse Systems
www.pulsesystem.com

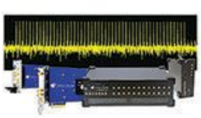
Active Tripler Model A796-3X-14

Spacek Labs A796-3X-14 is a 76 to 82 GHz active frequency tripler. Requiring 15 dBm input power, it generates 16 dBm typical output power across the frequency range with better than 30 dBc undesired harmonic rejection. This multiplier is ideal for use in automotive collision avoidance systems. Applied bias is between +8 and +11 VDC requiring 100 mA of current. Overall size is less than 1 in. cube. This tripler can also be configured as a frequency doubler or quadrupler.

Spacek Labs
www.spaceklabs.com

DDS Generators

VENDORVIEW



Spectrum Instrumentation launched a family of DDS generators named the 96xx series, forming a new product category in the company's portfolio. The new DDS Instruments offer up to 50 sine wave carriers on one single output channel. This feature provides a new way for engineers and scientists to produce and independently control multi-tone sine signals. DDS, which is short for "Direct Digital Synthesis," is a powerful technique for generating high-purity signals (typically sinewave cores, also called carriers or tones) with ultra-fast switching between output frequencies and fine frequency resolution.

Spectrum Instrumentation
www.spectrum-instrumentation.com

Surface-Mount DROs

Synergy Microwave has added several new products in the GSDRO "GOLD Standard" series of surface-mount dielectric resonator oscillators (DROs). This product series combines ultra-low phase noise with extended operating temperature range and fundamental frequency output. These DROs are ideally suited for free running and phase locked applications in 5G and 6G high data rate clocking converters, radar, military communications and test instrumentation. Other features include mechanical and electronic tuning for optimized fundamental center frequency adjustment and PLL phase locking.

Synergy Microwave
www.synergymwave.com

United States Postal Service

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f. Total Distribution (Sum of 15c. and 15e.) ▶			25,106	24,695
g. Copies not Distributed (See Instructions to Publishers #4 (page #3))			154	156
h. Total (Sum of 15f. and g.) ▶			25,260	24,851
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16. Electronic copy Circulation		
If present, check box →		[ ]
a. Paid Electronic Copies		
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Carl S. Sheffres	Publisher	09/23/2024

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PS Form 3526, July 2014

Reviewed by: Doug Jorgesen

Bookend

EW 102: A Second Course in Electronic Warfare

By David Adamy

David Adamy's "EW 102: A Second Course in Electronic Warfare" is an excellent continuation of its predecessor, "EW 101: A First Course in Electronic Warfare." It delves deeper into the complex world of electronic warfare with the same clarity and engaging tone that made the first book so accessible. This follow-up expands on the foundational knowledge established in EW 101, focusing on more specialized topics that are crucial for those directly involved in the development and strategic application of EW systems.

In general, EW 101 covered the basic concepts of EW systems (such as receivers, EW processing, antennas and jamming), while EW 102 covers more in-depth tactical topics (such as details on communication systems and optical systems). However, some topics in EW 102, such as threats and radar characteristics, could be considered foundational. Other topics include EW against communication signals, the accuracy of emitter location systems and communication satellite links.

Adamy's EW 102 is particularly relevant for EW system architects, designers and operators in the field. It provides in-depth insights that go beyond the basic concepts discussed in the first book, making it an invaluable resource for warfighters and those involved in higher-level strategic planning within EW.

While EW 101 is sufficient for those seeking a general understanding of electronic warfare, EW 102 is a great choice for microwave engineers who enjoy having a deeper comprehension of the strategic elements of EW operations. Adamy continues to impress with his ability to make complex subjects not only understandable but genuinely interesting. This book is a rewarding read for anyone with a keen interest in advancing their knowledge of electronic warfare, proving once again that Adamy is a masterful educator in the field.

