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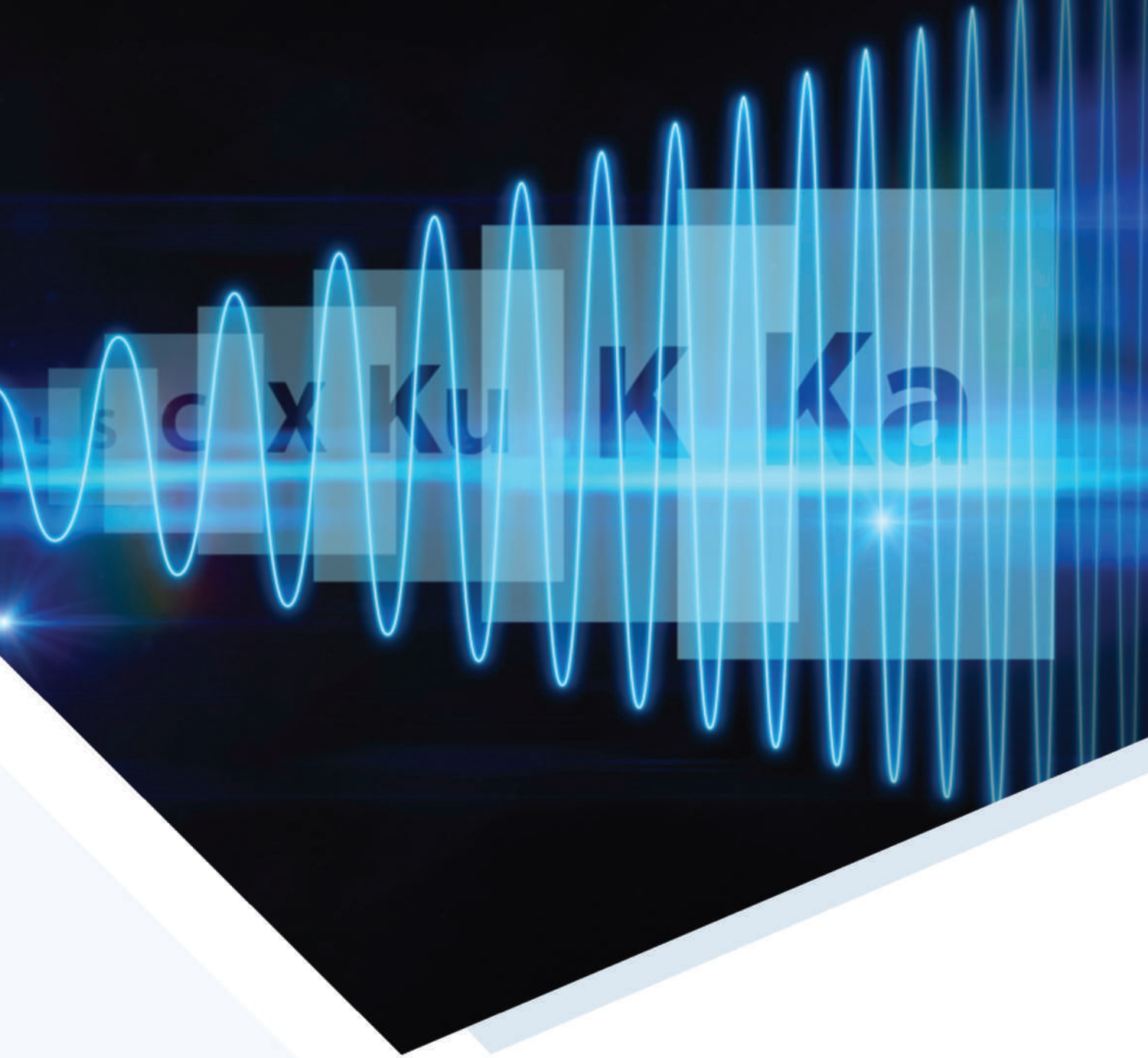

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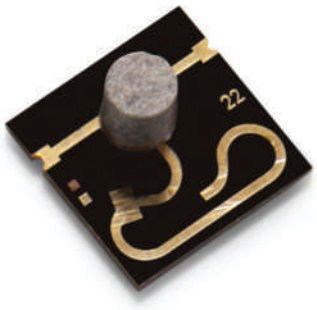

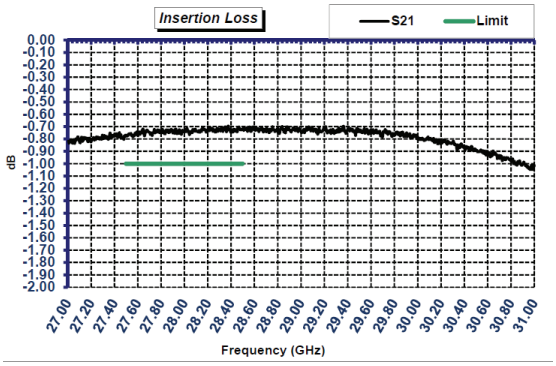

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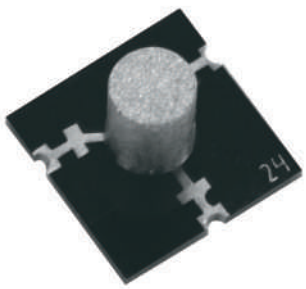

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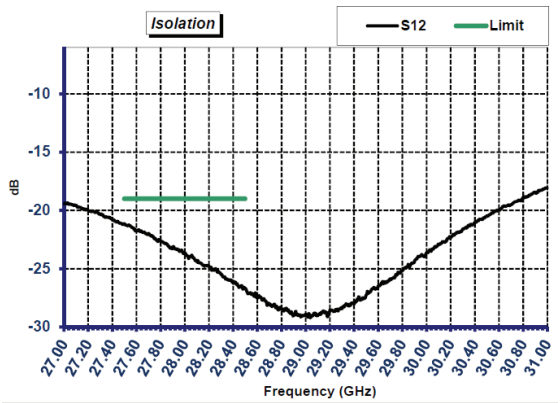

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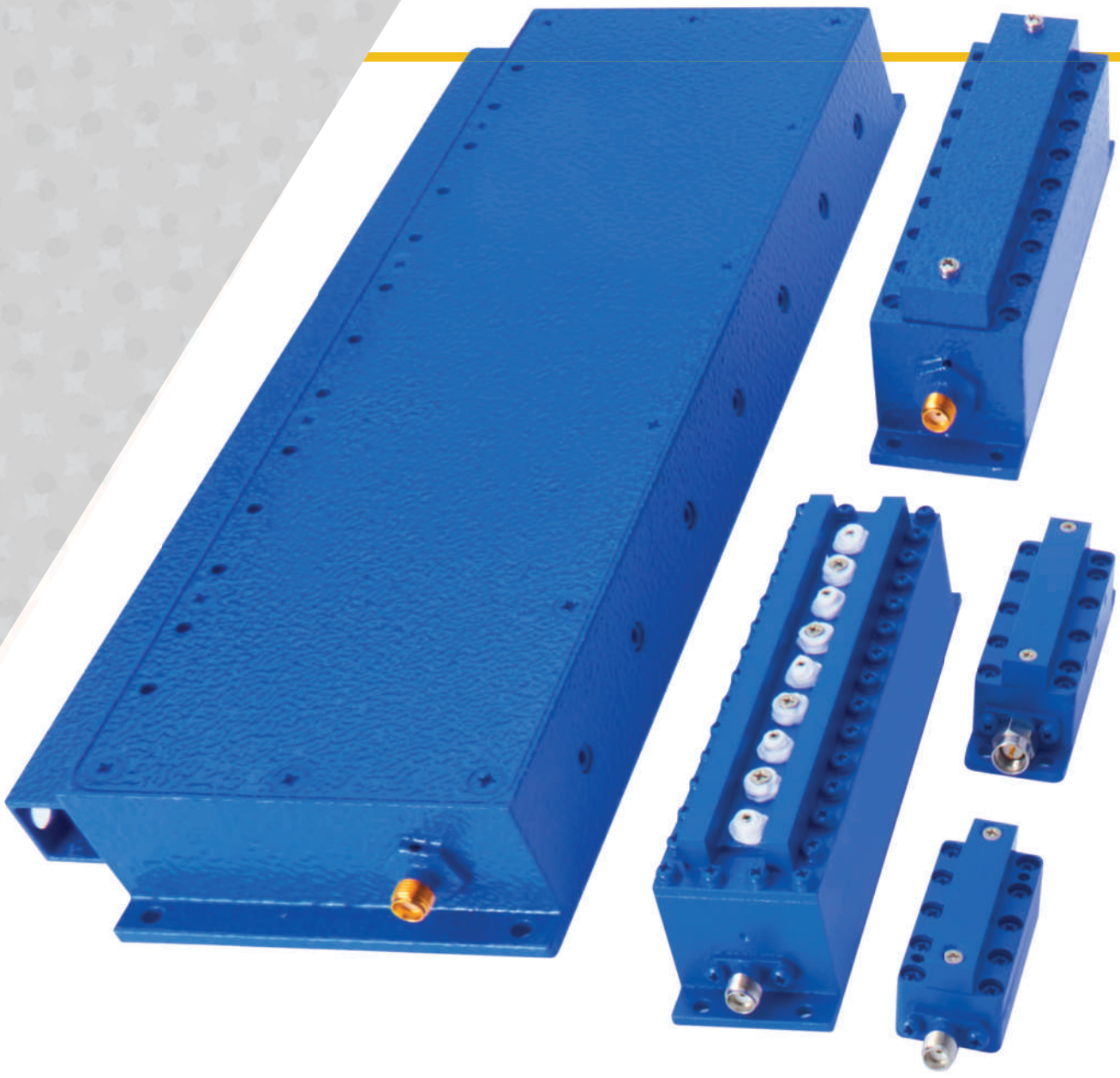

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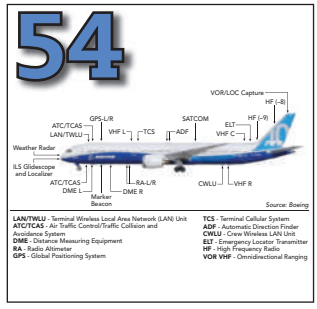

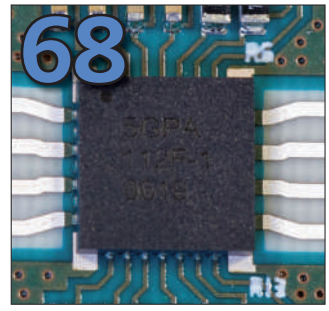

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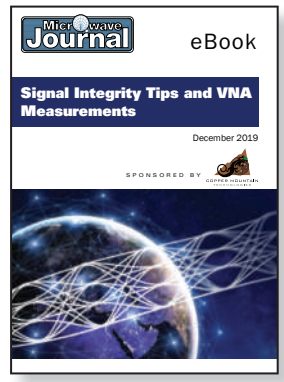

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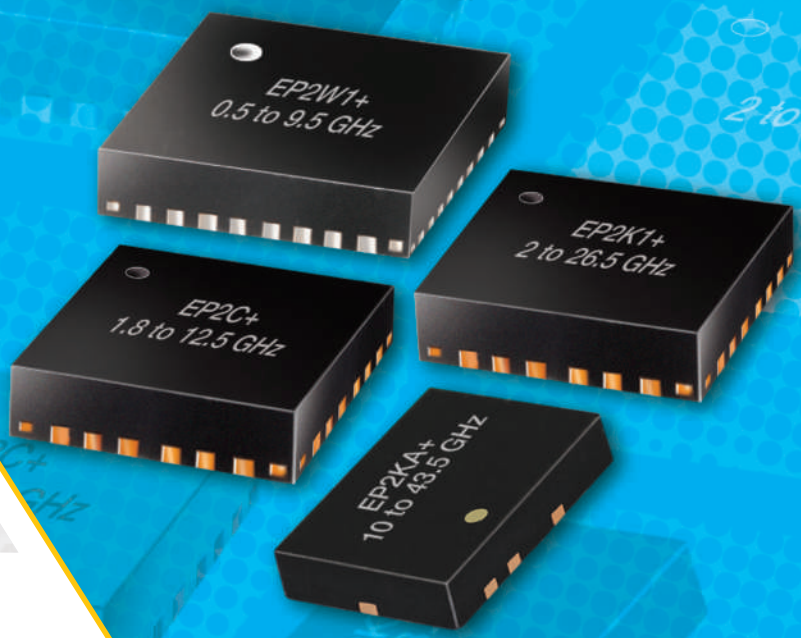

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Horus: A Testbed for Fully Digital Phased Array Radars

C. Fulton, R. Palmer, M. Yeary, J. Salazar and H. Sigmarsson
University of Oklahoma, Advanced Radar Research Center, Norman, Okla.

M. Weber
University of Oklahoma/National Oceanic and Atmospheric Administration, Norman, Okla.

A. Hedden
Combat Capabilities Development Command, Army Research Laboratory, Adelphi, Md.

Leveraging years of experience, the Advanced Radar Research Center (ARRC) at the University of Oklahoma (OU) is building the first-ever, mobile polarimetric, all-digital phased array radar (PAR),[1] as depicted in ***Figure 1***. As technology has significantly evolved over the last 10 to 15 years, especially in the areas of analog-to-digital converters (ADC), digital-to-analog converters (DAC), high-power amplifiers and field-programmable gate arrays (FPGA), the possibility of moving significant portions of a radar system closer to the aperture of a phased array antenna has become a reality. ***Figure 2*** depicts the overarching architecture of the all-digital PAR system, wherein an independent digital receiver and digital transmitter exist for each horizontal (H) and vertical (V) channel for each of our dual-pol elements.

RADAR EVOLUTION

Over the last 15 years, the ARRC has been engaged in the national Multifunction Phased Array Radar (MPAR) initiative, and subsequently the Spectrum Efficient National Surveillance Radar (SENSR) Program, as initially coordinated by the Federal Aviation Administration (FAA), Department of Defense (DoD), Department of Homeland Security (DHS) and National Oceanic and Atmospheric Administration (NOAA). Consequently, the ARRC is developing a scalable all-digital polarimetric S-Band phased array that addresses the requirements for weather and long-range aircraft scanning. The array will also support other important modes of operation including MIMO and general communications.

Agile beam steering and multifunction capabilities now make phased arrays the best candidates for multi-mission radar systems, offering efficient and cost-effective solutions. Advancements in GaAs, SiGe, CMOS and GaN technology provide reliable, highly integrated and affordable RF components that have enabled phased array antennas to become a core technology for modern remote sensing and communication. High levels of integration and more efficient components have allowed for phased array antenna architectures with multiple transceivers that can be used to increase functionality and performance at reduced cost, size and weight compared to their predecessors that exclusively used analog beamformers: for instance, 5G will certainly leverage phased array technology. Arrays with analog beamforming are inherently constrained to the beamforming scheme imposed by the exact configuration of front-end beamforming electronics.

Presently, digital beamforming (DBF) at the sub-array level is a common approach to increase the flexibility of phased array radars, as demonstrated by the 76-panel Advanced Technology Demonstrator (ATD) operated by NOAA's National Severe Storms Laboratory (NSSL) and the University of Massachusetts' (UMass) Raytheon Low-Power Radar (i.e., Skyler). Yet, the move towards element-level DBF architectures offers unprecedented capabilities. Examples of such systems include; Australia's CEA-FAR naval radar, the U.S. Navy's FlexDAR radar,[2] Israeli Elta's MF-STAR, AFRL's BEEMER (Baseband-digital at Every Element MIMO Experimental Radar) and Space Fence, to name a few. Moreover, digital at every element makes exquisite control of polarimetry a possibility, with single H, single V, simultaneous H&V for slant 45, LHC, RHC or arbitrary polarization states.

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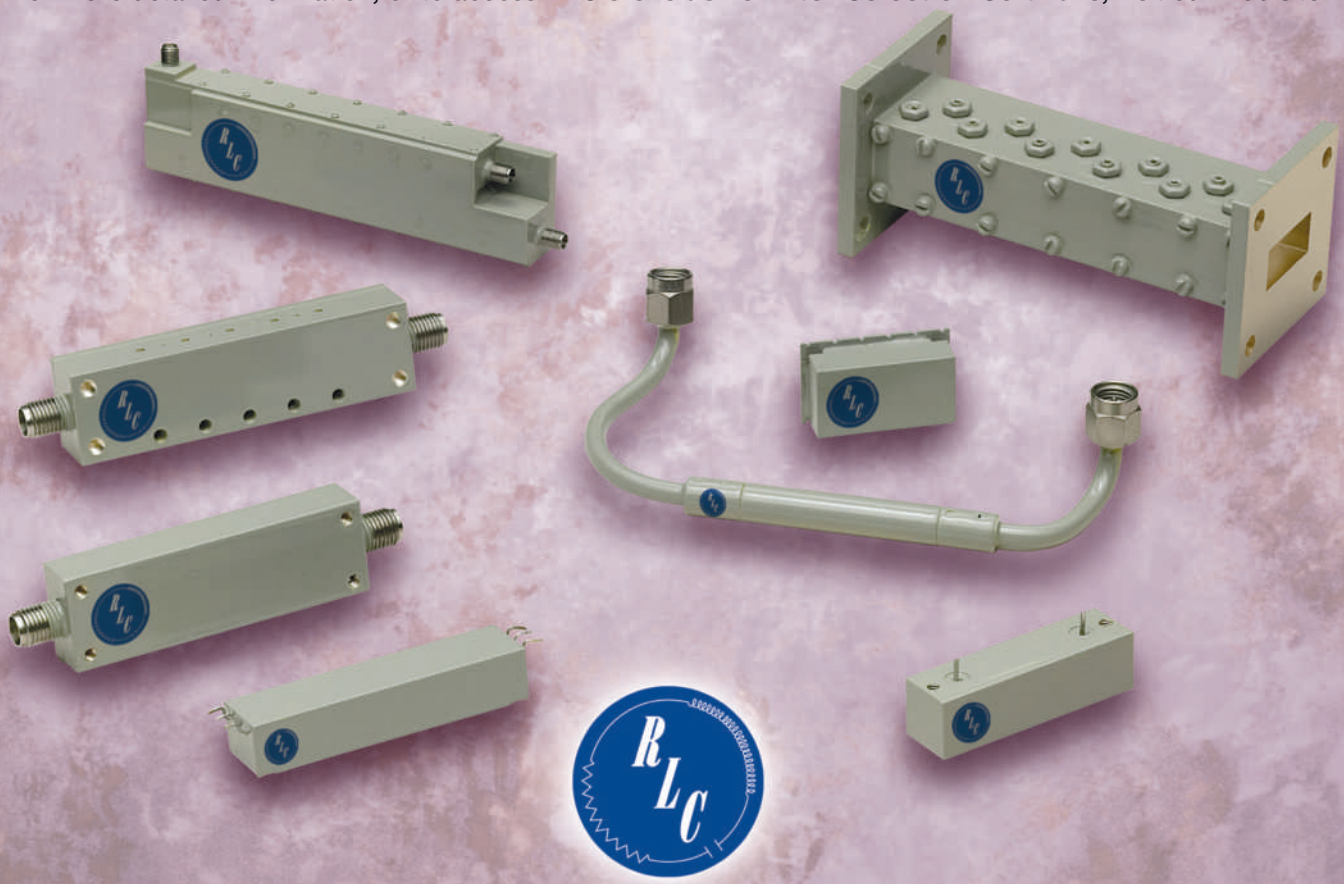

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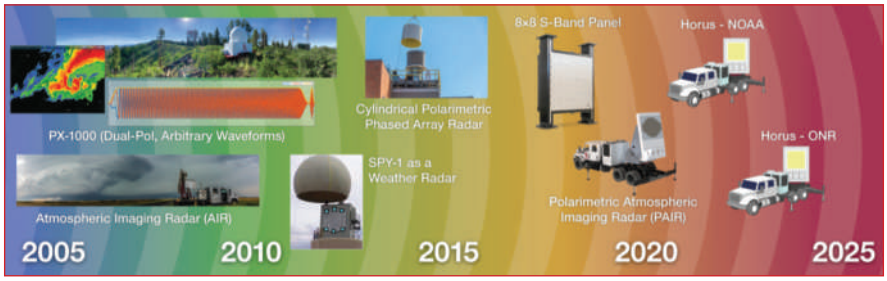

Fig. 1 **Genesis of the ARRC's mobile polarimetric all-digital phased array radar development.**

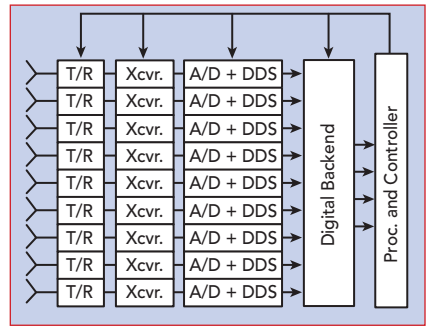

Fig. 2 **An independent digital receiver and digital transmitter exist for each element.**

Combat Capabilities Development Command Army Research Laboratory's (CCDC ARL) research is the development of robust techniques for array calibration. Operation in crowded and contested environments depends critically on protecting radar operations and maintaining calibration in dynamic environments. Factory calibration is insufficient for digital arrays, and methods for robust in-situ calibration are needed that are also computationally efficient. In conjunction with partners including OU and CCDC ARL is developing mutual coupling-based calibration techniques to address this problem. CCDC ARL is conducting proof-of-concept experiments to quantify performance of initial algorithms using an element-level digital array laboratory test asset. Moving forward, CCDC ARL will extend these techniques for wider bandwidth performance and focus on scalability to large-format arrays, as well as suitability for operational environments outside of the laboratory test bench.

FULLY DIGITAL ARCHITECTURE

Even though implementation of dual-polarization on PAR has proven challenging, significant progress has been made recently, as reported by a community workshop of radar technologies sponsored by the National Science Foundation (NSF),[5] such as MIT Lincoln Lab's S-Band panels at the ATD,[6] BCI/LMCO's S-Band prototype, NCAR's C-Band airborne phased array radar system, UMass' X-Band radar, and OU's S-Band cylindrical polarimetric phased array radar (CPPAR) demonstrator.[7] In order to improve the temporal resolution on spotlight operation, the single-polarized X-Band Atmospheric Imaging Radar

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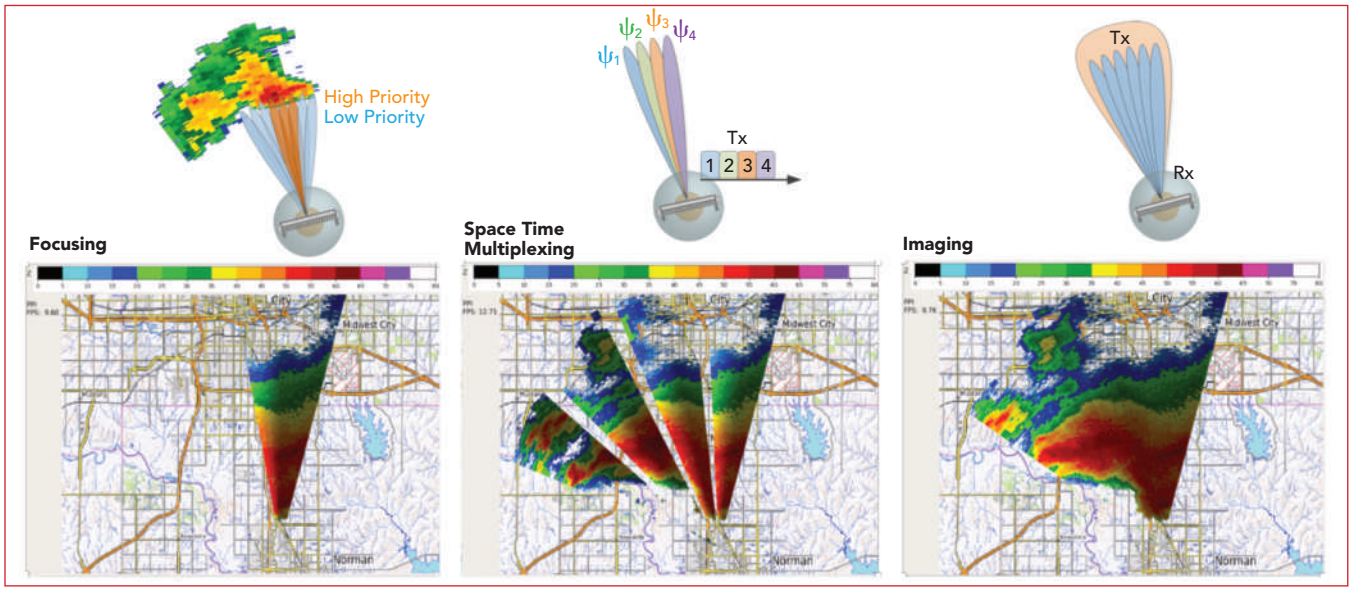
(AIR) was developed by the ARRC several years ago, as shown in Figure 1. The AIR operates in a "floodlight" mode, utilizing a 20-degree vertical fan beam on transmit and 36 receiving arrays capable of fine scale digital beamforming. In other words, a range height indicator (RHI) of radar measurements can be formed simultaneously, similar to taking a picture with an electromagnetic camera. This configuration, combined with 20 degrees/sec mechanical scanning in azimuth, allows the current AIR to collect 180 by 20 degree volumes in approximately nine seconds; hence, the world's highest resolution observations of tornado genesis.[8] A similar system with floodlight operation is the X-Band PAR located at Osaka University.