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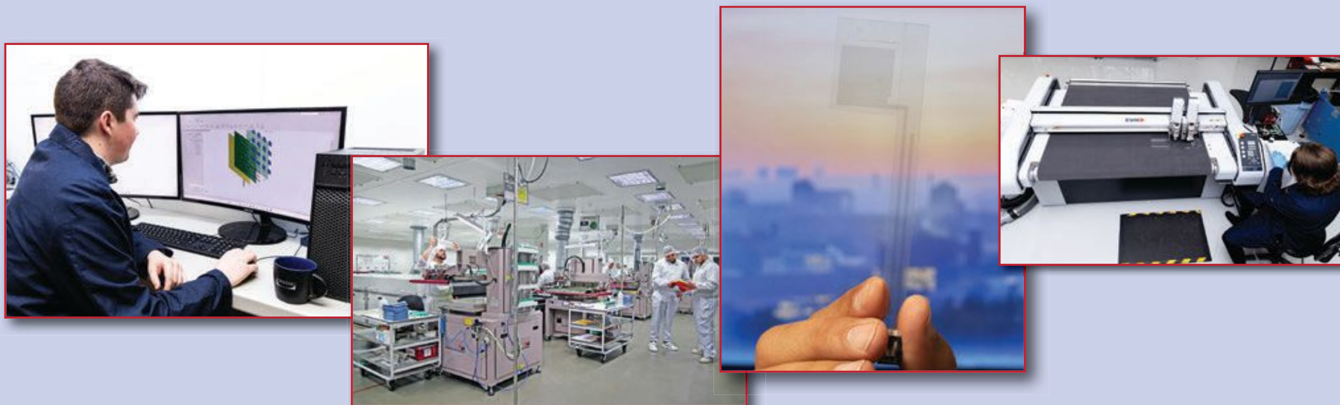
FABS and LABS

CHASM Advanced Materials: Redefining What is Possible



Single-wall carbon nanotubes were "officially" discovered in 1991, but anecdotal evidence indicates these structures may predate the official discovery by nearly 40 years. A nanotube is a tube-like structure at nanometer dimensions. Carbon nanotubes (CNT) are attractive because they combine mechanical strength, high thermal conductivity and tunable electrical properties. These features make this technology attractive for diverse applications ranging from concrete and composite materials to battery storage, automotive, electronics, medical and defense markets. Nanotechnology performance benefits are widely known, but cost and usability issues have impeded widespread adoption. CHASM Advanced Materials looks to shift that paradigm.

The story of CHASM Advanced Materials starts with Chasm Technologies, a consulting firm founded in 2005 by Dave Arthur and Bob Praino. Shortly after co-founding Chasm Technologies, Dave Arthur left to be CEO of SouthWest NanoTechnologies (SWeNT), one of Chasm's first clients. SWeNT became a leading producer of carbon nanotube materials for electronics and composites applications and formalized a strategic alliance with Chasm Technologies in 2009. In 2015, Chasm Technologies agreed to acquire SWeNT and Dave Arthur became the CEO of the newly formed CHASM Advanced Materials. CHASM's headquarters and application development center are in a 10,000 sq. ft. facility in Canton, Mass.

One of the challenges for carbon nanotubes is scale. The SWeNT acquisition brought an 18,000 sq. ft. state-of-the-art manufacturing plant in Norman, Okla., specially engineered and configured to produce high-purity carbon nanotubes. This facility is implementing the world's largest CNT production platform, with an annual production capacity of 1500 metric tons, as part of CHASM's growth and innovation strategy. CHASM touts this platform as the most scalable, cost-efficient and sustainable method for mass-producing high-quality CNT additives. This effort is powered by proprietary catalysts and rotary kiln reactors for CNT synthesis, offering a production efficiency 5x greater than the traditional fluidized bed reactors prevalent among other CNT producers.

CHASM focuses on creating transparent, cost-effective materials. Their product lines include AgeNT™ performance films that are transparent, conductive, flexible and formable. These films have low patterning costs and low sheet resistance at high transparency. Companies in multiple industries use these films for transparent heaters, antennas and EMI shielding films. NTeC performance additives utilizing CNT and CNT-hybrid products are developed with industry partners for applications like batteries and construction materials such as cement and concrete. Signis™ CNT products have been engineered to satisfy requirements in advanced materials applications and be adaptable to various manufacturing technologies. Produced using the patented CoMoCAT™ synthesis process exclusively licensed from the University of Oklahoma, these CNTs are semiconducting or conductive due to the ability to vary and control chirality and tube diameter.

These capabilities result in transparent, flexible antennas for 5G, Wi-Fi or IoT antennas that can adhere to windows and heaters that deliver faster and more uniform heat to any surface to enhance ADAS and industrial HMI displays. RF shielding films provide transparency and RFI/EMI protection for windows and displays used in aircraft, vehicles and buildings. The CNT materials are also used in printable CNT inks and for improving battery technology.

CHASM is committed to fostering a culture of creativity and innovation. Its business model revolves around providing tailored material solutions that meet clients' specific needs. Selling these advanced materials and offering design and manufacturing services helps bring innovative concepts to life and redefine what is possible for the next generation of mobile devices, vehicles, appliances and more.

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