These advanced imaging surveillance modes of operation require digitization of multiple subarray chan-



▲ Fig. 3 **Three example radar modes that demonstrate the efficacy of an all-digital array.**

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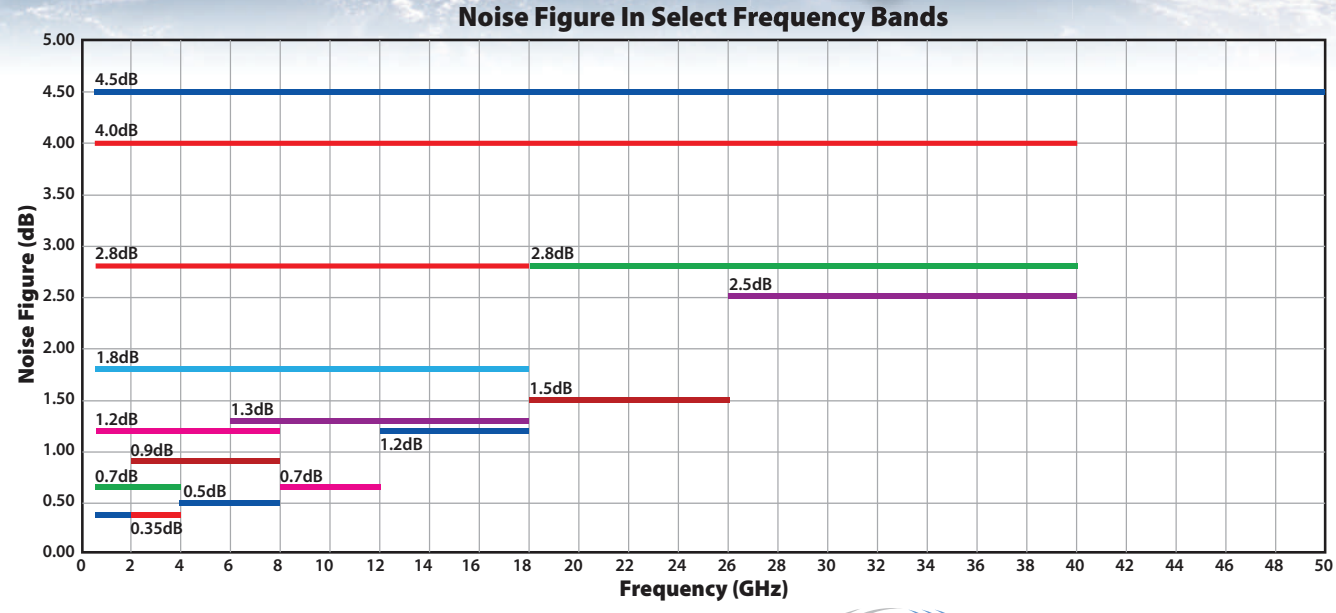

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nels. Increased levels of digitization also enable adaptive digital beamforming (ADBF), space-time adaptive processing (STAP) and even MIMO modes of operation. An ideal phased array architecture would feature digitization and control of both the transmitted and received signals at each antenna element, along with the ability to cover wide bandwidths. Because the element-level processing and subsequent beamforming are digital, it can be reconfigured and optimized for different applications. Digitization at the element level opens the door to new processing and beamforming schemes and delivers maximum flexibility with unprecedented dynamic range in large systems. For instance, given M elements and uncorrelated noise at each element, the signal-to-noise ratio of the system is increased by 10log(M). However, this comes with inherent technological risks and practical challenges associated with the amount of data to process and the use of less sophisticated transceivers.

Fig. 4 **Electronics and 8x8 dual polarized panel (left); Horus truck with an array of panels (middle); future application that employs a multitude of panels and leverages the scalable architecture (right).**

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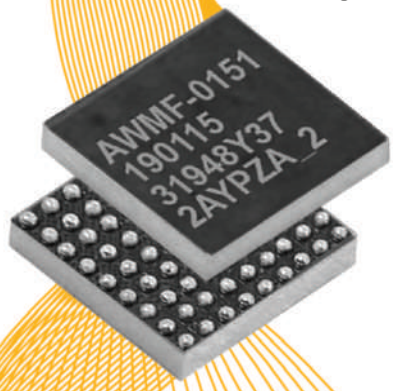

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Figure 3 shows three example modes of our all-digital PAR system. The left panel of Figure 3 depicts several typical high sensitivity beams and several low priority beams, which are needed for continuously dwelling in an area to glean important information. The middle panel of Figure 3 depicts a space time multiplexing paradigm whereby sets of independent samples can be collected from a surveillance area; this allows data to be collected with fewer samples. Since adaptive spatial filtering can be achieved via a phased array,[4] this greatly demonstrates the use of a phased array over a typical parabolic dish antenna. Finally, the right panel of Figure 3 depicts how our mobile demonstrator will leverage the team's imaging expertise so that rapid volume scanning may be achieved.[8]

For any future multi-mission radar, multiple interleaved functions are practically the only way to satisfy the bevy of mission requirements in a given timeline, so advanced beamforming flexibility through digitization is critical. Furthermore, additional missions over the lifetime of a digital PAR could be implemented with software upgrades, rather than costly hardware retrofits, resulting in significant operation and maintenance cost savings. The next section provides an overview of the development of an S-Band, dual-polarization PAR that is being designed and built at the ARRC that will achieve these goals. This system, which we call Horus, has a digital transceiver per polarization, per element and will be a valuable research tool in evaluating the benefits and challenges to such an approach.

DESIGN CONCEPTS OF THE "HORUS" RADAR

A mobile, S-Band, dual-polarized phased array system is currently under development by the ARRC. It has a fully digital architecture, and this system will consist of 1024 dual-polarized elements divided into 25 8×8 panels (16 are populated with electronics) as shown in ***Figure 4***. Each panel houses eight "OctoBlades" wherein virtually all radar electronics reside. Each OctoBlade, which drives an eight-element column of the panel's high performance antenna array with nearly ideal polarization along the principal planes through careful design, consists of a metal cooling plate (heat transport duct) with PCBs on each side to house a total of 16 GaN-based frontends (>10 W per element, per polarization), eight dual-channel digital transceivers from analog devices, four front-end FPGAs for processing and two FPGAs for control. Antenna sub-systems and their associated electronics can be organized in one of three primary architectures: conformal tile assembly, panel assembly (with slide-out OctoBlades) or separate structures that are separated by cables (see Figure 4). This design with slide-out OctoBlades provides the least maintenance costs since these electronic assemblies are easily hot-swappable. This convenient feature is ideal for ground-based systems that require service lives of several decades.

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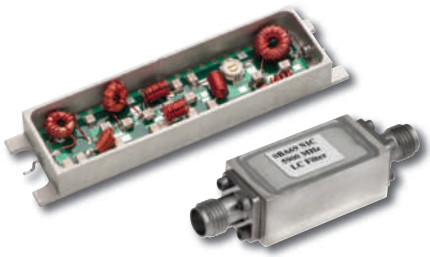

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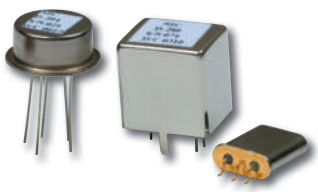
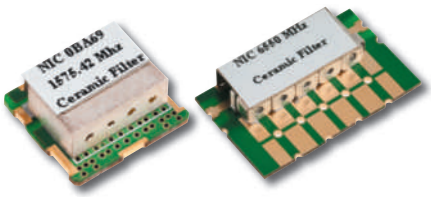
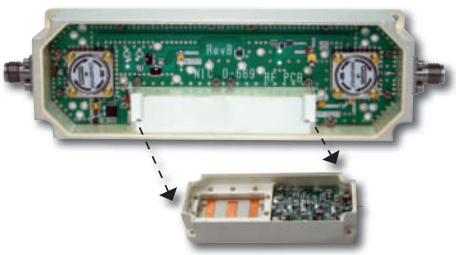


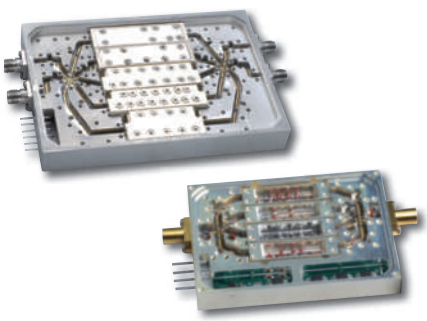
Ceramic Filters



Integrated Assemblies



Switch Filter Banks



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In general, the performance of large arrays depends on their digital interconnection structure on the backside of the array. Traditional and hierarchical topologies are currently in use, and their characteristics such as scalability, flexibility, high bandwidth, etc. are limited. For instance, some use a mesh topology. With a mesh topology, central channels are significantly burdened. This often leads to the congestion of the center area of the mesh. The solution for such a situation is to add routers in the mesh or to use torus topology which, with the symmetry introduced on the routers in the opposite edges, tends to mitigate unwanted congestion with a small increase of resources. Many open issues remain, and we believe that the three primary issues are: data transport mechanism (i.e., RapidIO, Gigabit Ethernet, etc.), degree of partial beamforming, and data routing topology (i.e., hierarchal, etc.). Balancing these issues will allow for array sizes to be conveniently scaled to meet a wide range of missions.

For normal radar operation of Horus, digital beamforming will be accomplished over a RapidIO network feeding the back of the panels. This will enable beam-bandwidth products for a notional multifunction PAR system (e.g., 200 MHz beams at suitable dynamic range). Hierarchical beamformers reduce the number of data streams at each level of the hierarchy, performing partial weighting and aggregation along the way. Systolic beamformers are similar, but instead of aggregating data in parallel at a given "stage," data is sent serially down a link of nodes or even elements, with partial beam data being aggregated along the way to produce outputs for subsequent processing stages. Virtually every digital array of moderate-to-large size known to the authors uses some form of hierarchical/systolic processing to form digital front ends. Importantly, and unlike analog arrays, with hierarchical/systolic beamforming, the number of beams can be traded against the signal bandwidth in the digital domain, with a fixed overall "beam-bandwidth" product remaining roughly constant at every point in the front-end processing chain.

For multi-tier hierarchies, the interconnection costs scale with the logarithm of the number of elements M, while data and front-end processing scale roughly linearly with M. Both scale with the overall system bandwidth. These types of considerations guide the design of any front-end DBF architecture within the overall trade space of calibration, beamforming, and adaptation. Finally, RapidIO supports arbitrary network architectures, like folded-Torus, that can reduce latency and improve reliability, and these will be explored in the future.

Figure 5 shows the laboratory measurements for the mobile demonstrator.[9] This fully digital active and dual-polarized phased array antenna was designed for full control of transmitted and returned signals of each antenna element. The antenna design for the ARRC's project

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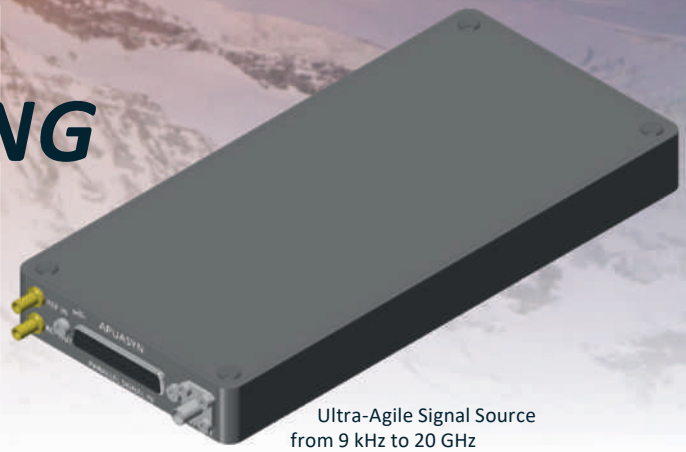

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	865-M	100 kHz to 40 GHz	20 µs
	APUASYN	9 kHz to 20 GHz	2 µs
Multi-Channel Signal Generators	855B	300 kHz to 6, 12, 20, 33 or 40 GHz	30 µs
Analog Signal Generators	845	100 kHz to 12, 20 or 26.5 GHz	30 µs
	865	100 kHz to 6, 12.75, 20, 26, or 40 GHz	25 µs
Vector Signal Generators	875	10 MHz to 3, 5, 20 or 40 GHz	200 ns

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was focused on achieving the same or improved performance compared to WSR-88D parabolic antennas. These design specifications are critical, given that the weather mission presents more challenging polarimetric requirements, in terms of target identification, than those for aircraft surveillance missions. Dual-polarized

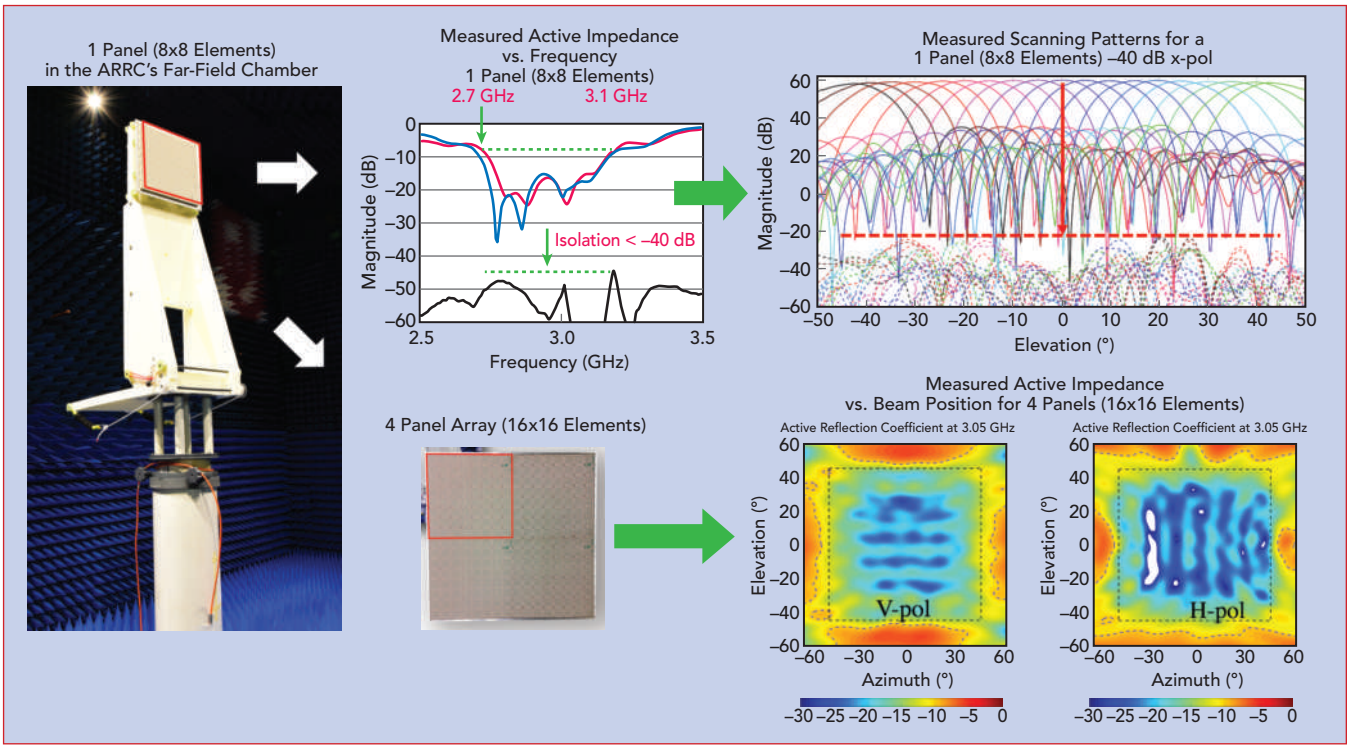

Fig. 5 **Experimental set-up and various parameter measurements.**

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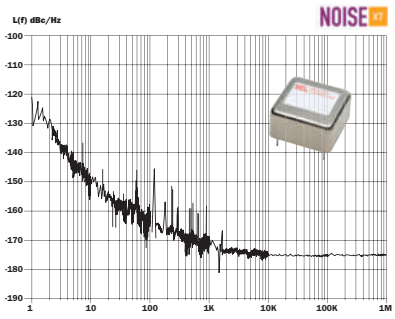
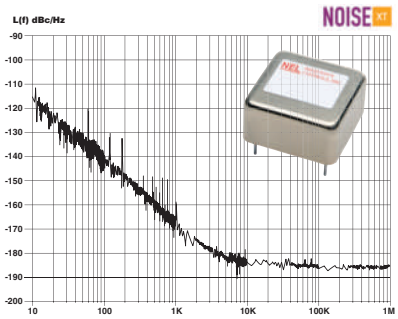
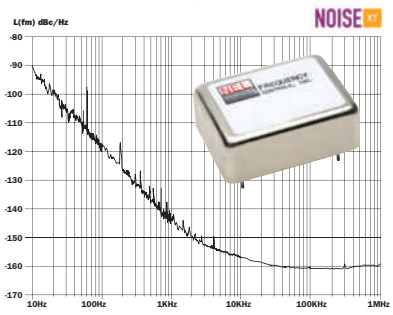


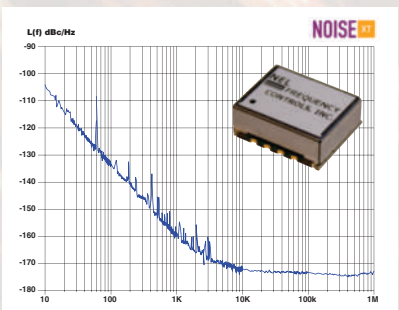
100 MHz Output Frequency



1 GHz Output Frequency



ULPN TCXO @ 100 MHz with Low G Sensitivity



0.2ppb/ G

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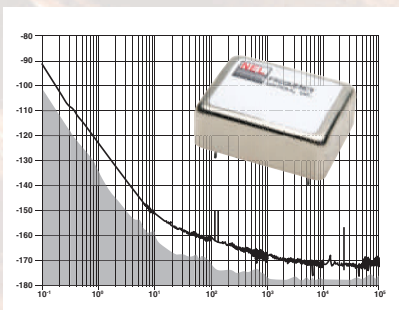

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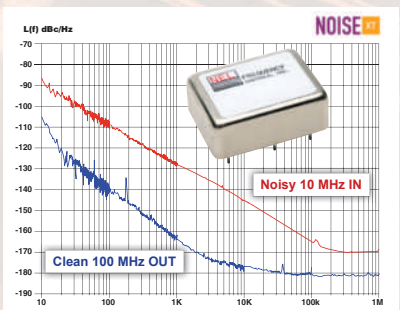
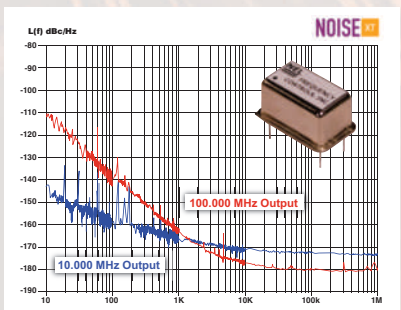


Atomic clock stability with low phase noise

DIP 14 OCXO— 10 MHz or 100 MHz



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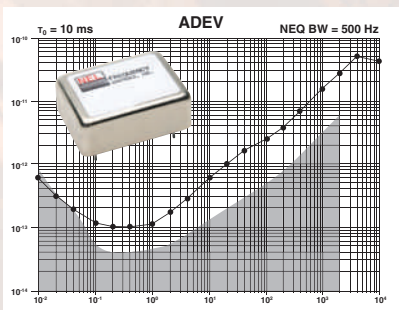

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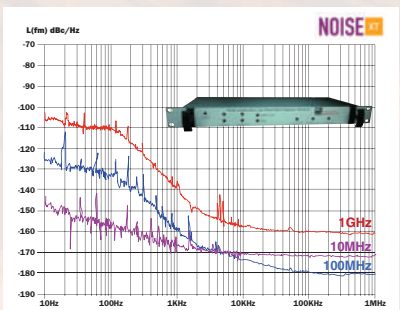

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radars require both low cross-polarization levels (better than −40 dB) and well-matched patterns (lower than 0.1 dB) to successfully determine the polarimetric variables of the scanned atmosphere sector.

In general, when the cross-polarization levels of the antenna increase, all the biases in the polarimetric variables are increased. Multiple factors in the antenna element were investigated during the design process of the 8×8 array, and these factors included: edge diffraction suppression; bandwidth in excess of 10 percent with a central frequency of 2.8 GHz; port-to-port isolation in the element on the order of −50 dB; cross polarization levels below −45 dB and co-polar mismatch below 0.1 dB at ±60° and ±10° for scanning range at the azimuth and elevation planes, respectively. After careful calibration; an active reflection coefficient of at least −10 dB at ±60° and ±10° can be achieved for scanning range at the azimuth and elevation planes, respectively. Consequently, a new stacked cross microstrip patch radiator with electromagnetic coupling was developed for Horus,[9] and an 8×8 panel of these are depicted on the left side of Figure 5. The radiators and the feeding network were separated into two different assemblies to prevent them from bending after fabrication. The radiator assembly consists of two conducting layers and a radome of RT/Duroid 5880LZ bonded with RO4450F.

Modern day and next-generation radars are challenged to operate in complex, dynamic environments as demand for precious spectrum continues to grow. For instance, the desire for resilient systems that can adapt to and counter new sources of interference across the spectrum is a common theme that crosscuts the Army's modernization strategy. Consequently, in order to mitigate interference, the integration of miniaturized filters, both static and frequency reconfigurable, into the antenna panels is being investigated in parallel with the antenna development. These filters are based on capacitively-loaded, substrate-integrated waveguide (SIW) resonators that are completely integrated into the feeding network assembly. The static filters provide added out-of-band rejection, and the reconfigurable filters can be used to achieve in-band interference rejection.[10]

PROJECT STATUS AND FUTURE R&D PLANS

This article provides a summary on a project that will provide solutions to modern-day radar challenges by delivering the full flexibility of digital at every element (i.e., digital Tx and Rx for both H and V on every element). The list below provides a concise summary of possibilities for demonstrations with the Horus system:

- Advanced aperture and waveform agility, performing many different tasks/objectives simultaneously;
- MIMO radar—multiple transmit and receive antennas;
- Spectrally agile active phased arrays;
- Advanced DBF for a higher an-

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- In situ array calibration using the mutual coupling method.■

ACKNOWLEDGMENTS

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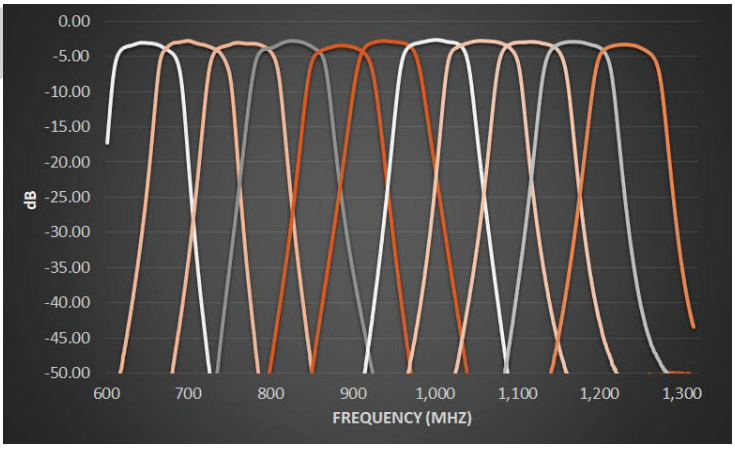

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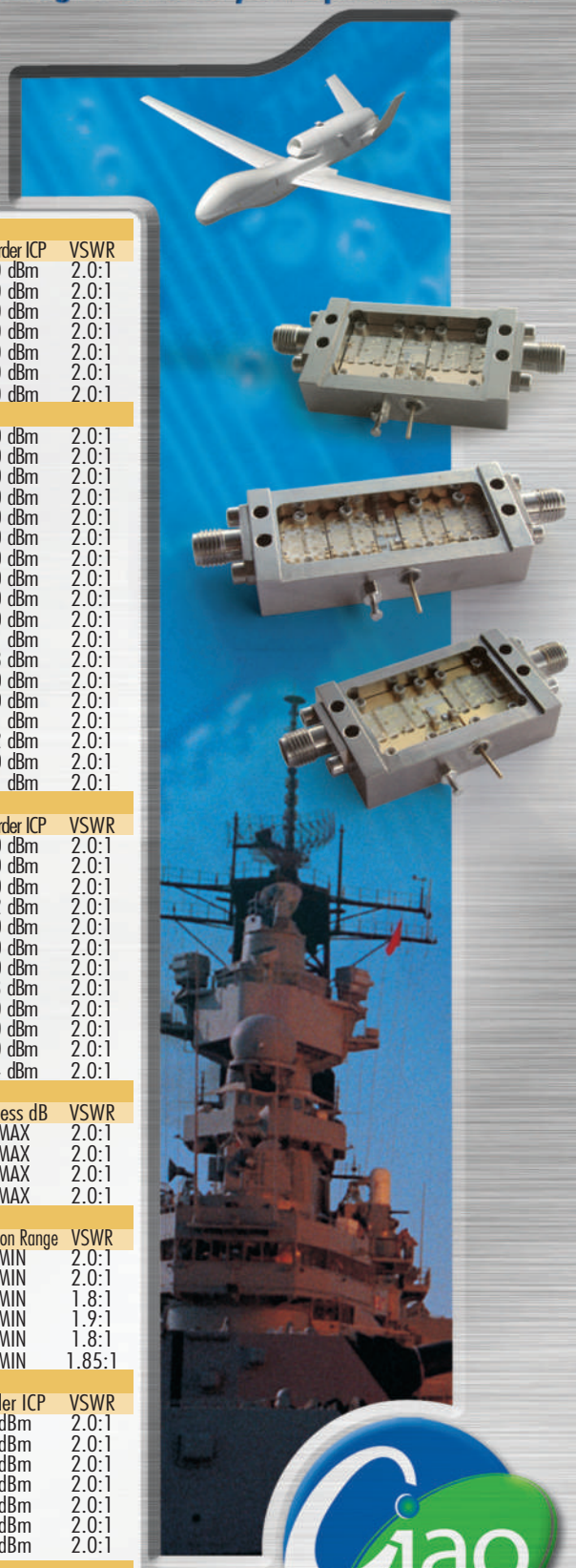

OCTAVE BAND LOW NOISE AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2110	0.5-1.0	28	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA12-2110	1.0-2.0	30	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA24-2111	2.0-4.0	29	1.1 MAX, 0.95 TYP	+10 MIN	+20 dBm	2.0:1
CA48-2111	4.0-8.0	29	1.3 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA812-3111	8.0-12.0	27	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA1218-4111	12.0-18.0	25	1.9 MAX, 1.7 TYP	+10 MIN	+20 dBm	2.0:1
CA1826-2110	18.0-26.5	32	3.0 MAX, 2.5 TYP	+10 MIN	+20 dBm	2.0:1

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2111	0.4 - 0.5	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA01-2113	0.8 - 1.0	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3117	1.2 - 1.6	25	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3111	2.2 - 2.4	30	0.6 MAX, 0.45 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3116	2.7 - 2.9	29	0.7 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA34-2110	3.7 - 4.2	28	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA56-3110	5.4 - 5.9	40	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA78-4110	7.25 - 7.75	32	1.2 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA910-3110	9.0 - 10.6	25	1.4 MAX, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA1315-3110	13.75 - 15.4	25	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3114	1.35 - 1.85	30	4.0 MAX, 3.0 TYP	+33 MIN	+41 dBm	2.0:1
CA34-6116	3.1 - 3.5	40	4.5 MAX, 3.5 TYP	+35 MIN	+43 dBm	2.0:1
CA56-5114	5.9 - 6.4	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6115	8.0 - 12.0	30	4.5 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6116	8.0 - 12.0	30	5.0 MAX, 4.0 TYP	+33 MIN	+41 dBm	2.0:1
CA1213-7110	12.2 - 13.25	28	6.0 MAX, 5.5 TYP	+33 MIN	+42 dBm	2.0:1
CA1415-7110	14.0 - 15.0	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA1722-4110	17.0 - 22.0	25	3.5 MAX, 2.8 TYP	+21 MIN	+31 dBm	2.0:1

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA0102-3111	0.1-2.0	28	1.6 Max, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA0106-3111	0.1-6.0	28	1.9 Max, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-3110	0.1-8.0	26	2.2 Max, 1.8 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-4112	0.1-8.0	32	3.0 MAX, 1.8 TYP	+22 MIN	+32 dBm	2.0:1
CA02-3112	0.5-2.0	36	4.5 MAX, 2.5 TYP	+30 MIN	+40 dBm	2.0:1
CA26-3110	2.0-6.0	26	2.0 MAX, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA26-4114	2.0-6.0	22	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA618-4112	6.0-18.0	25	5.0 MAX, 3.5 TYP	+23 MIN	+33 dBm	2.0:1
CA618-6114	6.0-18.0	35	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA218-4116	2.0-18.0	30	3.5 MAX, 2.8 TYP	+10 MIN	+20 dBm	2.0:1
CA218-4110	2.0-18.0	30	5.0 MAX, 3.5 TYP	+20 MIN	+30 dBm	2.0:1
CA218-4112	2.0-18.0	29	5.0 MAX, 3.5 TYP	+24 MIN	+34 dBm	2.0:1

LIMITING AMPLIFIERS

Model No.	Freq (GHz)	Input Dynamic Range	Output Power Range Psat	Power Flatness dB	VSWR
CLA24-4001	2.0 - 4.0	-28 to +10 dBm	+7 to +11 dBm	+/- 1.5 MAX	2.0:1
CLA26-8001	2.0 - 6.0	-50 to +20 dBm	+14 to +18 dBm	+/- 1.5 MAX	2.0:1
CLA712-5001	7.0 - 12.4	-21 to +10 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1
CLA618-1201	6.0 - 18.0	-50 to +20 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	Gain Attenuation Range	VSWR
CA001-2511A	0.025-0.150	21	5.0 MAX, 3.5 TYP	+12 MIN	30 dB MIN	2.0:1
CA05-3110A	0.5-5.5	23	2.5 MAX, 1.5 TYP	+18 MIN	20 dB MIN	2.0:1
CA56-3110A	5.85-6.425	28	2.5 MAX, 1.5 TYP	+16 MIN	22 dB MIN	1.8:1
CA612-4110A	6.0-12.0	24	2.5 MAX, 1.5 TYP	+12 MIN	15 dB MIN	1.9:1
CA1315-4110A	13.75-15.4	25	2.2 MAX, 1.6 TYP	+16 MIN	20 dB MIN	1.8:1
CA1518-4110A	15.0-18.0	30	3.0 MAX, 2.0 TYP	+18 MIN	20 dB MIN	1.85:1

LOW FREQUENCY AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure dB	Power-out @ P1-dB	3rd Order ICP	VSWR
CA001-2110	0.01-0.10	18	4.0 MAX, 2.2 TYP	+10 MIN	+20 dBm	2.0:1
CA001-2211	0.04-0.15	24	3.5 MAX, 2.2 TYP	+13 MIN	+23 dBm	2.0:1
CA001-2215	0.04-0.15	23	4.0 MAX, 2.2 TYP	+23 MIN	+33 dBm	2.0:1
CA001-3113	0.01-1.0	28	4.0 MAX, 2.8 TYP	+17 MIN	+27 dBm	2.0:1
CA002-3114	0.01-2.0	27	4.0 MAX, 2.8 TYP	+20 MIN	+30 dBm	2.0:1
CA003-3116	0.01-3.0	18	4.0 MAX, 2.8 TYP	+25 MIN	+35 dBm	2.0:1
CA004-3112	0.01-4.0	32	4.0 MAX, 2.8 TYP	+15 MIN	+25 dBm	2.0:1

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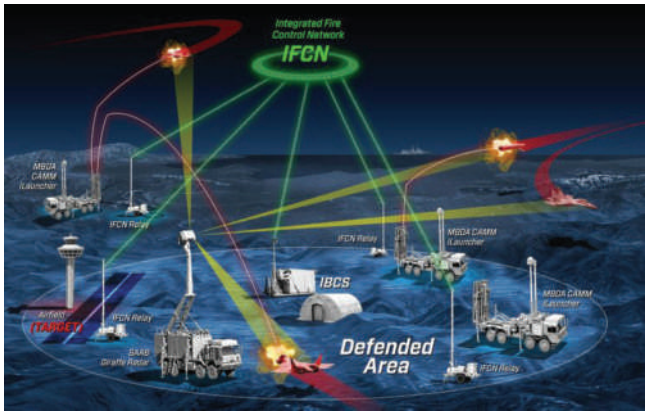
Integration of Disparate Missile & Radar Systems into IAMD Battle Manager

Northrop Grumman Corp. (NGC), MBDA and Saab have successfully completed a collaborative effort to demonstrate the ability to integrate MBDA's Common Anti-Air Modular Missile (CAMM) family and Saab's Giraffe radar system family into NGC's Integrated Air and Missile Defense (IAMD) Battle Command System (IBCS). CAMM was the first non-U.S. missile system to be demonstrated with IBCS earlier this year, and Giraffe represents the first non-U.S. sensor system to be demonstrated.

Simulated air targets were fed to the Giraffe radar emulator, which passed the radar information to IBCS to assess and track threats. IBCS operators planned and executed optimized engagements based on that data using the CAMM missile emulators which engaged multiple threats simultaneously. IBCS then closed the loop by displaying the outgoing missiles detected and reported by the Giraffe emulators. The event successfully demonstrated both distributed fire direction and advanced integrated fire control engagements.

"Building on lessons learned from the CAMM family integration, we were able to integrate the Giraffe radar onto the IBCS network even more rapidly and cost effectively, continuing to demonstrate the dynamic and flexible nature of IBCS's open architecture in adding capabilities when and as needed," said Bill Lamb, director, international battle management, NGC. "Together we are creating a revolutionary IAMD enterprise that maximizes the combat potential of all sensors and weapons across all domains and fills gaps in today's air defense capabilities."

MBDA's CAMM family is the next-generation of air defense missiles for multi-domain applications. Designed to defeat the most challenging of modern and future threats, including saturation attacks by precision-guided munitions and maneuvering high speed missiles attacking simultaneously from multiple directions, the CAMM family of missiles features a solid-state active radar seeker, 2-way data-link, low-signature rocket motor and a 360 degree soft-vertical launch system.



IFCN (Source: Northrop Grumman Corp.)

Saab's Giraffe AMB radar delivers key capabilities as part of short- and medium-range surveillance and ground-based air defense. It integrates powerful 3D surveillance radar and C3 functionality in one and the same system and provides forces with swift understanding of the air situation, enabling an immediate and effective response to changing threats, new tactics and shifting operational conditions.

IBCS creates a paradigm shift for IAMD by replacing legacy stove-piped systems with a next-generation, net-centric approach to better address the evolving complex threat. The system integrates disparate radars and weapons to construct a far more effective IAMD enterprise. IBCS delivers a single integrated air picture with unprecedented accuracy and broadens surveillance and protection areas. With its open systems architecture, IBCS allows incorporation of current and future sensors and effectors and interoperability with joint C2 and the ballistic missile defense system.

IBCS is managed by the U.S. Army Program Executive Office for Missiles and Space.

Echodyne Radars Anchor DARPA's Urban Drone Testing

Echodyne announced that its radars were key active sensors deployed by DARPA for its Aerial Dragnet program in San Diego. In conjunction with the Applied Physics Laboratory at the University of Washington (APL-UW), Echodyne's EchoGuard and EchoFlight radars provided comprehensive surveillance of drone activity in San Diego's urban airspace.

The DARPA testing involved radar sensors on two large tethered aerostat balloons flying at up to 400 ft. above ground level over San Diego and National City, as well as fixed building-top and tower mounted locations providing large-area coverage. The sensors were tuned to detect and track small drones and distinguish them from background objects such as buildings, vehicles and birds. The testing assessed how well the system could detect, track and identify over 150 models of drones including various COTS models, which simulated unauthorized/unidentified drones flying in the city.

Drone sales into the consumer and commercial segments will result in nearly 2 million UAVs in the U.S. in 2020, and the global market is expected to grow at a CAGR of 20.5 percent to reach nearly $43 billion in 2024, per the FAA Aerospace Forecast.

San Diego was a natural choice to test this system given the city's participation in the FAA's UAS Integration Pilot Program (IPP). While DARPA's focus is on protecting U.S. troops from drone attacks in urban settings

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overseas, the system under development could ultimately help protect U.S. metropolitan areas from potential drone-enabled terrorist threats.

"In conjunction with APL-UW, we operated more than a dozen radars on aerostats and rooftops to detect and track urban drone flights," said Tom Driscoll, CTO, Echodyne. "Our performance demonstrated that Echodyne's innovative, beam steering, electronically scanning radars have unique operational, sensitivity and intelligence characteristics necessary to conduct networked airspace surveillance over a major U.S. city."

Japan Protected with SPY-7

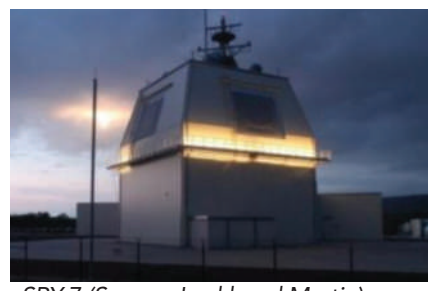
Lockheed Martin (LM) and its trading partner in Japan recently contracted with the Japanese Ministry of Defense to produce two solid-state radar (SSR) antenna sets for Aegis Ashore Japan. Recently designated by the U.S. government as AN/SPY-7(V)1, this technology is derived from current radar programs and significant LM investment. Variants of the SPY-7 radar will also be utilized through partnerships with the U.S. government, Spain and Canada. To date, the technology has been selected for a total of 24 systems.

Equipped with the latest digital, SSR technology, Aegis Ashore will integrate the SPY-7 radar with the Aegis Combat System and protect Japan with a robust system that:

- Can detect, track and engage sophisticated ballistic missile threats;
- Provides several times the detection range and sensitivity of traditional SPY-1 Aegis Ashore systems; and
- Engages multiple targets simultaneously with proven interceptors.

The combat system for Aegis Ashore will be compatible with the country's current Aegis naval fleet for full interoperability. Aegis Ashore will be updated from the same Common Source Library of software updates that all Aegis assets utilize.

The Aegis Weapon System is the most deployed combat system in the world, and its flexible system architecture enables it to fulfill a variety of missions. Its unique open architecture allows the system to maintain interoperability across global domains on 118 ships, 10 ship classes and seven countries to protect warfighters.



SPY-7 (Source: Lockheed Martin)

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Changes Ahead with Innovative 5G Uses

With 46 5G networks deployed globally as of November 2019, 5G networks are expanding the value of wireless communications like never before. According to IHS Markit, up to 13.2 trillion worth of sales enablement and 22.3 million jobs will be supported by 5G by 2035. In its new whitepaper, "5G Services Innovation," 5G Americas identifies emerging services across a wide range of uses, including home broadband replacement, cloud gaming, smart utility grid enhancements, UAVs and others.

The white paper presents a comprehensive introduction of the adoption and barriers in implementing 5G. It highlights detailed use cases that could serve as potential new revenue streams for enterprises and network providers.

In addition, it explores how 5G will use a wide array of available low, mid and high spectrum bands and support licensed, shared and unlicensed spectrum to deliver new services. Spectrum diversity enables 5G to scale from traditional wide area, to enterprise and to indoor/outdoor hotspot deployments.

Chris Pearson, president, 5G Americas said, "Once the full commercial capabilities of 3GPP Release 15 and 16 are deployed, use case opportunities will increase immensely as new services and applications emerge in a new hyper connected world."

With 1.3 billion 5G subscribers predicted as early as 2023, according to Ovum, there have been at least 21 potential unique 5G use cases identified that will affect productivity and enhance economic activity across a broad range of industry sectors. The white paper identifies some of these promising use cases, such as:

- **FWA:** 5G FWA can replace home or business broadband, eliminating the need for costly deep-fiber fixed access infrastructure deployment and offer connectivity solutions that can achieve 10 to 100× more capacity than 4G networks.
- **Cloud Gaming:** Cloud gaming represents a fundamental change in gaming because it shifts the computationally intensive graphics rendering and processing from the user's device to network servers. 5G low latency connectivity enabled by edge servers will be required to deliver enhanced cloud gaming services on mobile devices.
- **Smart Grid:** Two-way communication networks for the electricity grid will allow wirelessly connected devices to remotely detect, monitor and adjust electricity usage and power consumption. 5G will be a catalyst, allowing networks to provide the required throughput and ultra-low latencies essential for smart grid applications.
- **Extended Reality (XR)—AR & VR:** 5G will provide renewed momentum towards expansion of the XR market. XR applications are some of the most critical edge applications being developed by the industry.
- **Non-Terrestrial Networks (NTN):** The aerospace industry is on the verge of a revolution as a result of innovation and investment in the areas of LEO and high altitude platform station (HAPS) systems. LEO and HAPS systems represent a new opportunity for network operators to establish NTNs to serve many different use cases that would otherwise be difficult with traditional Earth networks.
- **UAVs:** Ultra-low latency is a key requirement for 5G and coupled with robotics will usher in a new era of remote medicine, factory robotics and drones—or UAV. 5G will enhance UAV capabilities and Traffic Management System (UTM) operations.
- **Healthcare:** Healthcare, specifically telemetry, is one of the leading IoT use cases expected to deliver the fastest spending growth over the 2017-2022 forecast period. New treatment devices will rely on the URLLC and time synchronization capabilities of 5G to support accurate and timely information sharing and control. Tasks may range from sharing video to diagnostic purposes, to controlling an insulin pump or performing a robotic surgery.

Smart Cities are Getting Smarter

In its new whitepaper, "5 Ways Smart Cities Are Getting Smarter," ABI Research identifies digital twins and urban modeling, resilient cities, circular cities, micro-mobility and smart spaces as the five new urban strategy shifts that will make smart cities surprisingly smarter.

Cities have faced challenges like congestion, pollution and safety for decades, and most have a plan to combat them. While they continue to face these traditional issues, new threats such as cyberattacks, climate change and other emerging problems are mounting.

While smart city tech investments will reach over $61 billion globally in 2026, most of the expenditure will be for incremental improvements. "In fact, it is an illusion to believe that adding just a shallow layer of IoT technology to legacy urban environments will allow cities to address the urban challenges of the future, ranging from the provision of sustainable energy to the adoption of smart mobility and the construction of resilient cities," explains Dominique Bonte, VP, ABI Research.

The first strategy shift on the horizon is holistic, real-time modeling (digital twins of entire cities) and the automated, generative design of urban environments, both brownfield and greenfield. "Modeling cities and optimizing operations through digital twins is great; designing them from scratch with AI tools is better," says Bonte.

The second strategy shift is migrating from a focus on "safe and secure cities" to resilient cities. This shift

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is where next-generation technologies and paradigms can be fully leveraged. Due to their dense character, urban areas are extremely vulnerable to both loss of life and economic value (GDP). Cities need to be ready and prepared for such events in terms of evacuation emergency response procedures. To make cities fully resilient, it is vital to be able to predict (with the help of advanced AI and deep learning approaches) and, whenever possible, avoid disasters.

Moving from green and sustainable cities to circular cities is the third strategy shift. "It is about turning entire cities into circular entities, eliminating their 'outside of the city' footprints entirely by achieving large degrees of self-support and self-sufficiency in areas like energy generation," says Bonte. Sharing, recycling, repairing, refurbishing and repurposing materials, assets and natural resources are guiding principles of circular economies. "This represents the endgame for smart cities."

Adding micro-mobility into the mix is a strategy shift known as Mobility 2.0. With mass market uptake of both driverless vehicles and consumer-owned EVs not expected any time soon, cities are embracing electric, two-wheel, micro-mobility to reduce congestion and provide cleaner mobility to address rampant air pollution. Bonte explains, "While earlier docked, non-electric bike-sharing schemes never really took off, citizens across the globe are now massively adopting dockless electric bike and scooter sharing, and to a lesser extent electric motorbike sharing, offering a much higher level of convenience due to their ubiquitous availability and powered operation."

The last strategy shift is rethinking the urban built environment through smart spaces. Many of the shifts discussed earlier are impacting how public space is used. The most obvious example is the decommissioning and repurposing of parking lots and buildings in cities enjoying high levels of car-sharing adoption. Catering to new forms of mobility, modular roads and energy-generating roads and sidewalks are just some of the possibilities considered. The expansion and active management of green spaces is also high on the agenda of urban designers.

Cities are experiencing somewhat of a revolution as to how they plan to tackle the myriad fundamental challenges that they are facing. "Bolder, more holistic, cross-vertical and closed-loop approaches are required to optimize and maximize the potential of available resources and services. This can only be done by leveraging a range of very advanced technologies including, urban modeling and digital twins, AI and automation, demand-response software, edge/cloud platforms and generative design," Bonte concludes.

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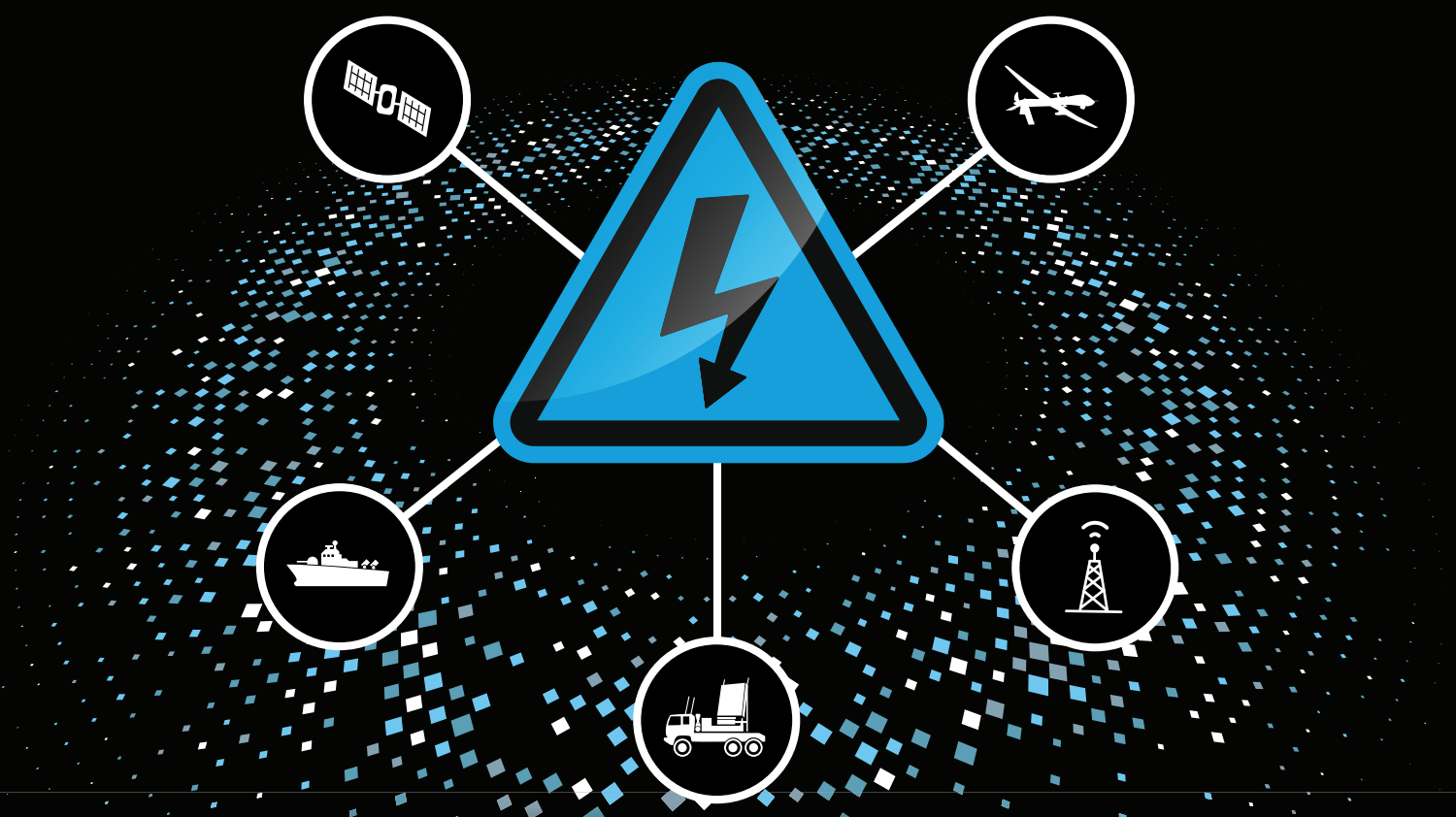

Part Number	Frequency (GHz)	Voltage	Package (mm)	Description
QPD1013	DC-2.7	65	7.2x6.6 DFN	150W GaN-on-SiC HEMT
QPD1025/QPD1025L	0.96-1.215	65	NI-1230	1800W GaN-on-SiC HEMT
QPA1027	2.8-3.5	50	6x6x0.85	60W GaN-on-SiC PA

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Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Cadence Design Systems and **National Instruments Corp.** announced that they have entered into a definitive agreement pursuant to which Cadence expects to acquire **AWR Corp.**, a wholly owned subsidiary of National Instruments (NI). AWR is an industry leader in high frequency RF EDA software technology and will bring a highly talented RF team to Cadence. Concurrently, Cadence and NI also entered into a strategic alliance agreement to expand their relationship to enhance electronic system innovation with a focus on communications. Under the terms of the definitive agreement, Cadence will pay approximately $160 million in cash at closing and expects approximately 110 AWR employees to join Cadence.

Smiths Interconnect announced that it has completed the acquisition of **Reflex Photonics Inc.** to expand in high speed data transmission market. Reflex complements Smiths Interconnect's product offering with the addition of a core fibre optic capability that will help address the needs arising from high speed data transmission in market segments requiring high-reliability. Reflex's products, patents and references will provide significant differentiation to Smiths Interconnect, supporting the company's ambition to be partner of choice for innovative and high speed connectivity solutions for demanding applications. In addition, Reflex's location in Canada will open this key geographical market to Smiths Interconnect.

Gowanda Components Group (GCG) announced the acquisition of **RCD Components**, headquartered in Manchester, N.H. RCD is a manufacturer of passive components—including resistors, capacitors, coils and delay lines—for the commercial, military and aerospace industries. This is the ninth acquisition for GCG within the last seven years. Terms of the deal were not disclosed but GCG has stated that RCD will maintain its operations in Manchester as well as their support facilities in the Caribbean and Asia. In addition to RCD's facilities, GCG has seven other manufacturing and design facilities located within the U.S.

Wireless Telecom Group (WTG) will acquire **Holzworth Instrumentation Inc.** Holzworth complements WTG's test & measurement segment. WTG will pay $8 million in cash at closing, $500,000 in WTG common stock and $1.5 million in a deferred cash payment based on EBITDA performance. WTG requires debt financing to cover the $8 million cash payment, which it is seeking. WTG said the acquisition will close "in the months ahead."

Drone Aviation Holding Corp., a developer of specialized, tethered aerial monitoring and communications platforms serving national defense and homeland security customers, has announced their merger with **ComSovereign Corp.**, the U.S.-based consortium of 5G telecommunications radio, silicon photonics and power systems designed for the next-generation of global networks. The newly merged company will focus on supplying ComSovereign's existing global wireless carrier customer base with new infrastructure technology including industry-leading carrier backhaul capability and 5G/NR connectivity for fixed and mobile aerial applications. Through this unique and synergistic business combination, ComSovereign gains an immediate capability, enabling Drone Aviation to emplace entire LTE networks, from small private networks to city-scale systems, in a matter of days instead of years.

COLLABORATIONS

Keysight Technologies Inc. announced that **Sprint** has selected Keysight's 5G network emulation solutions to validate the performance of 5G new radio (NR) mobile devices, accelerating U.S. 5G commercial deployment of fixed wireless access (FWA) and enhanced mobile broadband (eMBB) applications. This collaboration leverages Keysight's 5G Protocol and RF Carrier Acceptance Toolsets—part of the company's suite of 5G network emulation solutions—to optimize the end-users' experience while accessing 5G services on the mobile operator's network. In addition, the collaboration has resulted in a carrier-specific test plan covering both protocol and RF tests in frequency range 1 (FR1).

ZTE Corp. announced that ZTE and **China Telecom** have jointly launched the world's first commercial 5G maglev (magnetic levitation) high speed network test in Shanghai. The test measured communications within a train traveling at a maximum speed of 500 km/h. During the test, the 5G commercial terminal was stable and easy to support various high performance mobile broadband services, demonstrating that the 5G network can provide high speed maglev trains with ideal broadband communications. Shanghai Maglev is the world's first maglev line for commercial operation and at present it is also the fastest commercial high speed train. It has been a business card for Shanghai and even for China since its operation.

The Next Generation Mobile Networks Alliance (NGMN) and the **5G Alliance for Connected Industries and Automation (5G-ACIA)** have announced to jointly shape and promote industrial 5G applications. The agreement comes as both NGMN and 5G-ACIA look to enhance cooperation between operators and industries to realize the opportunities that 5G technology offers. The partnership between NGMN and 5G-ACIA will provide the technological foundation for new business models that will enable industrial 5G applications, new

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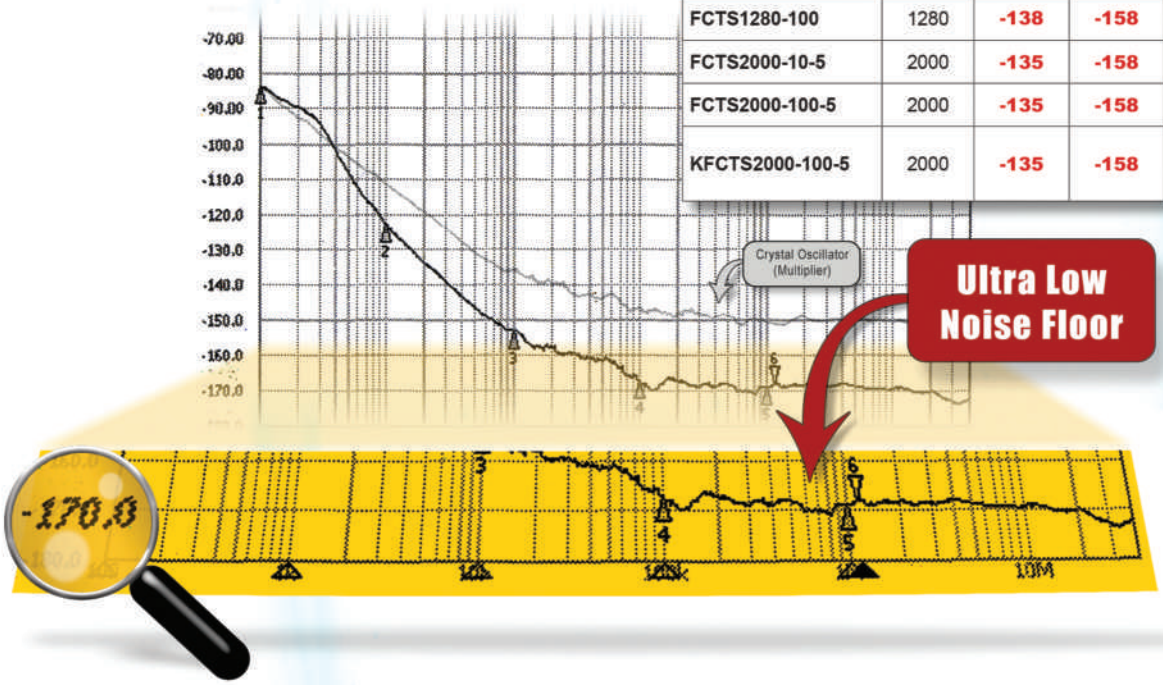
Model	Frequency (MHz)	Phase Noise (dBc/Hz) [Typ.] @10 kHz	@100 kHz	Package
VFCTS128-10	128	-155	-160	
FCTS800-10-5	800	-144	-158	
KFCTS800-10-5	800	-144	-158	
FSA1000-100	1000	-145	-160	
KFSA1000-100	1000	-145	-160	
FXLNS-1000	1000	-149	-154	
KFXLNS-1000	1000	-149	-154	
FCTS1000-10-5	1000	-141	-158	
KFCTS1000-10-5	1000	-141	-158	
FCTS1000-100-5	1000	-141	-158	
FCTS1000-100-5H	1000	-144	-160	
FCTS1040-10-5	1040	-140	-158	
FCTS1280-100	1280	-138	-158	
FCTS2000-10-5	2000	-135	-158	
FCTS2000-100-5	2000	-135	-158	
KFCTS2000-100-5	2000	-135	-158	



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ACHIEVEMENTS

RFMW was recognized by **Smiths Interconnect** with the 2019 award for Best Distributor-Relative Growth. Ceremonies took place at Smiths Interconnect Shanghai and Singapore offices. The "Relative Growth" award is given to the Asia region distributor with the highest percentage of sales growth within the Smiths Interconnect sales channel.

Quectel Wireless' NB-IoT module BC66-NA has now been approved by **T-Mobile US**. This is T-Mobile's first certificate for a Cat NB2 module which supports 3GPP Release 14 features like higher transport block size along with supporting bands 2, 4, 12, 66, 71 and 85. As the new-gen multi-band LTE Cat NB2 module, the BC66-NA is based on MediaTek MT2625 chipset. Well received in North America, LATEM, EMEA and APAC, the single module is capable of making customers' devices globally accepted. It works on LTE bands of B1/B2/B3/B4/B5/B8/B12/B13/B17/B18/B19/B20/B25/B28/B66/B71/B85 to support operators worldwide.

Dedrone has been awarded certification from the **U.K.'s Centre for the Protection of National Infrastructure (CPNI)** for its counter-drone technology platform, DroneTracker. DroneTracker detects, tracks and identifies drones by using multi-sensor capability combining RF, radar and optical sensors. The new CPNI drone detection standard is the first official validation of counter-drone technology. It enables organizations deemed to be of critical national importance to adopt drone detection technology with the assurance that it has been tested rigorously.

China Mobile Hong Kong (CMHK) is Hong Kong's first mobile network operator to have successfully accomplished 5G Standalone (SA) network test and also completed the first voice over NR (VoNR) call. The radio cell sites supporting both 5G SA and Non-Standalone (NSA) network are now installed for trial test at China Mobile 5G Innovation Center Hong Kong Open Lab in Hong Kong Science Park and Mita Internet Data Center in Kwai Chung.

CONTRACTS

General Dynamics Mission Systems (GDMS) announced that it has been awarded a $731.8 million cost-plus-award-fee and firm-fixed-price IDIQ sole-source contract for the Mobile User Objective System (MUOS) ground system sustainment. MUOS is a next-generation SATCOM system that provides secure voice and data communications for U.S. forces worldwide. GDMS provides the integrated ground segments for MUOS, which will soon provide secure cell phone-like communications for warfighters on the move. The contract was awarded by the **U.S. Navy** and most of the MUOS work will be completed in Scottsdale, Ariz., with completion expected by November 2029.

L3Harris Technologies has received a $50 million follow-on delivery order for Falcon III AN/PRC-160 HF radios and related equipment from the **U.S. Marine Corps** as part of its High Frequency Radio II modernization program. The order is part of the Navy Portable Radio Program five-year IDIQ contract received in 2017. The Marine Corps selected the AN/PRC-160 to replace legacy L3Harris HF radios. The AN/PRC-160 is a modern solution for beyond-line-of-sight communications in a satellite-denied environment. It is the smallest, lightest and fastest wideband HF manpack available—providing 10× throughput over legacy systems.

Comtech Telecommunications Corp. announced that during the second quarter of fiscal 2020, its Santa Clara, Calif.-based subsidiary, **Comtech Xicom Technology Inc.**, which is part of Comtech's Commercial Solutions segment, received orders totaling $3.6 million for solid-state power amplifiers (SSPA) to be used in airborne, in-flight connectivity (IFC) applications. The product range encompasses power levels from 8 W to 3 kW, with frequency coverage in sub-bands within the 2 to 52 GHz spectrum. Amplifiers are available for fixed and ground-based, ship-board and airborne mobile applications.

BAE Systems has been awarded a contract by the **U.S. DARPA** to develop software that will enable semi-autonomous multi-domain mission planning. The technology will be designed for military operators to leverage battlespace resources from across various domains, such as space, air, land and sea, for more effective, efficient missions. DARPA's Adapting Cross-Domain Kill-Webs (ACK) program will seek to help operators adapt to dynamic situations with software technology that automatically identifies the best options. In response, BAE Systems' FAST Labs™ research and development organization, along with teammate Carnegie Mellon University, will create software called Multi-domain Adaptive Request Service (MARS).

Sypris Electronics LLC, a subsidiary of Sypris Solutions Inc., announced that it has recently received contract awards from **Collins Aerospace**, a United Technologies Company, to manufacture and test electronic assemblies for the environmental control and life support and the power management and distribution systems of the Orion spacecraft. Production will begin in 2019 and continue into 2020. Terms of the agreement have not been disclosed. For the first time in a generation, NASA is building a new human spacecraft that will usher in a new era of space exploration. A series of increasingly challenging missions awaits, and this new spacecraft will take the U.S. farther than ever before, including Mars.

General Atomics Aeronautical Systems Inc. (GA-ASI) has been advised that the **Australian government** has selected GA-ASI's MQ-9B SkyGuardian® variant to provide the Armed Remotely Piloted Aircraft Systems (RPAS) for the Australian Defence Force (ADF) under Project Air 7003. The ADF expects to take first delivery in the early 2020s. The ADF joins other top-tier military

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Around the **Circuit**

forces in choosing a GA-ASI RPAS because of its proven multi-role combat performance.

Leonardo has signed a multi-year, performance-based logistics contract with **Draken International** to ensure a high availability rate for the Grifo-L radars used to train U.S. Air Force pilots. The contract marks an important milestone in the partnership between Draken and Leonardo, and paves the way for future activities relating to other Leonardo products and services in high-usage domains like adversary air. Leonardo's Grifo family of radar systems is in service with six international Air Forces plus private operator Draken International, together reaching over 150,000 flight hours.

Akoustis Technologies has announced that it has received a pre-production order through a distribution partner for its band n79 (4400 to 5000 MHz) filter solution intended for a tier-1 cellular infrastructure provider for use in 5G small cell base station network equipment. This is the first of several ultra-high band filters that they are expected to deliver to the 5G base station market over the next several quarters. The solution was specifically designed for the challenging filtering needs of band n79 in the emerging 5G small cell network infrastructure deploying across China.

PEOPLE

▲ *Dylan J. Kelly*

Resonant has appointed **Dylan J. Kelly** as COO effectively immediately. Kelly will report to Resonant's Chairman and CEO George B. Holmes and be responsible for Resonant's engineering, product marketing and operations functions. Kelly's extensive semiconductor business expertise and professional network across a broad range of areas, including smartphones, wireless infrastructure and test & measurement, are a natural fit for this new role focused on optimizing company-wide operational performance and expanding the customer and industry relationships.

▲ *Akash Palkhiwala*

Qualcomm Inc. announced that its Board of Directors has unanimously approved the appointment of **Akash Palkhiwala** as executive VP and CFO. Palkhiwala has been serving the company as interim CFO since August. Previously, he was SVP and finance lead for QCT, with responsibility for finance and accounting for all chipset products and segments including mobile, RF front end, compute, auto, connectivity and networking and IoT. Palkhiwala joined Qualcomm in 2001 and has held a variety of roles in finance, including treasurer and lead for corporate finance overseeing Qualcomm's overall financial planning and analysis. He has been part of the senior finance leadership team for more than 10 years.

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Around the **Circuit**

The **SATELLITE Conference and Exhibition** has announced that **Elon Musk**, founder and chief engineer of **SpaceX**, will speak at the SATELLITE 2020 conference on Monday, March 9 at 4:00 p.m. EST at the Walter E. Washington Convention Center in Washington, D.C. Musk appeared at SATELLITE 2009, just after SpaceX was awarded the multibillion-dollar NASA Commercial Resupply Services program contract to send supplies to the International Space Station (ISS) on its Dragon capsule. SpaceX has set industry records with its Falcon 9 and Falcon Heavy rockets, and unveiled a massive new rocket called Starship, a large, long-duration spacecraft capable of carrying passengers or cargo to Earth orbit, planetary destinations and between destinations on Earth.

REP APPOINTMENTS

Raltron has expanded its representative network to better support customers in the Southwestern U.S. and Mexico. Raltron has partnered with **Arotech Inc.** and **Tandem Technical Sales**, respectively, to help customers shorten design cycles and simplify the supply chain process. Both companies will support Raltron's full product offering, which includes the most comprehensive line of frequency management devices in the industry. From simple tuning fork crystals to high stability OCXOs, Raltron's commitment to research and development enables the continued development of application-specific crystal devices, LTCC filters, oscillators, SAW devices, wireless antennas and more.

California Eastern Laboratories (CEL) and **LITEC Corp.** announce a partnership allowing CEL to exclusively promote and sell LITEC's RF PIN diode products in the Americas, Israel and India. CEL has a 60+ year history of marketing RF components to those territories. LITEC PIN diodes have been designed into most of the commercial radio systems in Japan used in ambulances, fire trucks and police cars. CEL will now provide local design support and bring these high-quality products to customers in the aforementioned territories outside Japan. This new agreement perfectly fits with CEL's long history of marketing high-quality RF components manufactured in Japan.

PLACES

Mini-Circuits has opened a regional sales office in Shin-Yokohama, Kanagawa Prefecture, Japan to expand its service to customers in Japan and South Korea. The new office will work in conjunction with Mini-Circuits' local sales representatives and distributors to provide additional resources and support in growing business and addressing customer needs. The company has appointed **Thomas Joyce** as regional sales director, Japan and South Korea, to manage Mini-Circuits' office in Yokohama and to continue growing its sales and service presence in the region. Joyce brings 33 years of experience in electronics design, management and marketing as well as extensive knowledge of the Japanese and South Korean markets.

INVITED PAPER

Self-Interference Cancellation for Co-Located TDD Radios Sharing the Same Band

Joel Brand
Kumu Networks, Sunnyvale, Calif.

A self-interference canceller on a chip enables real-time software programmable suppression of the interference a transmitter presents to a co-located receiver, even if the two radios operate with zero guard band between them. This allows unprecedented densification and spectrum utilization in every RF environment.

A Boeing 787 Dreamliner has more than 20 antennas protruding from its fuselage, with multiples operating in the HF, VHF and UHF bands (see ***Figure 1***). To minimize interference between radios using the same band, their antennas are spread around the airplane to maximize the isolation among them.[1] Nowadays, nearly every military platform packs multiple radios and antennas: satellites, planes, ships, ground vehicles, drones—even the backs of soldiers, which carry tactical manpack radios. The smaller the platform, the closer the antennas and the stronger the interference.

The conventional solution is to use RF filters to block the transmission of one radio from affecting the receiver of another. However, filters are plagued with many problems: they are in the RF path of the receiver, affecting its noise figure. The sharper the desired frequency response, the larger and heavier the filter. On moving platforms, weight and size are at a premium, especially if the "platform" is a soldier's back. The filter is static; it can never adjust its passband or stopband, which represents an impossible problem for frequency-hopping radios that share the same band and hop across the entire band. As good as a filter might be, it still requires a certain guard band, since the cutoff response is never perfect, resulting is some unutilized channels near the transmitter.

This problem affects every RF environment. In the 2.4 GHz ISM band, Wi-Fi transmissions often desensitize the receivers of co-located IoT radios, such as Zigbee or Bluetooth Low Energy (BLE) or co-located Bluetooth receivers for audio streaming applications.[2] This, for example, is why Bluetooth speakers typically do not share the same enclosure as Wi-Fi access points. Similarly, in the 5 GHz ISM band—and soon the 6 GHz band—multiple co-located Wi-Fi radios never share the same frequency segment. The so-called Wi-Fi mesh devices always ensure that one Wi-Fi radio is limited to the lower part of the 5 GHz band (UNII-1 and UNII-2a), while the other is confined to the upper part of the band (UNII-2c and UNII-3). This scheme works by using the 160 MHz gap in the middle of the 5 GHz band. With the projected release of UNII-4 and higher frequencies in the 6 GHz band, this approach is likely to fall apart.

As 5G networks migrate from FDD to TDD, they will suffer self-interference from co-located radios. An AT&T radio operating in physical and frequency proximity to a Verizon Wireless radio will interfere with each other unless the radios are synchronized to transmit

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ADF - Automatic Direction Finder
CWLU - Crew Wireless LAN Unit
ELT - Emergency Locator Transmitter
HF - High Frequency Radio
VOR VHF - Omnidirectional Ranging

Fig. 1 **Antennas on a Boeing 787.**

and receive at the exact same time, all the time.

This article describes a self-interference cancellation solution to the co-existence challenges of co-located radios operating on nearby frequencies.[3]

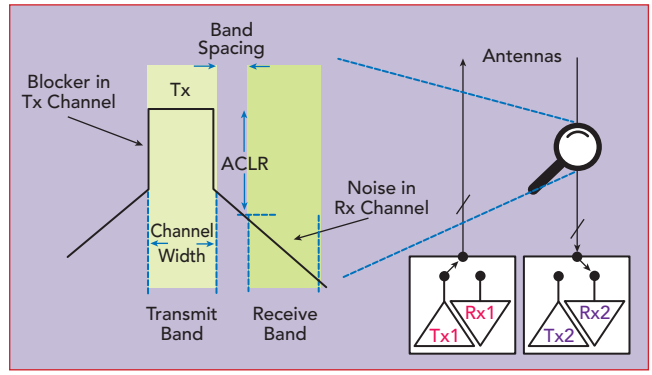

Fig. 2 **Adjacent channel interference.**

THE TECHNICAL CHALLENGE

A transmitting radio obviously emits a large amount of energy in its intended channel. This energy is a "blocker" for a nearby receiver, even if the receiver is listening on a different channel. The transmitter also leaks noise into the adjacent channels where nearby receivers may be listening, a phenomenon known as the "noise skirt" of the transmitter (see ***Figure 2***). Both sources of interference must be suppressed for a receiver to operate normally in the presence of a nearby transmitter.[4]

Filters are only useful when the transmitter and receiver are sufficiently far away in frequency to ensure a sufficient guard band between them. Since filters are static and passive, any change in the desired response between the interfering and interfered radios requires a different filter. In practical systems, this results in large filter banks that are undesirable.

In highly regulated environments, the interference problem is typically solved through predefined frequency allocations, large guard bands—with enormous spectrum waste—and strict spectral masks and output power limitations. That is obviously not the case in the defense space, nor is it true in the unlicensed spectrum bands allocated to ISM and used for Wi-Fi, IoT, Bluetooth and other consumer applications.

SELF-INTERFERENCE CANCELLATION

Self-interference cancellation technology offers a superior solution to some of the most challenging radio filter applications, promising dramatic size, weight and performance benefits. While conventional radio filters have changed little since vacuum tube days, self-interference cancellation brings radio filtering into the software-controlled, IC era. Instead of blocking certain frequencies, cancellation directly addresses the source of interference by "cancelling" it.[5] Fundamentally, self-interference cancellation is simi-

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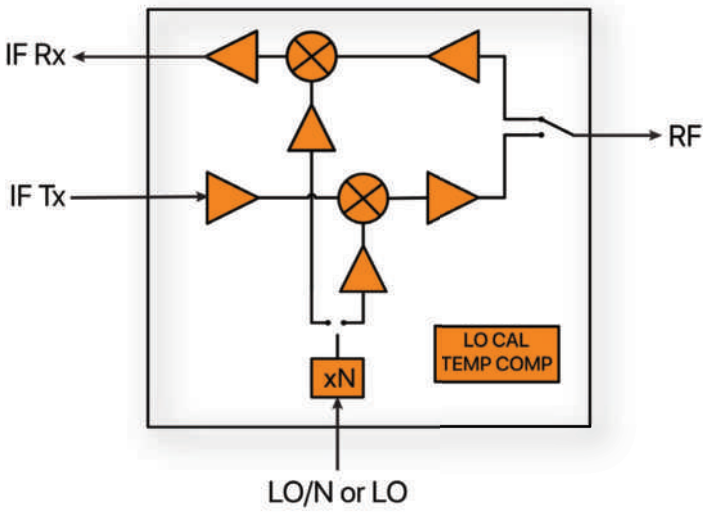

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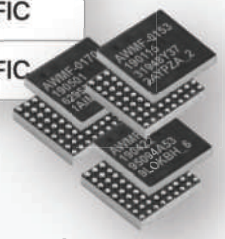

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lar to noise-cancelling headphones. Noise-cancelling headphones sample the noise, measure key parameters and create a cancellation signal 180 degrees out of phase with the noise. When the cancellation signal is combined with the noise, the two signals cancel each other. Likewise, self-interference cancellation samples the interference, measures key parameters and creates a cancellation signal. When the cancellation signal is combined with the interfering signal, the two signals cancel each other (see ***Figure 3***).

While conceptually simple, implementing a canceller is challenging. The transmitter noise seen by the receiver is not static: it is affected by channel effects like fading and by dynamically varying multipath due to reflections off moving objects near the radio. As such, the canceller must track the changing self-interference channel with a speed and accuracy to achieve the amount of desired cancellation. Further, the solution must not introduce noise that decreases the receiver sensitivity, meaning it must handle the large blocking signal while not introducing noise above the receiver's sensitivity level. This translates to a very large dynamic range where the circuit must be linear.

TEST SETUP FOR RADIO CO-EXISTENCE

A class of consumer and enterprise products commonly known as tri-band Wi-Fi routers—tri-band because such products integrate one 2.4 GHz and two 5 GHz radios—typically use filters to isolate one 5 GHz radio from the other. Within the FCC allocation, one 5 GHz radio always selects a channel between 5170 and 5330 MHz, while the other radio picks a channel between 5490 and 5835 MHz. The unallocated 160 MHz gap between the two bands is used as the transition band for the filter. ***Figure 4*** shows the response of commonly used filters.[6] A smaller gap would be an impossible challenge for the filter, as its roll-off would not be sharp enough to handle the narrower guard band.

To test the performance of cancellation in a live environment, a test setup in the unlicensed 5 GHz ISM band was constructed. The goal was to operate the two radios anywhere

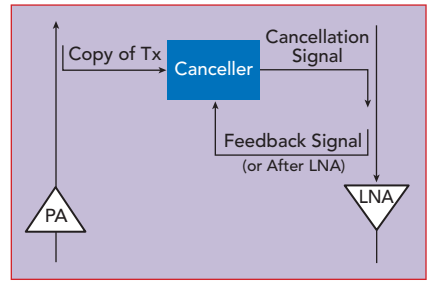

Fig. 3 **Architecture for self-interference cancellation.**

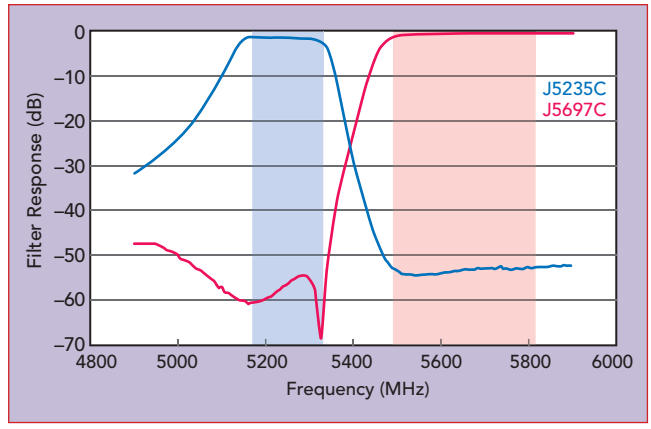

Fig. 4 **Frequency response of Cirocomm Wi-Fi filters.**

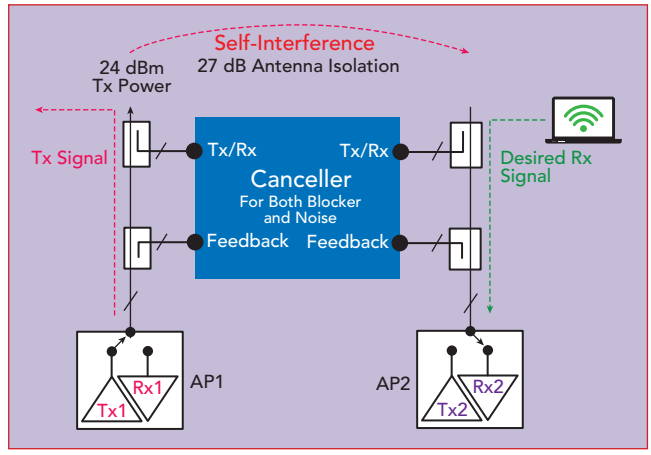

Fig. 5 **Dual 5 GHz radio test setup.**

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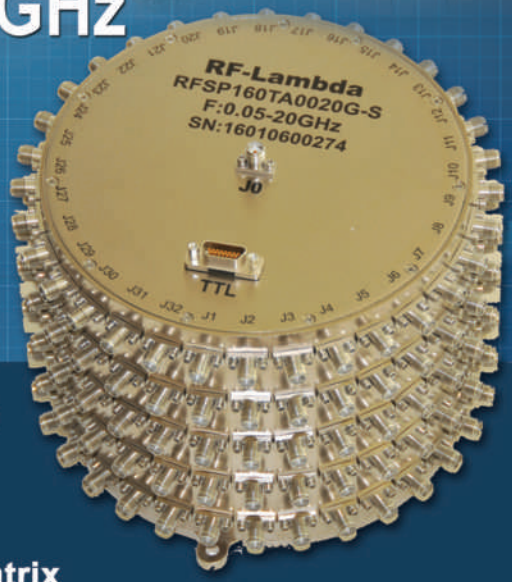

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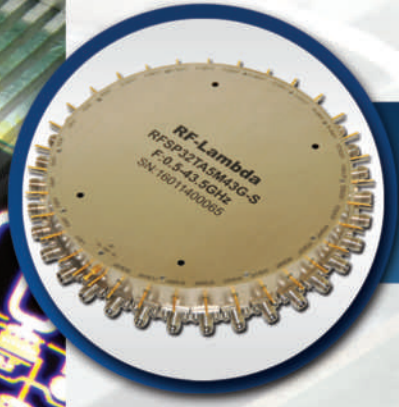
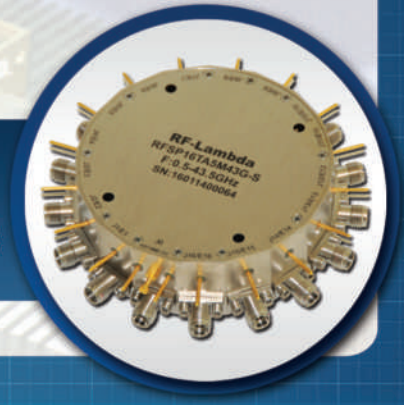


PN: RFSP32TA5M43G
SP32T SWITCH 0.5-43.5GHz

PN: RFSP16TA5M43G
SP16T SWITCH 0.5-43.5GHz



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in the band, even with no guard band between them (see ***Figure 5***). Unlike a filter, the cancellation technology is tunable for the desired frequency of operation, so it allows the two 5 GHz radios to operate anywhere in the band, not requiring them to be at opposite ends of the spectrum. The setup included two radios using the standard Qualcomm 802.11ax reference design based on the recently introduced IPQ8074 SoC. To represent a practical use case, instead of randomly placing the antennas, the setup used the antenna configuration of a Cisco Aironet 3800 enclosure. The self-interference canceller used Kumu Networks' MIMO-capable KU1500 RFIC, tuned using patented, real-time tuning algorithms (see ***Figure 6***).

The challenge is to transmit from one of the Wi-Fi radios, operating at its maximum output power of 24 dBm and maximum bandwidth of 80 MHz, while receiving on the other Wi-Fi radio. The critical metric is the sensitivity degradation of the receiving radio. Commonly used Wi-Fi filters affect receiver sensitivity by approximately 2.5 dB due to their insertion loss, even when the radios operate 160 MHz apart. Unlike filters, the self-interference cancellation is not in the RF path; it is only connected to the RF path using couplers, which negligibly contribute to the insertion loss.

MEASURED PERFORMANCE

A spectrum analyzer measured the transmitter's interference at the input of the "victim" receiver's LNA. The analyzer screen shots in ***Figures 7, 8*** and ***9*** show the noise the transmitter makes in its intended channel (i.e., the blocker) and the noise leaking to the adjacent channels, where the receiver operates (i.e., the noise skirt). In each, the self-interference is measured with the canceller off (yellow) and on (purple).

To establish a baseline and ensure that cancellation is not worse

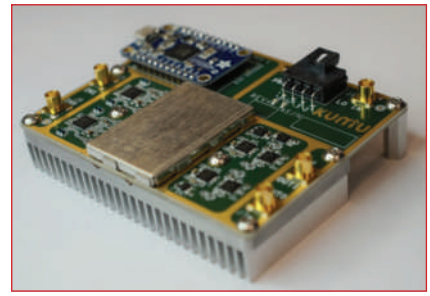

Fig. 6 Kumu Networks' RFIC evaluation board.

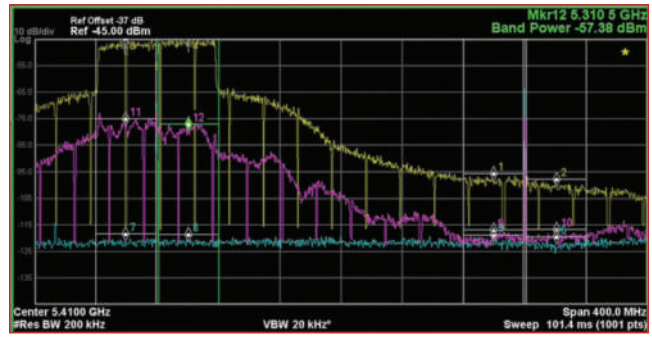

Fig. 7 Two 5 GHz radios with 160 MHz gap.

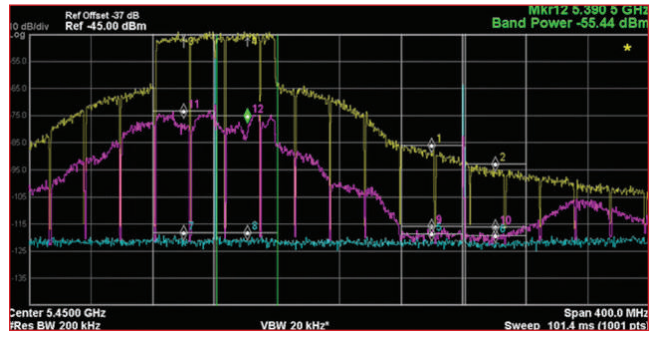

Fig. 8 Two 5 GHz radios with 80 MHz gap.

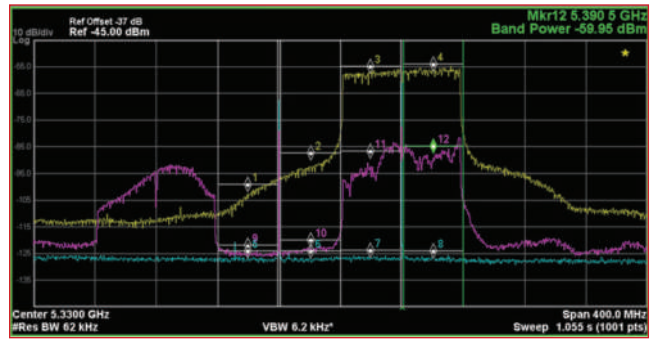

Fig. 9 Two 5 GHz radios with 0 MHz gap.

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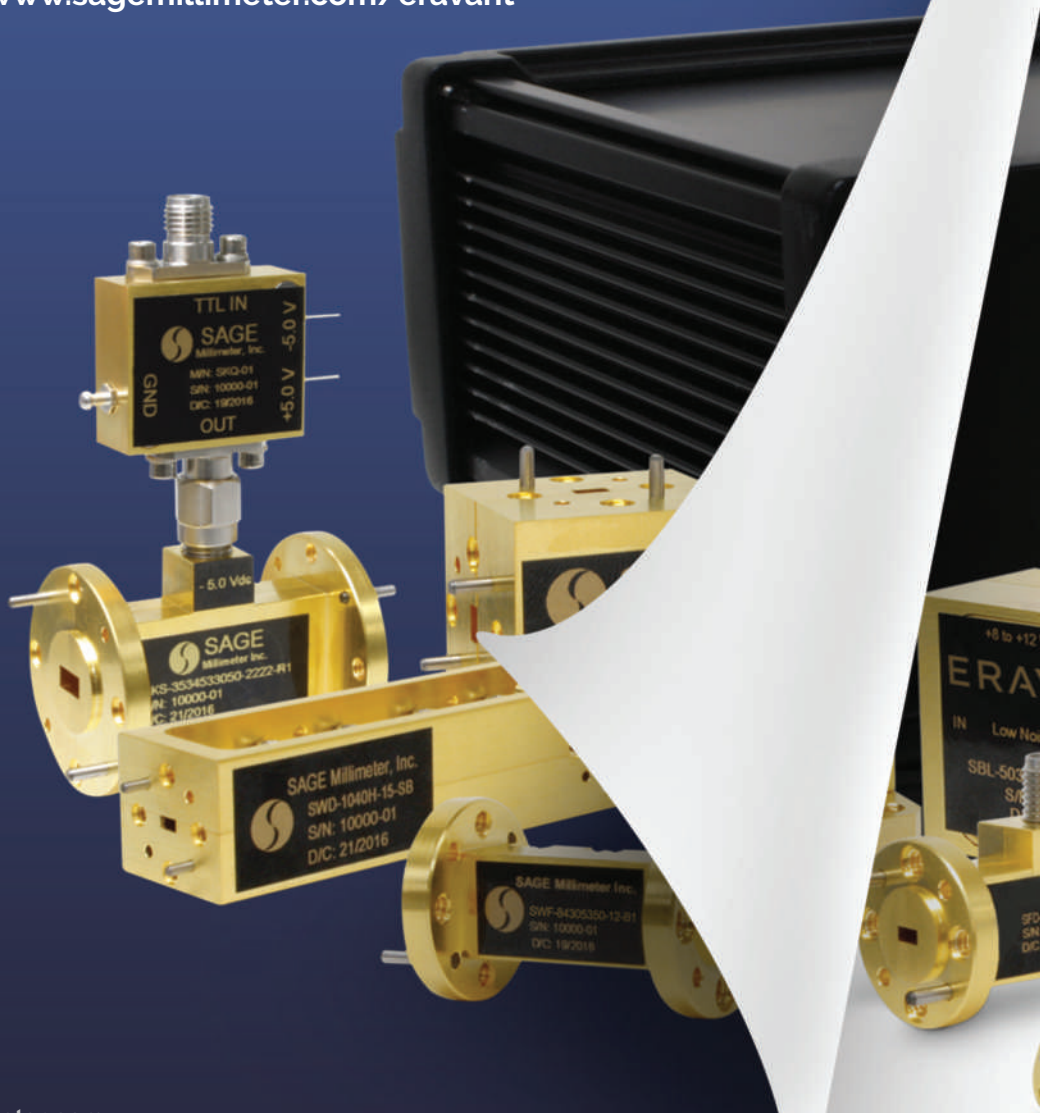

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than using the filter, the initial test used a 160 MHz gap between the interfering transmitter and co-located receiver (see Figure 7). Markers 7 and 8 represent the interfering transmitter and markers 9 and 10 the co-located receiver. This 160 MHz gap is the minimum supported by commercial off-the-shelf filters used in current tri-band Wi-Fi designs. With a transmit noise level in the receive channel of approximately −81 dBm, the canceller suppresses it to around −99 dBm, very close to the noise floor. While this is only 18 dB cancellation, the amount is limited by the noise floor, and the new noise level of −99 dBm represents a noise figure hit lower than the insertion loss of the Wi-Fi filters. Even if the radios are using separated channels where traditional filters are effective, the cancellation circuit provides better performance. Simultaneously, the canceller suppresses the Tx channel blocker by 33 dB to avoid saturating the receiver LNA.

When the guard band is smaller, 80 MHz for example, it is usually not feasible to use fixed filters, as the Tx /Rx guard band is not large enough. With the canceller, the transmit noise in the receive channel is reduced close to the noise floor (see Figure 8). With a gap of 80 MHz, the transmit noise of approximately −76 dBm in the receive channel is suppressed to −98 dBm, 22 dB cancellation—only limited by the noise floor. Tx blocker suppression is similar to the first case.

The ultimate challenge is to maximize spectral use by eliminating the guard band and operating co-located radios on immediately adjacent frequencies, i.e., with zero guard band between them. Fixed filters obviously cannot be used in this configuration. However, self-interference cancellation can (see Figure 9). In this case, about 40 dB cancellation in the immediately adjacent channel is achieved. Adding to the challenge, the interfering transmitter is now operating at a higher frequency than the receiver. Switching the radios is

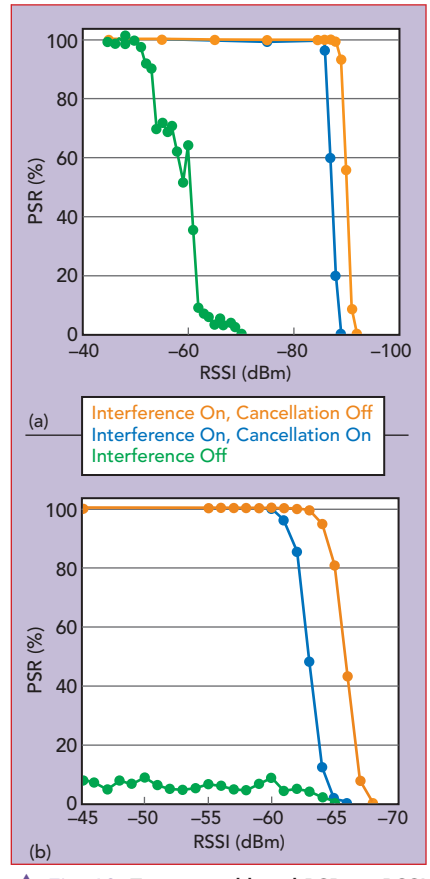

Fig. 10 Zero guard band PSR vs. RSSI for MCS-0 (a) and MCS-9 (b).

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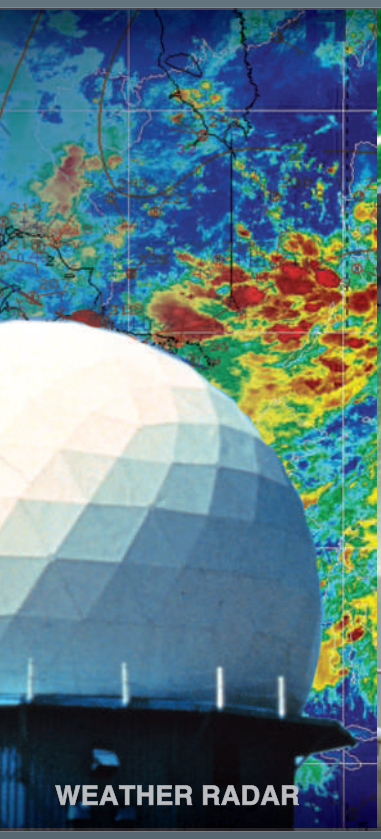

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possible with the software configuration of the canceller, yet impossible using fixed filters. It is immensely valuable to have this flexibility, especially when the two radios have different MIMO orders. The spectrum analyzer response shows a "hump" in the cancellation signal to the left of the receive channel; this reflects insufficient I/Q imbalance compensation in the test board.

In addition to cancellation and noise figure, the packet success rate (PSR) in the presence of local interference was measured (see ***Figure 10***), evaluating radio performance at different received signal strengths (RSSI) and modulation and coding schemes (MCS), selected to show performance at two extremes: MCS-0 is the lowest data rate coding, BPSK rate $^1/_2$ and MCS-9 is 256-QAM, rate $^5/_6$. Without cancellation, using the high data rate MCS-9 is impossible, and packets at MCS-0 barely squeak by. The performance with cancellation very closely mirrors the performance of the system without interference. The delta relative to the optimal performance with no interference is often smaller than the insertion loss of filters.

SUMMARY

For applications where two physically co-located radios must operate on close frequency channels, self-interference cancellation provides a solution that is often better than using traditional fixed filters. Fixed filters introduce insertion loss into the receive chain; the cancellation circuit is only attached to the receiver via a coupler, minimizing the impact to noise figure. Cancellation is software programmable and can adjust to changing transmit and receive frequencies, crucial for frequency-hopping systems such as IoT and military radios. Cancellation can also operate with absolutely no guard band, i.e., when the interfering radio is on the channel immediately adjacent to the receiver.

These scenarios when two co-located radios need to co-exist without interference are common, found on nearly every military platform and consumer electronics in the unlicensed bands. Soon the challenge will be with 5G systems using the TDD bands, where radios from different operators will interfere with each other unless they are synchronized.■

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INVITED PAPER

A Single Chip SMT-Packaged 4-Channel mmWave 5G PA

Mohammed Tahir, Stuart Glynn, Liam Devlin, Andy Dearn and Graham Pearson
Plextek RFI, Great Chesterford, Saffron Walden, U.K.

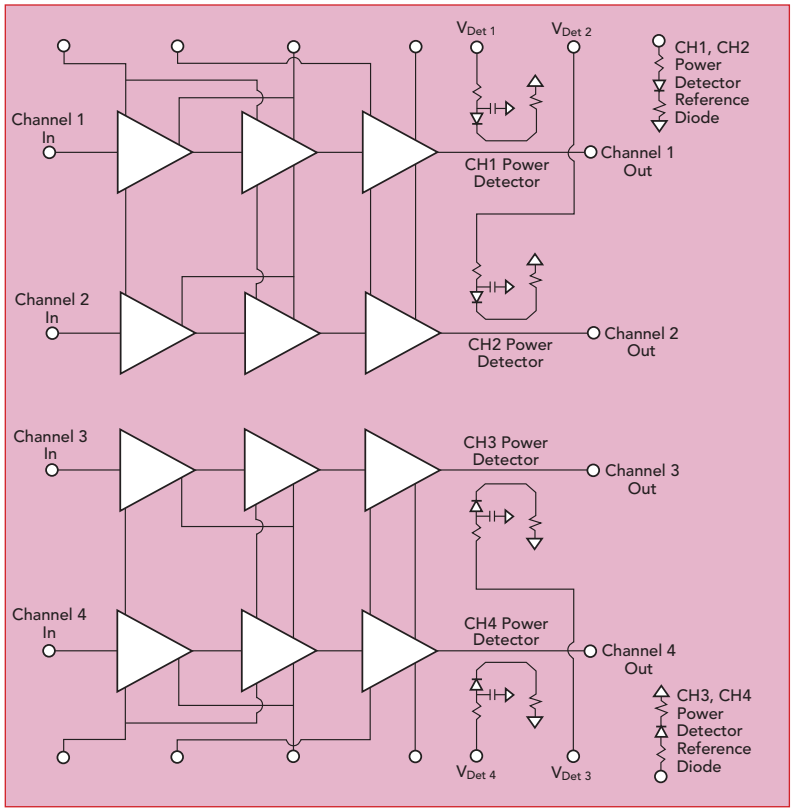

Fig. 1 4-channel PA block diagram.

The rollout of the first mmWave 5G systems has begun. While many of the initial installations provide fixed broadband access, mmWave 5G also provides broadband access to mobile terminals. To address the difficulties of non-line-of-sight communications at mmWave, 5G mobile terminals will adopt a phased array or switched antenna topology. This will require multiple, identical RF front-end components, such as power amplifiers (PA). As well as having adequate gain, output power and linearity, the PA demanded by 5G terminals must be efficient, compact and low-cost. The availability of multi-channel mmWave components is key to achieving these goals.

This article describes the design and evaluation of a four-channel, SMT-packaged PA for the 28 GHz 5G NR band (i.e., 27.5 to 28.35 GHz), offering a compelling solution for 5G terminals. The PA was fabricated on Sanan IC's P15EP process, a 4 V, 0.15 µm enhancement-mode GaAs PHEMT process. The four-channel PA is integrated on a single die and assembled in a 5 mm × 5 mm, plastic overmolded, SMT-compatible QFN package, making it compact and low-cost. It offers good performance from 26 to 29 GHz, covering the full 28 GHz 5G band.

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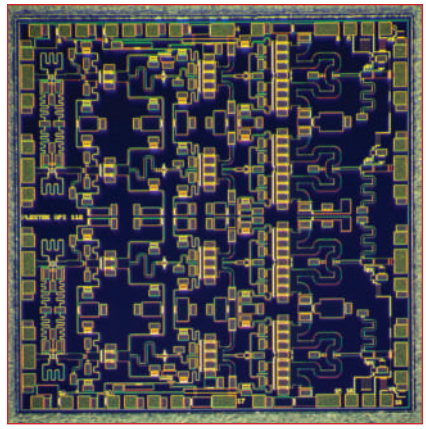


Fig. 2 4-channel PA die.

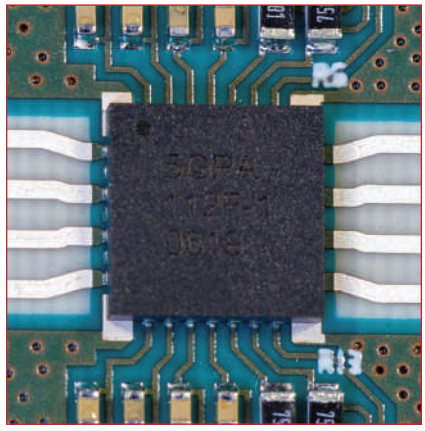


Fig. 3 SMT-packaged PA on an evaluation board.

PA ARCHITECTURE

Figure 1 shows the block diagram of the four-channel PA IC. It comprises two halves that are the mirror image of each other, and each half contains two identical channels: the top contains channels 1 and 2, the bottom channels 3 and 4. Each channel consists of a three-stage PA with an integrated output power detector. The RF inputs and outputs of each channel are on the left- and right-hand sides of the die, respectively. Channels 1 and 2 share the same DC bias pads, which are shown on the top side of the block diagram. One pad provides the gate bias for stages 1 and 2 of channels 1 and 2, another the gate bias for stage 3 of channels 1 and 2. Similarly, one pad provides the drain voltage for stages 1 and 2 of both channels, and a separate pad provides the drain voltage for stage 3 of both channels. Sharing the DC bias pads enables a more compact form factor. The nominal drain supply voltage is +4 V, and the gate bias voltages are adjusted

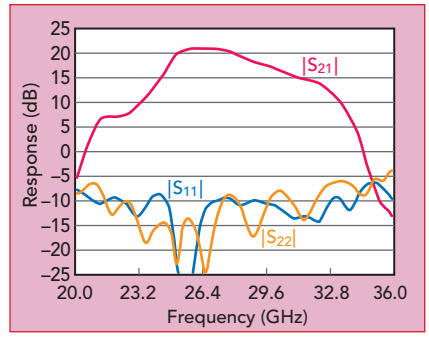


Fig. 4 Measured S-parameters.

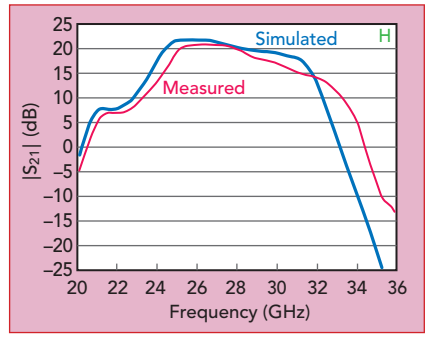


Fig. 5 Measured vs. simulated gain at 100 mA/mm bias.

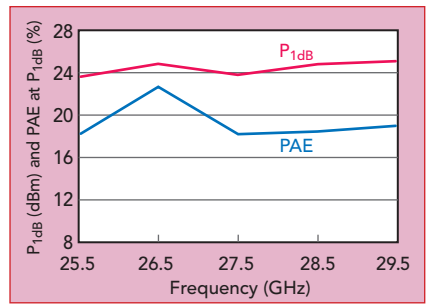


Fig. 6 Measured P_{1dB} and associated PAE.

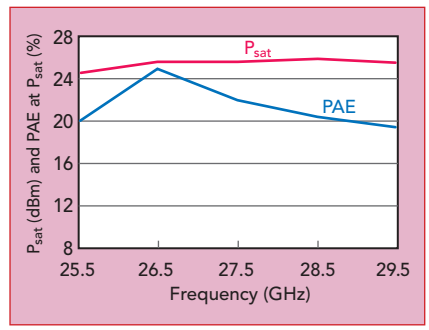


Fig. 7 Measured P_{sat} and associated PAE.

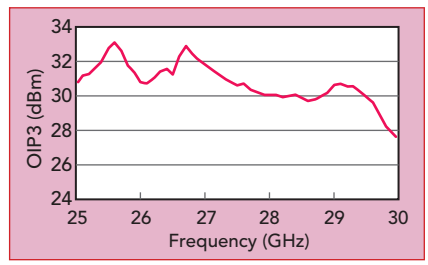
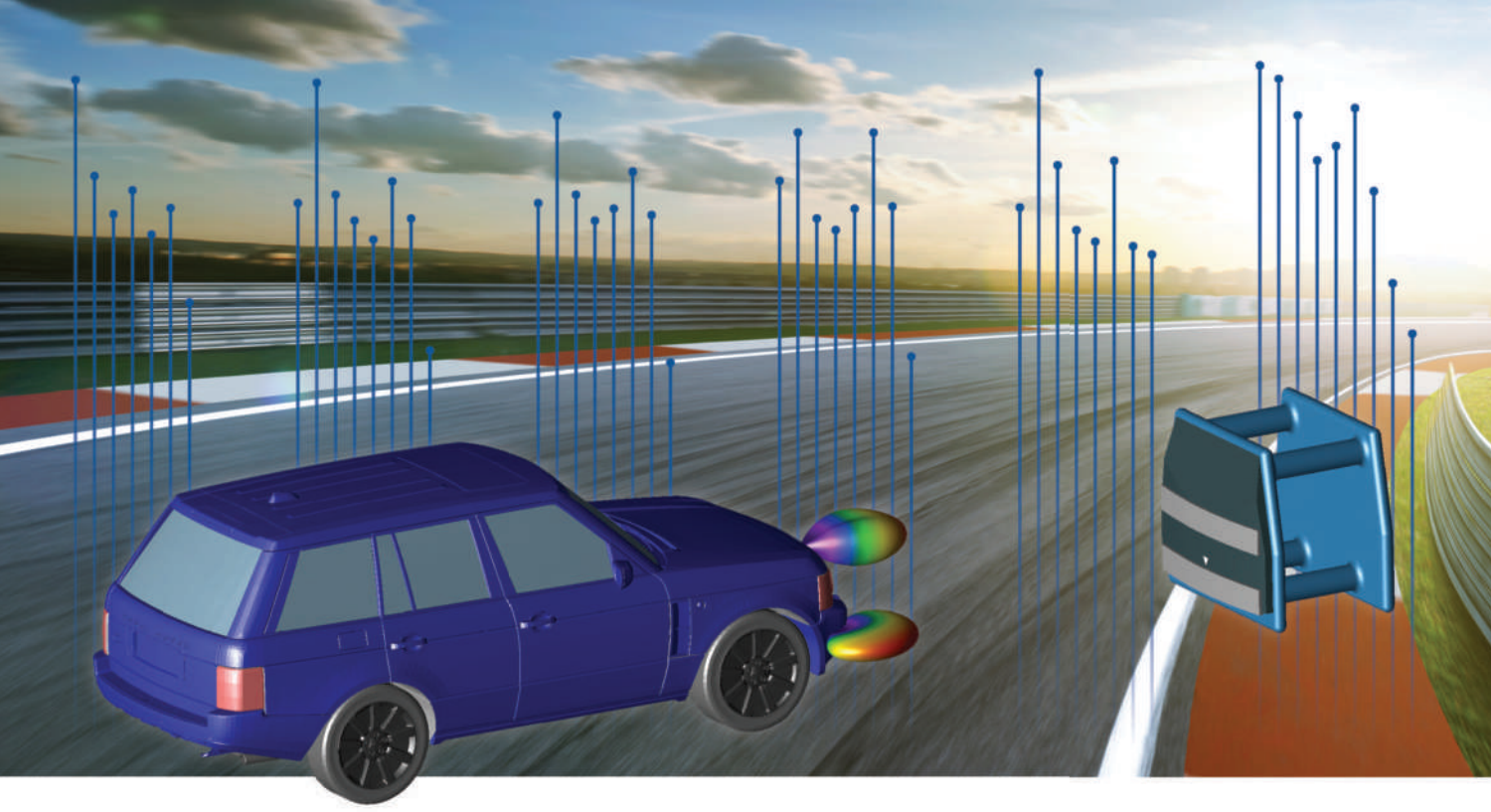


Fig. 8 Measured OIP3.



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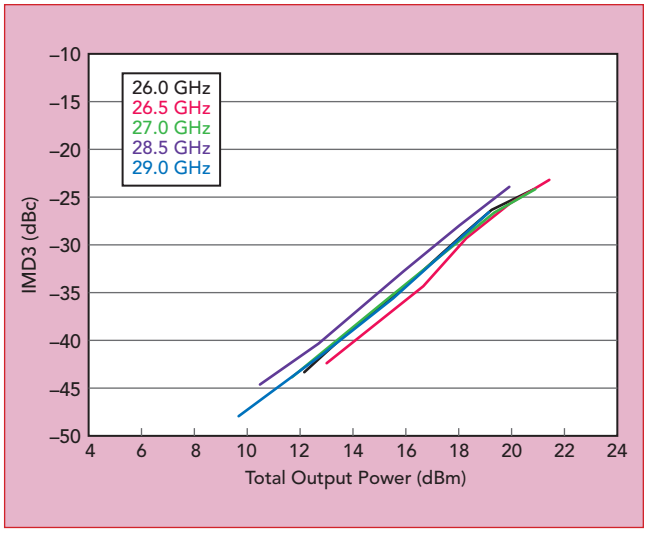

Fig. 9 Measured IMD3 vs. total output power at several frequencies.

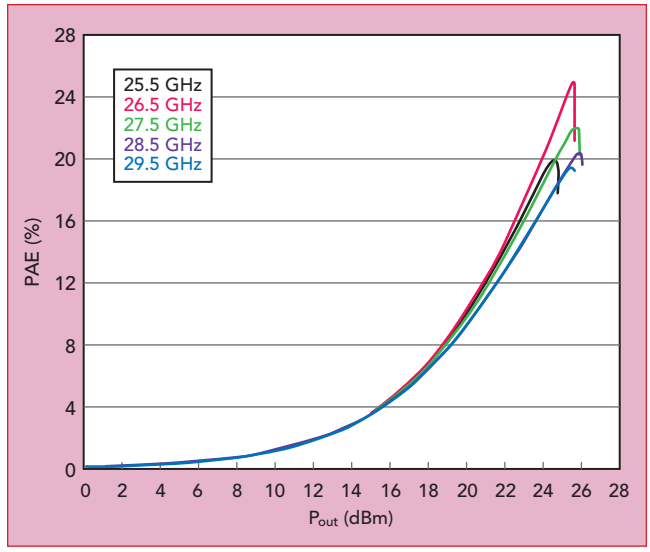

Fig. 10 Measured PAE vs. output power at several frequencies.

to achieve the target quiescent currents: 160 mA total for stages 1 and 2 of both channels and 240 mA total for stage 3 of both channels. At these supply currents, each transistor is biased at a nominal current density of 100 mA/mm.

The DC outputs of the RF power detectors for channels 1 and 2 are located on the top side of the die. Separate uncompensated detector outputs are provided for channels 1 and 2, with a detector reference voltage shared by the two channels. A temperature compensated detector output is created by taking the difference between the detector reference voltage and the uncompensated detector output for each channel.

With the mirror symmetry of the IC, the DC bias and power detector circuit and layout for channels 3 and 4 are the same as for channels 1 and 2, with the DC pads located on the bottom side of the block diagram (see Figure 1). As the PA was designed with an enhancement-mode process, no negative voltages are required. Commercial multi-channel digital-to-analog converters (DAC) are used to bias the PA gates, with analog-to-digital converters (ADC) used to monitor the power detector outputs.

Figure 2 shows a photograph of the four-channel PA die, which measures just under 3.4 mm × 3.4 mm. Its pad positions are like those shown in Figure 1, although the layout incorporates several ground pads to make the circuit testable using on-wafer probes.

SINGLE-CHANNEL MEASURED PERFORMANCE

Samples of SMT-packaged PAs were assembled on evaluation boards (see ***Figure 3***), which were designed using a low-cost laminate material suitable for mass production. The single-channel measurements described in this section were performed at room temperature on channel 2 of a typical device, biased at +4 V and a quiescent current density of 100 mA/mm. The measured performance was calibrated to the package pins and includes the IC to

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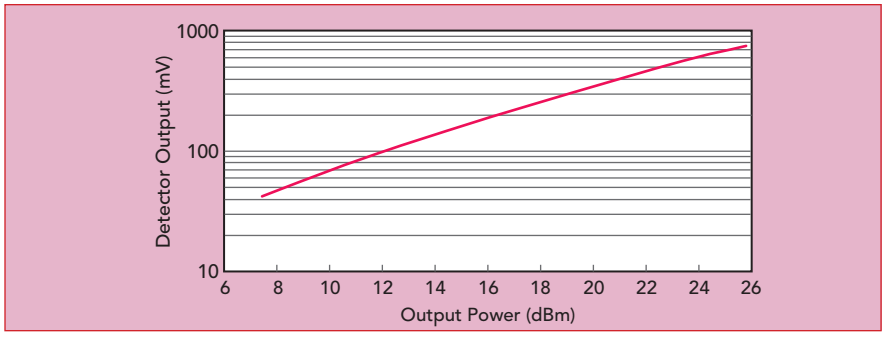

Fig. 11 Output voltage vs. RF power for the on-chip power detector at 27.5 GHz.

TABLE 1 SINGLE-CHANNEL MEASURED PERFORMANCE

Parameter	Units	Minimum	Typical	Maximum
Frequency Range	GHz	26		29
Gain	dB		19.6	
$\|S_{11}\|$	dB		10	
$\|S_{22}\|$	dB		10	
P_{1dB}	dBm		24.5	
P_{sat}	dBm		25.5	
PAE at P_{1dB}	%		19.5	
PAE at P_{sat}	%		21.5	
OIP3	dBm		31	
RF Power at 7 dB Back-Off	dBm		17.5	
IMD3 at 7 dB Back-Off	dBc		–31	
PAE at 7 dB Back-Off	%		6	

PCB transition. A TRL calibration tile was designed to calibrate the measured data to the reference planes of the package.

Figure 4 shows the measured S-parameters of channel 2 of a packaged PA mounted to the evaluation board. The gain was 19.6 ±1.4 dB across 26 to 29 GHz, and the $|S_{11}|$ and $|S_{22}|$ were approximately 10 dB across the band. ***Figure 5*** compares the measured gain with the simulation, where the simulated performance includes an electromagnetic simulation of all the matching networks. Although the PAs for 5G systems will be backed off to operate in the linear region and preserve modulation fidelity, the output power at 1 dB gain compression (P_{1dB}) was measured to provide a figure of merit for comparison. The power and associated power-added efficiency (PAE) are plotted versus frequency in ***Figure 6***. The typical P1dB is around 24.5 dBm, with a corresponding PAE of approximately 19.5 percent. ***Figure 7*** shows the measured P_{sat} and corresponding PAE, which are typically 25.5 dBm and 21.5 percent, respectively.

To reflect the wide channel bandwidths anticipated for 5G systems, the output third-order intercept point (OIP3) was evaluated using a tone spacing of 100 MHz. The measured OIP3 is plotted in ***Figure 8*** at an output power of +8 dBm per tone. The OIP3 is around +31 dBm average from 26 to 29 GHz. Third-order intermodulation distortion (IMD3) versus total output power was also measured at several frequencies (see ***Figure 9***). At an operating point of +17.5 dBm, corresponding to 7 dB back-off, the corresponding IMD3 is −30 dBc or better across the band. Drive-up curves showing PAE versus total RF output power were also measured at several frequencies (see ***Figure 10***). At a +17.5 dBm operating point, 7 dB back-off, the PAE is at least 6 percent across the band.

The on-chip power detector generates a DC voltage to enable monitoring the RF output power. ***Figure 11*** shows the temperature compensated detector output in mV, plotted on a logarithmic scale, versus the RF output power at 27.5 GHz. Over an 18 dB range, the voltage

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TABLE 2
FOUR-CHANNEL PERFORMANCE

Parameter	Units	Minimum	Typical	Maximum
Frequency Range	GHz	26		29
Number of Elements			4	
Effective P_{1dB}	dBm		30.5	
Effective P_{sat}	dBm		31.5	
Effective OIP3	dBm		37	
Effective RF Output at 7 dB Back-Off	dBm		23.5	

versus dBm characteristic is linear, which simplifies power monitoring.

Table 1 summarizes the measured performance of the single-channel packaged PA.

4-CHANNEL PERFORMANCE

If the four PAs are driven with coherent RF signals and used to drive a four-element antenna array, the RF output signals will combine to provide a 6 dB increase in RF power, i.e., $10\log_{10}(N)$, where N is the number of elements. By appropriately setting the phases of the signals to the four antenna elements, the direction of the antenna beam can be electronically steered. ***Table 2*** indicates the performance that can be achieved from an ideal four-element array, excluding output routing losses and assuming the PAs have identical performance. The table does not include the gain of the antenna elements, which will add to the total effective radiated isotropic power (EIRP), further increasing those parameters specified in dBm in the table.

SUMMARY AND CONCLUSIONS

The four-channel PA MMIC described in this article offers a compelling solution for 5G terminals requiring multiple power amplifiers. The IC demonstrates good performance from 26 to 29 GHz, making it suitable for the full 28 GHz 5G band. To measure and adjust the power, a temperature compensated output power detector is included on all channels.

Fabricated with a 0.15 µm enhancement-mode GaAs PHEMT process, the PA is straightforward to bias and monitor using commercial multi-channel DACs and ADCs. The IC is housed in a compact, low-cost, 5 mm × 5 mm plastic overmolded QFN SMT package, compatible with high volume, low-cost terminals.■

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RF Input Spectral Purity Input Spurious Levels: - 60 dBc Max Input Harmonic Levels: - 10 dBc Max	
RF Input Signal-To-Noise Ratio: 70 dB Min	
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SPECIFICATIONS

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Peak Frequency Error	15 MHz
Linear Bandwidth	16 GHz
Dynamic Range	-50 to +15 dBm
Max Input Power, Survival	+17 dBm CW
Mean Frequency Resolution	1 MHz
Recovery Time (After High Power Pulse Input)	100 ns Max
Control Logic:	14-Bit TTL Digital Output (Single Ended)
Physical	RF Connectors: SMA female Power/Control: 51-Pin Micro-D Calibration/Test: 15-Pin Micro-D Size: 5.98" x 5.79" x 1.28"

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A 28 GHz Beam Steering Antenna for 5G Cellular Phones

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Shanghai University, Shanghai, China

Zhanyi Qian
Huizhou Wireless Technology Co. Ltd., Huizhou, China

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Feng Chia University, Taichung, Taiwan

A 28 GHz beam steering cavity-backed slot antenna array for 5G cellular phones was implemented in the metallic casing of a mobile phone. The antenna array has eight cavity-backed slot array elements excited by two 4×4 Butler matrix feed networks (BMFN) that enable beam steering in desired directions with a coverage of approximately ±22 degrees. The measured 10 dB return loss band is from 26.2 to 29 GHz, and array element gain at 28 GHz is between 9 and 10.1 dBi.

5G cellular networking will use mmWave technology due to the large available bandwidth at these frequencies.[1-2] One differentiating feature of mmWave cellular communication is the use of antenna arrays at the transmitter and receiver for directional array gain. With antenna arrays, mmWave cellular systems can implement beamforming and beam steering at the transmitter and receiver to yield higher gain, compensating for frequency-dependent path loss, overcoming noise and reducing out-of-cell interference.[2] The mmWave antenna for 5G smartphones is an important development for the mobile industry, and it can be regarded as one of the key enabling technologies to complete the transition from 4G to 5G networks.

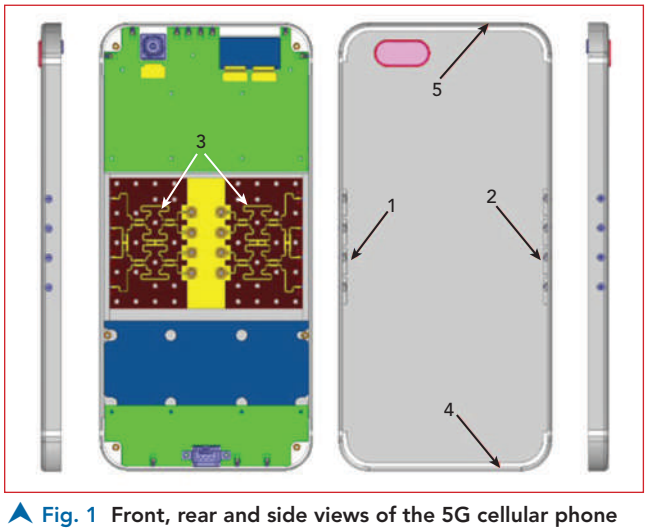

Fig. 1 **Front, rear and side views of the 5G cellular phone prototype.**

Recent beam steering antenna designs for 5G cellular phones have yielded good performance using low-cost substrates,[3-10] but these antennas may not be suitable for practical cellular phones, which employ metallic frames or casings. For example, Huo et al.[10] use an antenna in package (AiP) module solution to realize beam scan; however, the configuration of their AiP modules is unsuitable for use in a metallic environment. Even if a glass or ceramic casing were employed, the metallic frame of the phone would still affect AiP module performance, especially its radiation pattern.

In this article, a novel 28 GHz beam steering antenna for a 5G metallic-cased phone is described. Two arrays, each with four elements, were integrated on each side of the metallic casing. To achieve the beam

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4*4	±0.4	±2.0	±0.5	±5.0	±0.6	±6.0	±0.8	±8.0
8*8	±0.5	±3.0						
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steering performance of the array, two 4×4 BMFNs were used. Due to the phase shifting limitation of the 4×4 BMFNs, beam steering performance is limited to four states. For a realistic cellular phone implementation, this antenna design concept can be used with a 5G transceiver for a continuous beam steering solution.

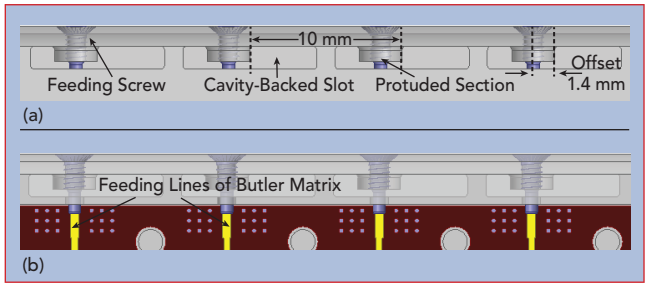

Fig. 2 Beam steering array with four cavity-backed slots (a) and Butler matrix feed (b).

Figure 1 shows the prototype configuration. The cover of the phone is made of a metallic material. Identical beam steering arrays (1 and 2) are built on the left and right edges of the phone, respectively. Each beam steering array comprises four cavity-backed slot antenna elements excited by a 4×4 BMFN.[3] The eight cavity-backed slot antenna elements are fabricated on the metallic back casing using a CNC lathe. The top and bottom metallic frames (4 and 5) are typically reserved for other antennas, such as 4G LTE main and diversity, GPS and Wi-Fi.

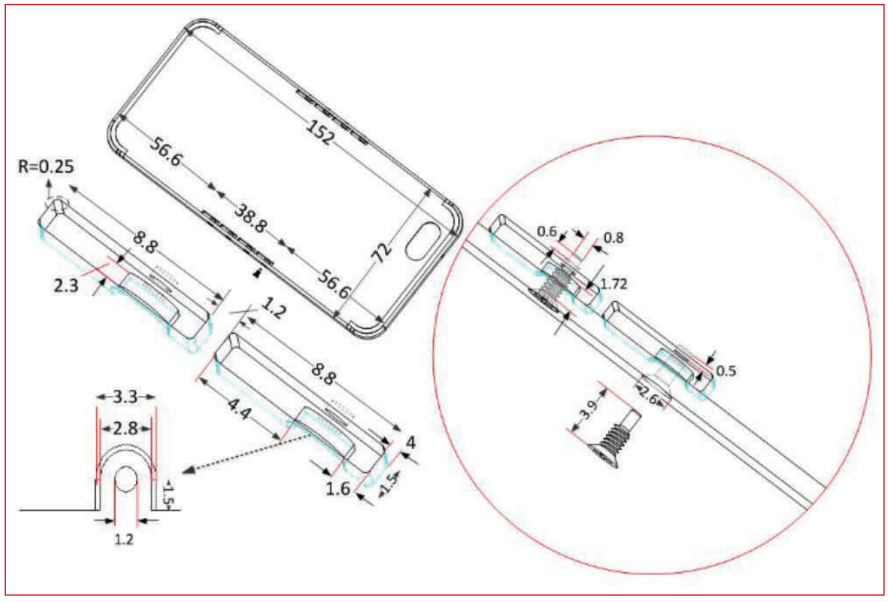

Fig. 3 Antenna detail (dimensions in mm).

ANTENNA ELEMENT AND ARRAY DESIGN

Figure 2a shows the design of one of the beam steering arrays, where each of the four cavity-backed slot elements is fed by a small screw structure inserted across the cavity-backed slot, via a protruded section, and soldered to one of the feeding lines of the BMFN (see ***Figure 2b***). The distance between the centers of the two slot elements is nearly 10 mm, which is approximately one wavelength at 28 GHz. To achieve a good impedance match, the center of the feeding screw is offset 1.4 mm from the middle of the cavity-backed slot. This array design, located at either the left or right edge of the metallic casing, ensures a good directional radiation pattern and high gain.

Figure 3 shows the dimensions and locations of the two identical beam steering arrays, as well as the cavity-backed slot on the metallic casing. The length and width of the cavity-backed slot are 8.8 and 1.5

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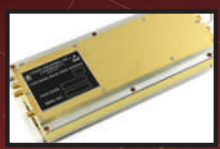

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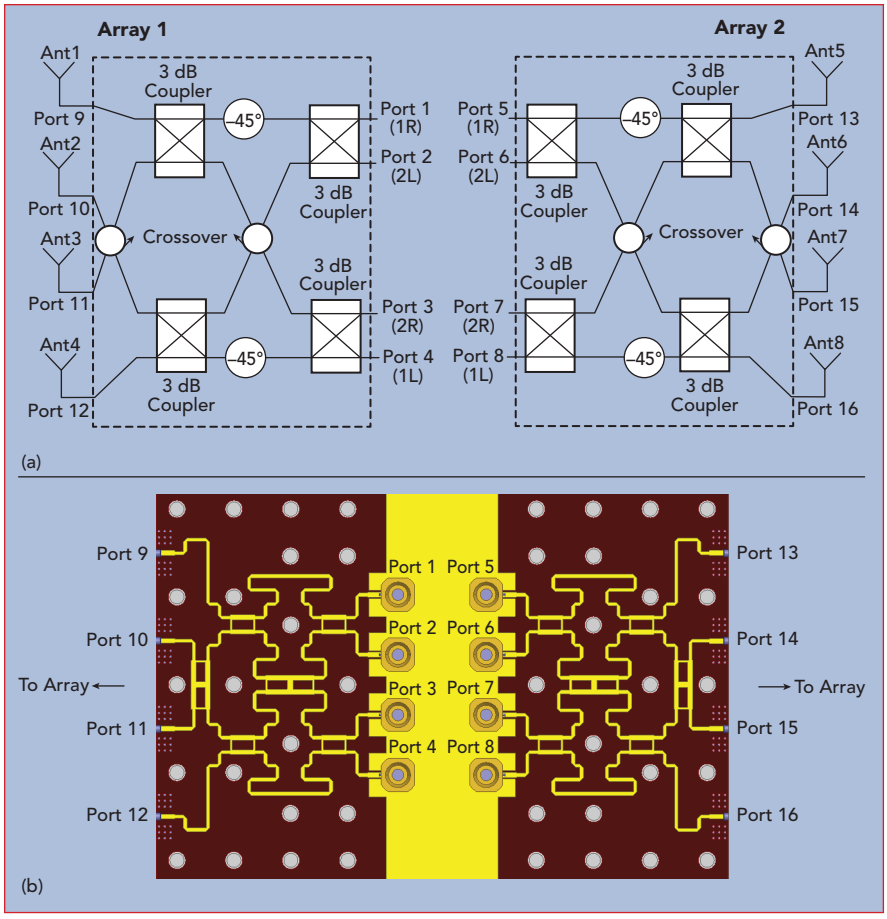

Fig. 4 Two 4×4 Butler matrix feed network block diagram (a) and layout (b).

TABLE 1

PHASE RELATIONSHIP BETWEEN FEEDING PORTS

	Port 1/5	Port 2/6	Port 3/7	Port 4/8
Output Phase Difference (°)	–45	+135	–135	+45

mm, respectively. Because the wave reflects from the bottom of the cavity, with a depth of 4 mm, and is superimposed with the wave radiated directly from the slot, the radiation pattern is unidirectional, as desired.

The block diagram and layout of the two 4×4 BMFNs are shown in ***Figure 4***. They are used to feed the two beam steering arrays because they provide the necessary bandwidth, beam steering capability and beamwidth. Each BMFN is comprised of four hybrid couplers, two crossovers and two pairs of phase shifters to achieve the required amplitude distribution and phase differences between the output ports. The feeding ports of the BMFNs are ports 1 through 8, and their corresponding outputs, which connect to all eight antenna elements, are ports 9 through 16. The feeding ports and output phase differences are shown in ***Table 1***. The BMFNs are fabricated on a 0.254 mm thick Rogers 5880 substrate, with $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$. Eight mini-SMP connectors are used for the measurements.

RESULTS AND DISCUSSION

The beam steering antenna arrays were simulated using HFSS Version 15, and the $|S_{11}|$ of the fabricated prototype were measured using ground-signal-ground RF probes, prior to the assembly of the mini-SMP connectors. The measured

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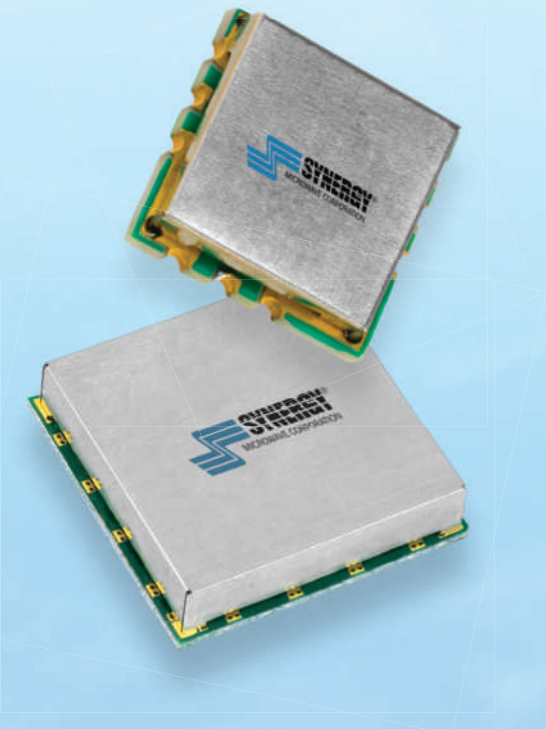
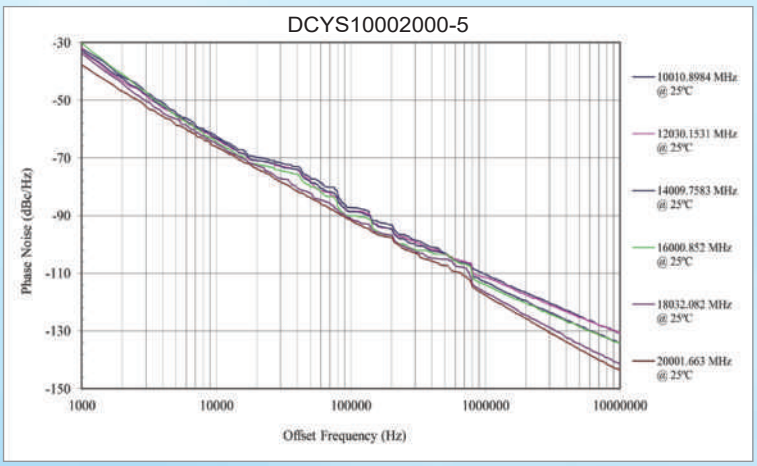
DCYS200400P-5	2 - 4	-93	-115	0 - 18	0
DCO300600-5	3 - 6	-75	-104	0 - 16	-3
DCYS300600P-5	3 - 6	-78	-109	0 - 16	+2
DCO400800-5	4 - 8	-75	-98	0 - 15	-4
DCO5001000-5	5 - 10	-80	-106	0 - 18	-2
DCYS6001200-5	6 -12	-70	-94	0 - 15	> +10
DCYS8001600-5	8 - 16	-68	-93	0 - 15	> +10
DCYS10002000-5	10 - 20	-65	-91	0 - 18	> +10





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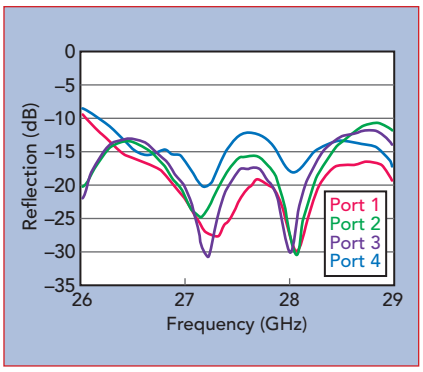

Fig. 5 Measured $|S_{11}|$ of the feeding ports.

$|S_{11}|$ for ports 1 to 4, plotted versus frequency in ***Figure 5***, shows a minimum 10 dB bandwidth of 2.8 GHz, from 26.2 to 29 GHz, which covers the 28 GHz FCC band of 27.5 to 28.35 GHz. For brevity, the results for ports 5 to 8 are not shown.

Antenna gains and radiation patterns were measured in a mmWave compact range. At 28 GHz, the measured performance compared with the simulations are shown in ***Figure 6*** for the four cavity-backed slot antenna elements fed by ports 1, 2, 3 and 4, demonstrating peak gains of 10.1, 9, 9.4 and 9.8 dBi, respectively. Losses are attributed to the BMFN, with an approximate insertion loss of 1.5 dB, as well as the screw feeding structure and mini-SMP connector. With different port excitations, uniform amplitudes with different phase distributions were achieved at the output ports, enabling the array to radiate beams at angles of −22 degrees (port 3), −8 degrees (port 1), +8 degrees (port 4) and +22 degrees (port 2), a total of ±22 degrees. The fabricated prototype is shown in ***Figure 7***.

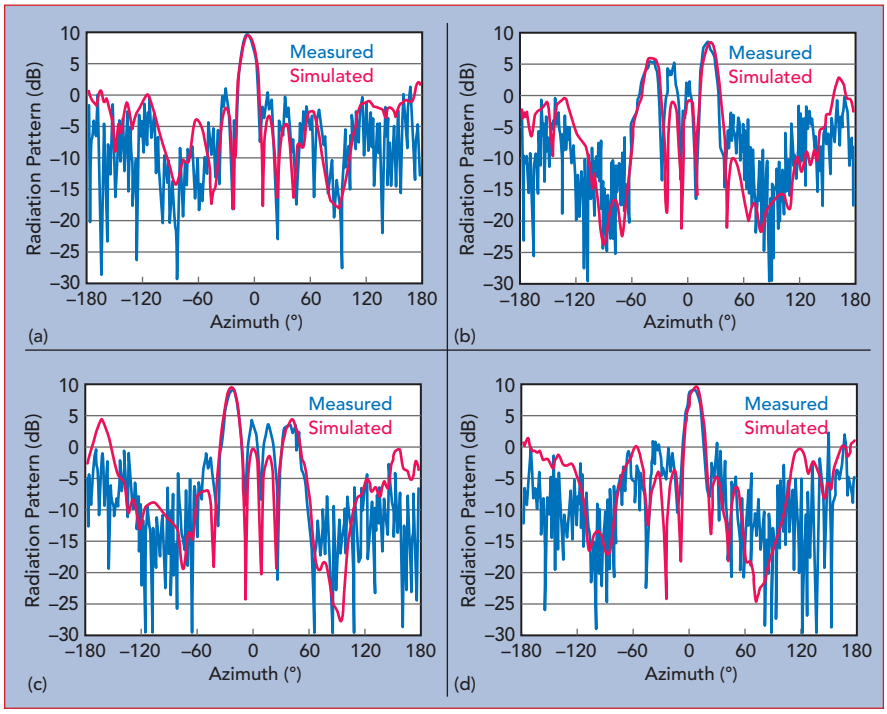

Fig. 6 Simulated vs. measured radiation patterns at 28 GHz.

CONCLUSION

A 28 GHz beam steering antenna array was successfully implemented in a metallic casing for cellular phones. As well as demonstrating good performance—return loss, gain and beam steering—the ex-

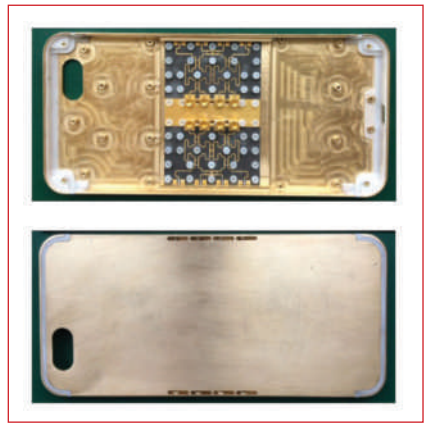

Fig. 7 Fabricated prototype.

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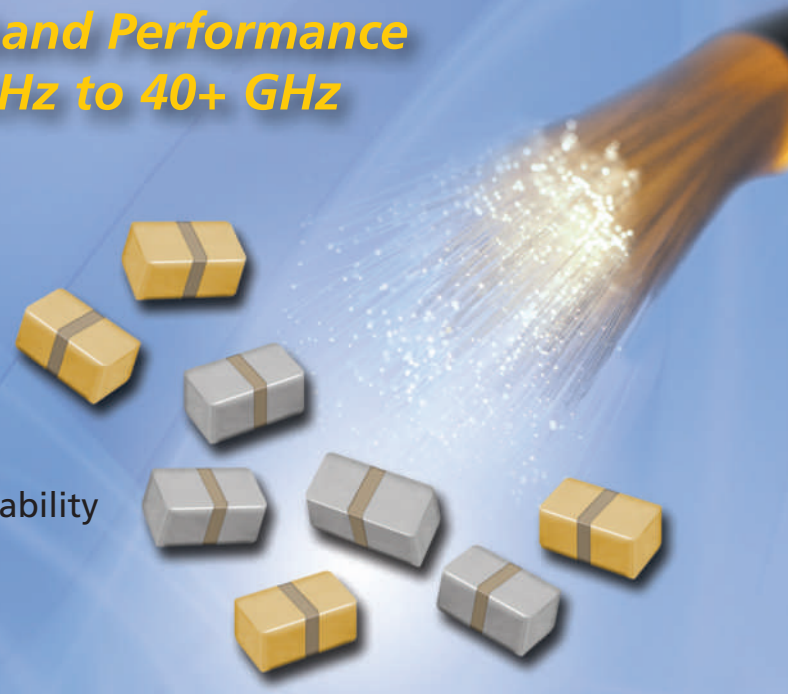

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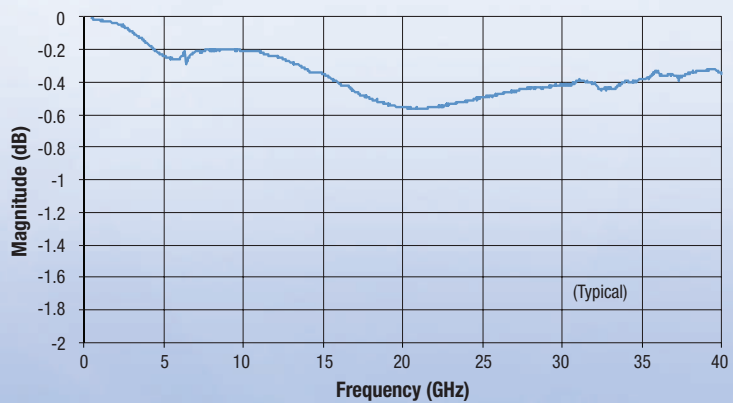

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perimental results were validated by simulation. Owing to its performance, ease of integration, low fabrication cost and fitting into the restricted volume of a cellular phone, the design approach offers an attractive solution for 5G mmWave cellular phones.■

ACKNOWLEDGMENTS

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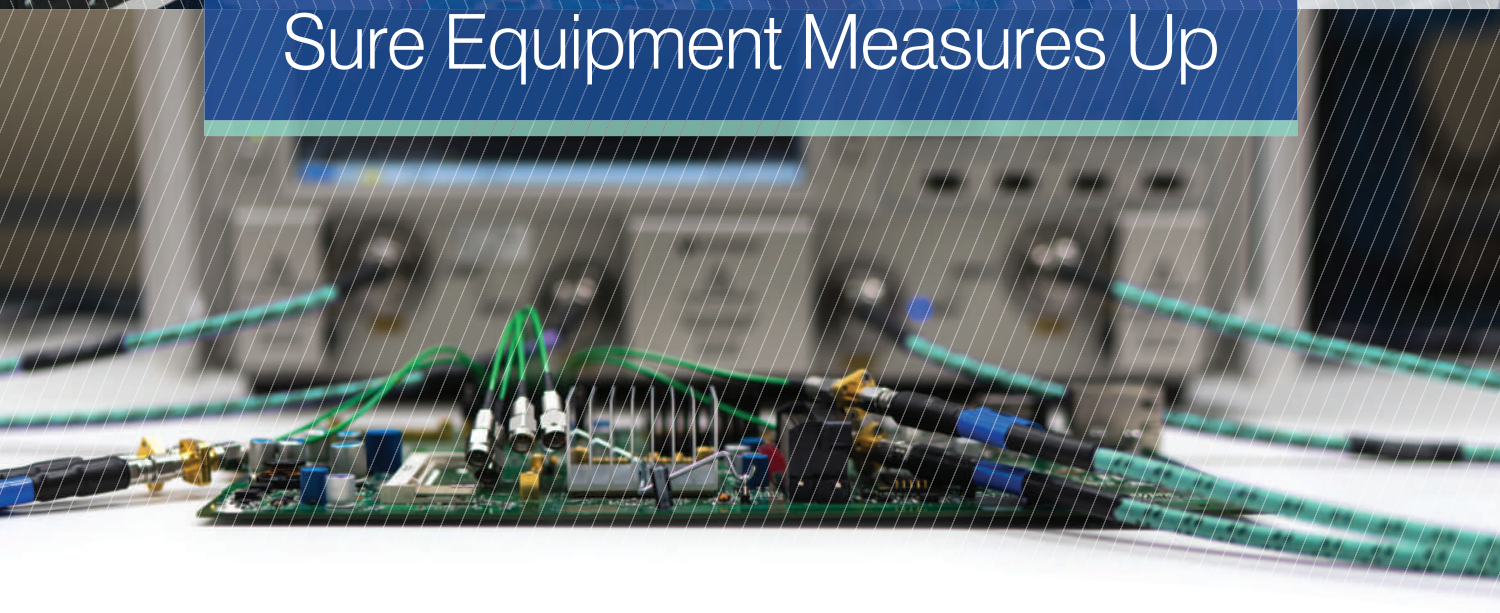

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INVITED PAPER

Integrated Transceivers Simplify Design, Improve Phased Array Radar Performance

Mike Jones and Peter Delos
Analog Devices Inc., Norwood, Mass.

Phased array radar systems use many transmit (Tx) and receive (Rx) channels to create steerable beams. Historically, these platforms were built using separate Tx and Rx ICs, including separate digital-to-analog converters (DAC) in the Tx chain and analog-to-digital converters (ADC) in the Rx chain. The use of discrete ICs led to large footprint, high-power consumption, high cost systems with long time to market, due partially to the manufacturing and calibration complexities. A newer approach uses integrated transceivers that combine the discrete functions into a single IC, enabling smaller, lower power consumption and lower cost phased array radar platforms with faster time to market. This article will discuss the benefits enabled by integration.

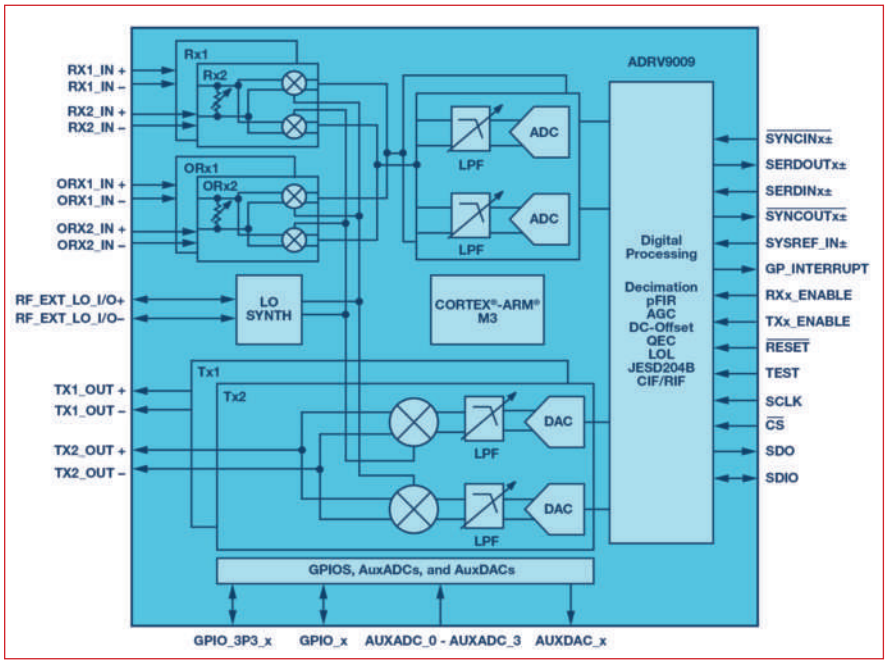

Fig. 1 The ADRV9009 is an example of an integrated transceiver that combines RF and digital functions on a single IC.

Integrated transceivers combine multiple functions onto a single IC, simplifying system design and streamlining a customer's time to market. The latest transceivers integrate DACs, ADCs, local oscillator (LO) synthesizers, microprocessors, mixers and more functions into a single monolithic chip, such as Analog Devices' 12 mm × 12 mm ADRV9009 (see ***Figure 1***). This product combines two Rx channels and two Tx channels with digital signal processing (DSP) and achieves 200 MHz Rx bandwidth and a tunable Tx bandwidth of 450 MHz. An application program interface (API) is provided to program and control the transceiver from the customer's platform. Gain and attenuation can be controlled using the on-chip front-end networks, and built-in initialization and tracking calibration

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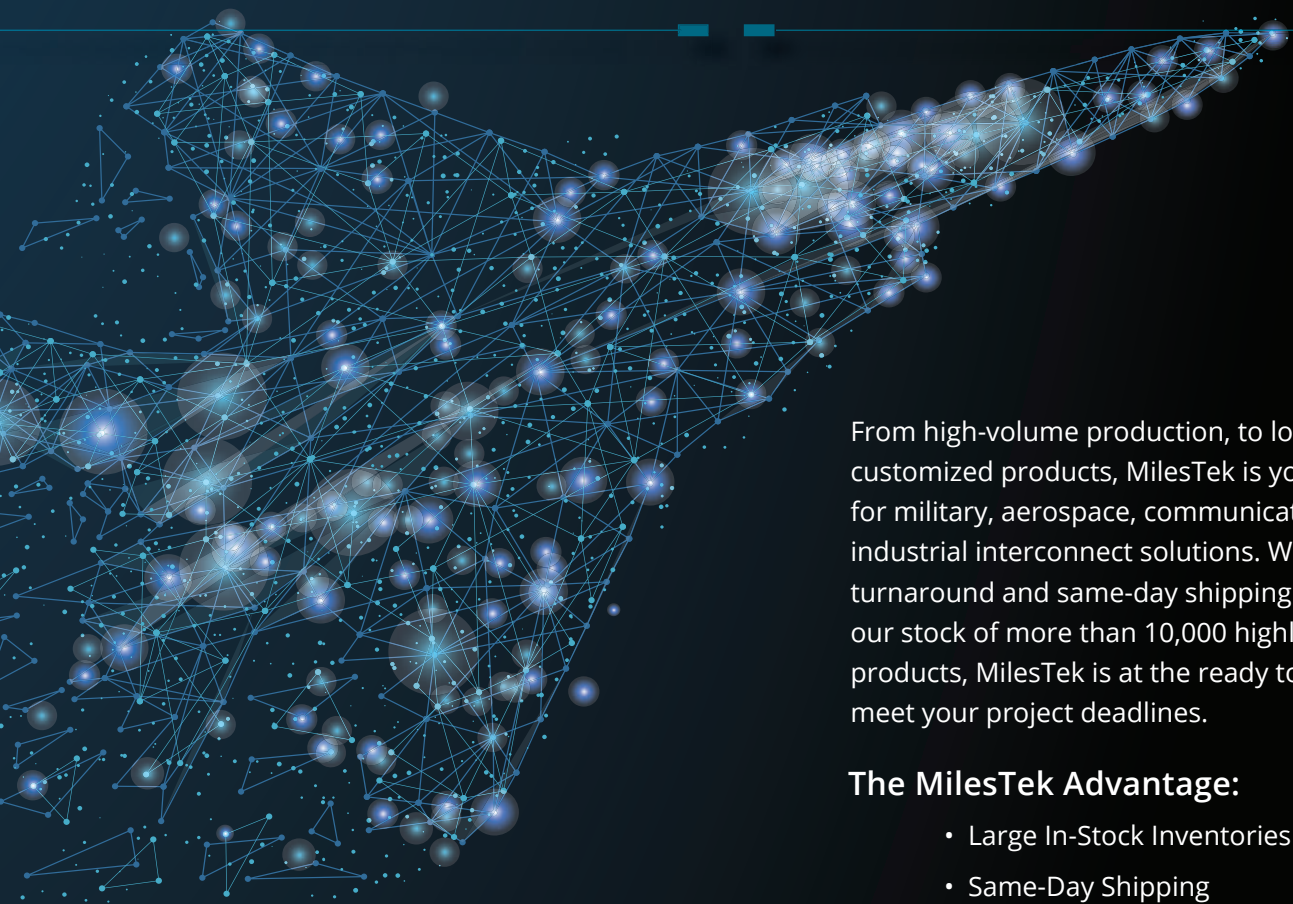

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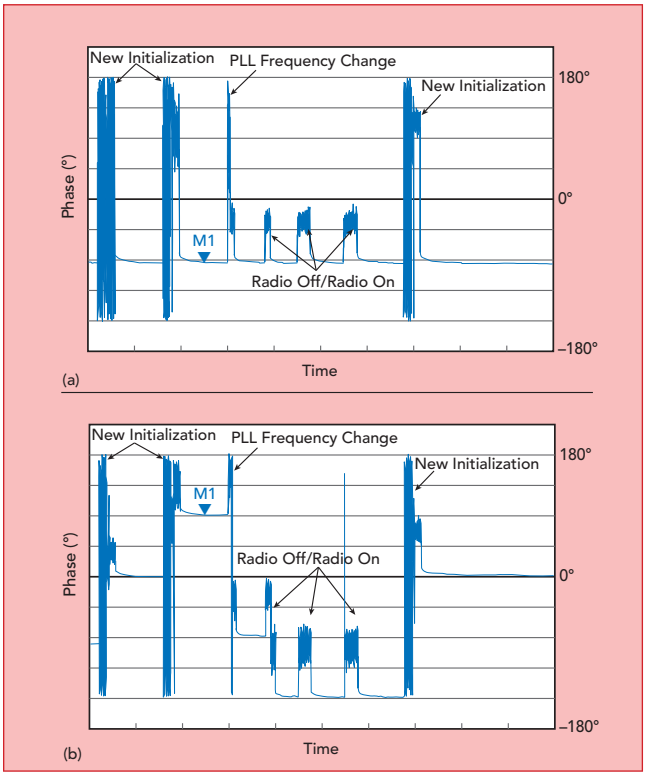

Fig. 2 Phase can be aligned to a reference source with the RFPLL phase sync enabled (a) vs. disabled (b).

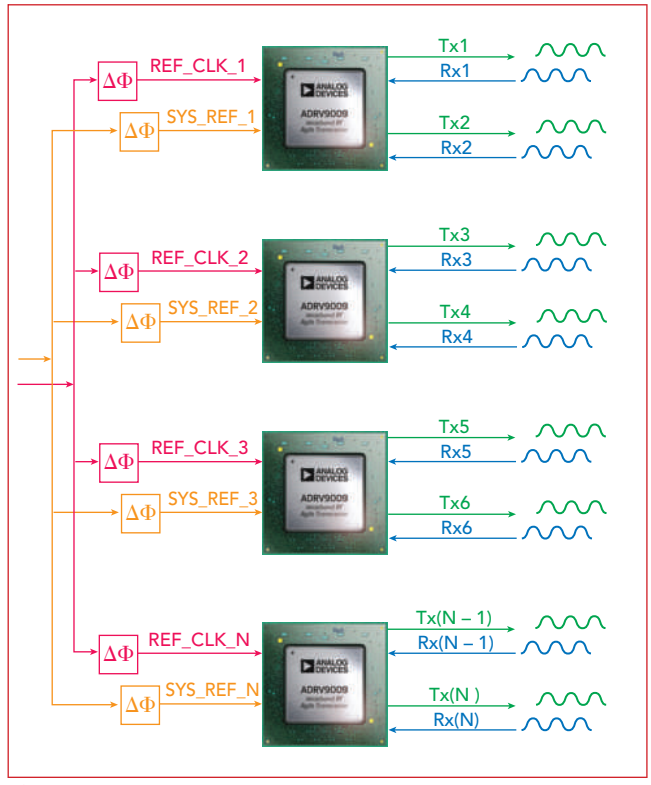

Fig. 3 The number of system channels can be increased using additional transceivers.

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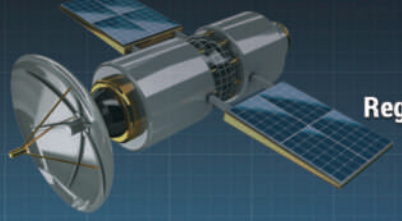

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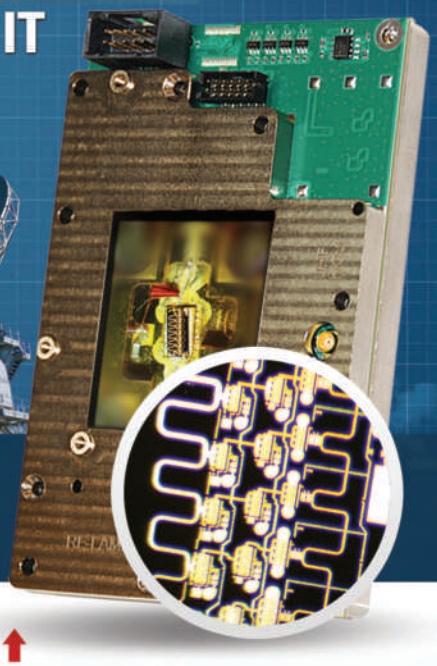

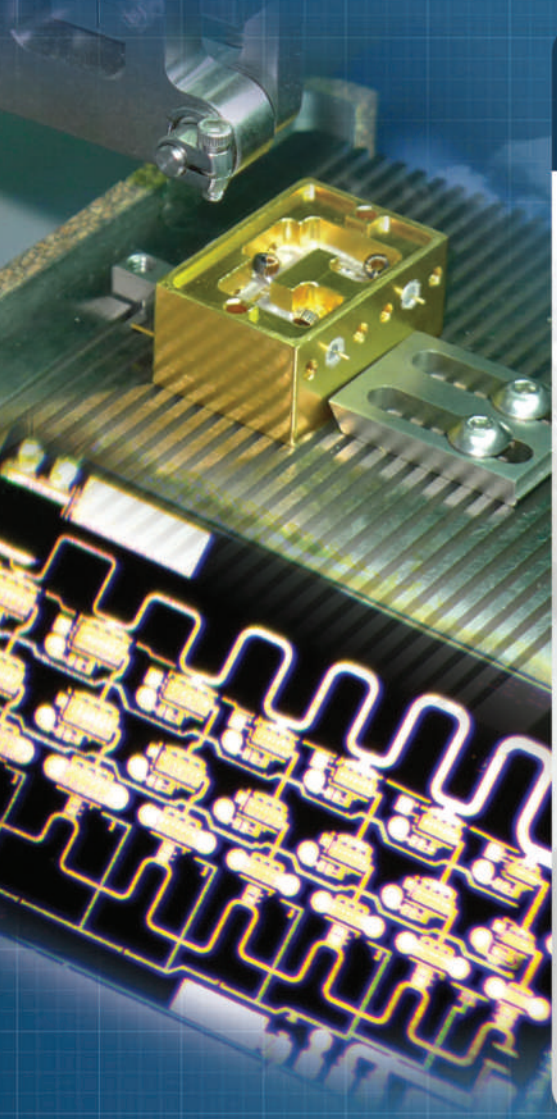

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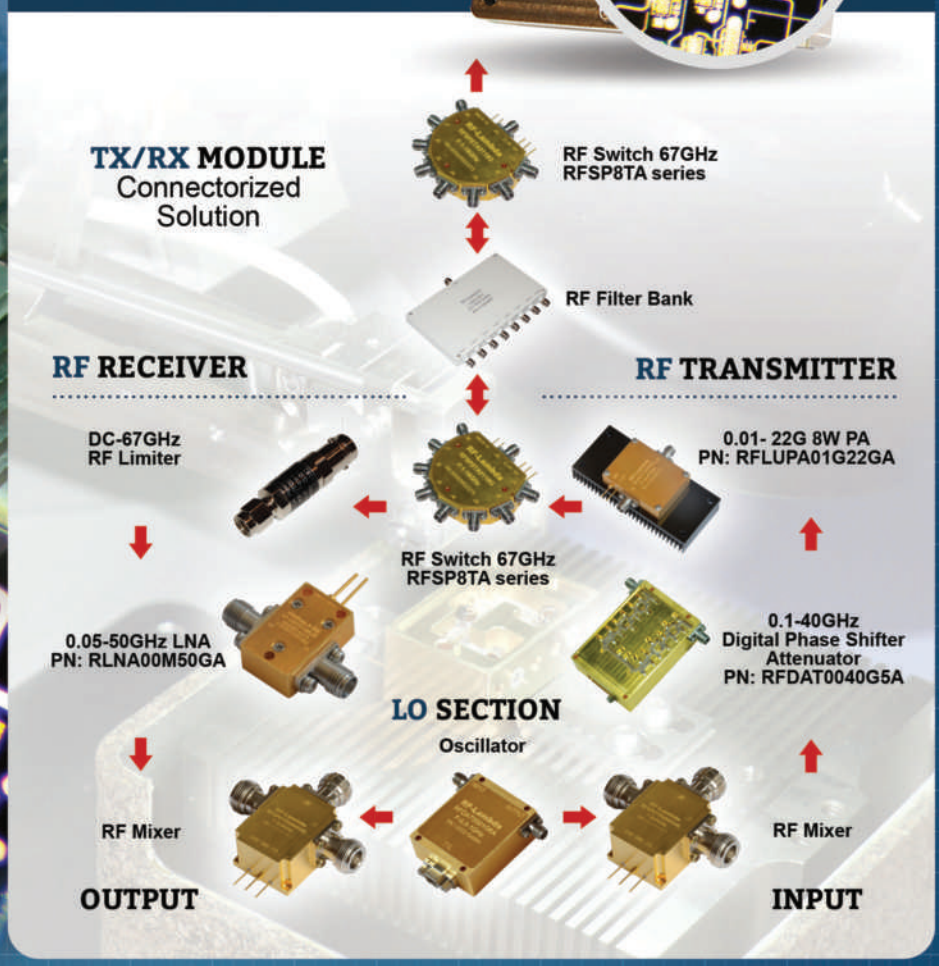

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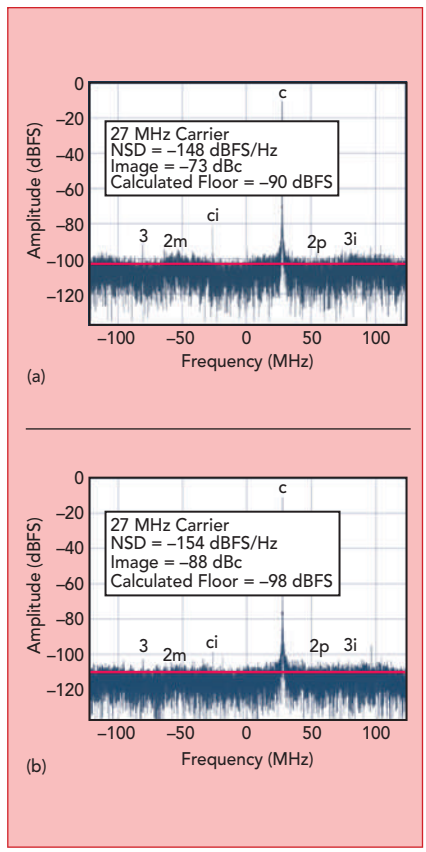
routines provide the performance required for many communications and military applications.

The integrated transceiver creates all the clock signals needed for Tx and Rx, injecting a single reference clock signal known as REF_CLK. On-chip phase-locked loops synthesize all the required clocks for DAC and ADC sampling, LO generation and the microprocessor. If the internal LO phase noise does not meet system requirements, the user can inject an external LO with lower phase noise. Data from the transceiver is offloaded via a standard JESD204b multigigabit serial data interface, enabling large amounts of simultaneous data for Tx and Rx. If deterministic latency and data synchronization are needed, the user can use the built-in multichip synchronization (MCS) feature and issue a SYS_REF signal to act as a master timing reference for an initial lane alignment sequence (ILAS).[1] The LO phase of a Tx or Rx channel can be deterministic with respect to a master reference phase using the built-in RFPLL phase sync feature. By using both the MCS and the RFPLL phase sync features, phase alignment can be replicated when initializing the transceiver, frequency tuning or toggling the radio on and off via the control software (see ***Figure 2***).

MULTIPLE INTEGRATED TRANSCEIVERS

If more than two Rx and two Tx are required for a system, the user can use multiple transceivers and benefit from the small size achieved with monolithic integration (see ***Figure 3***). Multiple transceivers can be synchronized using concurrent SYS_REF pulses to simultaneously trigger internal dividers for all the ICs. These SYS_REF pulses can be issued by either clock chips or baseband processors with pro-



▲ Fig. 4 Spectral performance of a single channel (a) vs. eight channels (b) using the ADRV9009 transceiver.

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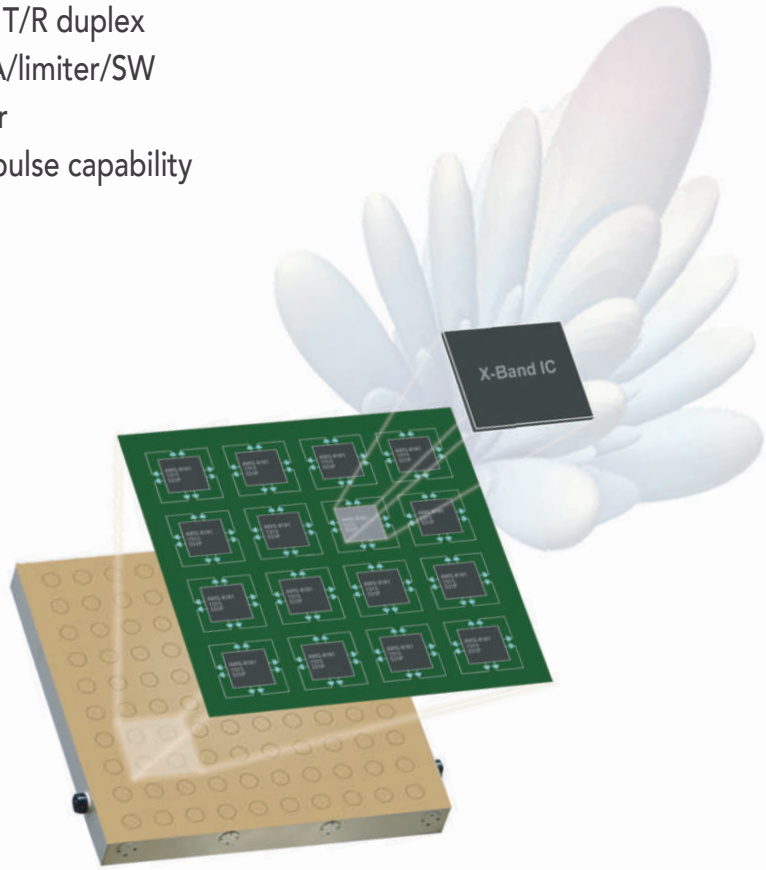

AWS-0101 for Low Noise Figure
AWS-0103 for High Input IP3
AWMF-0106 Front End IC

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grammable delays, to account for any length mismatches between the routes to the various ICs. Both the data paths and multiple LOs across multiple ICs are capable of being deterministic.

Increasing the channel count by using synchronized integrated transceivers enables these devices to serve as the backbone of a phased array radar. When combining phase- and amplitude-aligned Tx and Rx channels, using multiple integrated transceivers has demonstrated system-level dynamic range, spurious and phase noise improvements. On-chip DSP features such as numerically-controlled oscillators (NCO) and digital up-converters (DUC) or digital down-converters (DDC) enable system-level spurious decorrelation within a single IC.[2]

Combining Rx channels using multiple integrated transceivers has demonstrated both improved system-level noise spectral density (NSD) and spurious performance. This improves the dynamic range of a phased array radar by lowering the effective noise floor of the system while maintaining the full-scale power of the channel. ***Figure 4*** compares the measured system performance using a 27 MHz carrier and combining eight Rx channels to effectively increase the number of bits in the array. Although there are eight total channels, there are only four uncorrelated LOs (N_{LO} = 4) among the four transceivers used to create the eight channels. This gives a theoretical improvement in the NSD of

NSD Improvement (dB) = $10\log_{10}(N_{LO}) = 10\log_{10}(4) = 6$ dB

The measured results in Figure 4 are close to theoretical. NSD and the calculated noise floor, indicated by the horizontal line in each plot, are improved by approximately 6 dB when going from one to eight channels: the calculated noise floor improves from −89.9 to −98.3 dBFS, and the NSD goes from −148 to −154 dBFS/Hz. Another benefit is the undesired image frequencies sum in an uncorrelated manner to reduce system-level spurious. This

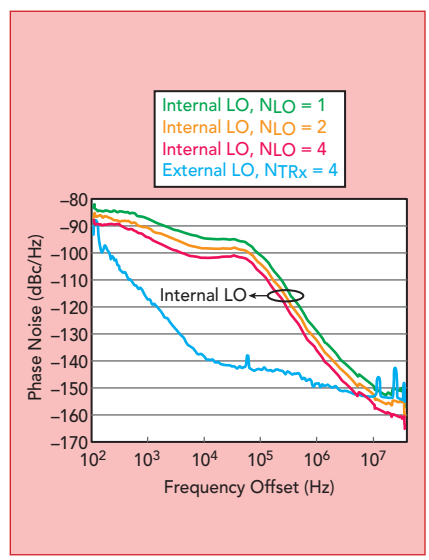

Fig. 5 Transceiver phase noise comparison using the internal vs. external LOs at 2.6 GHz. A Rohde & Schwarz SMA100B signal generator was the external LO.

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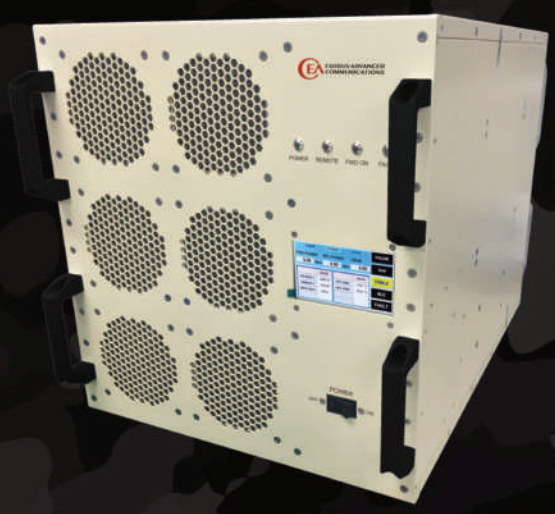

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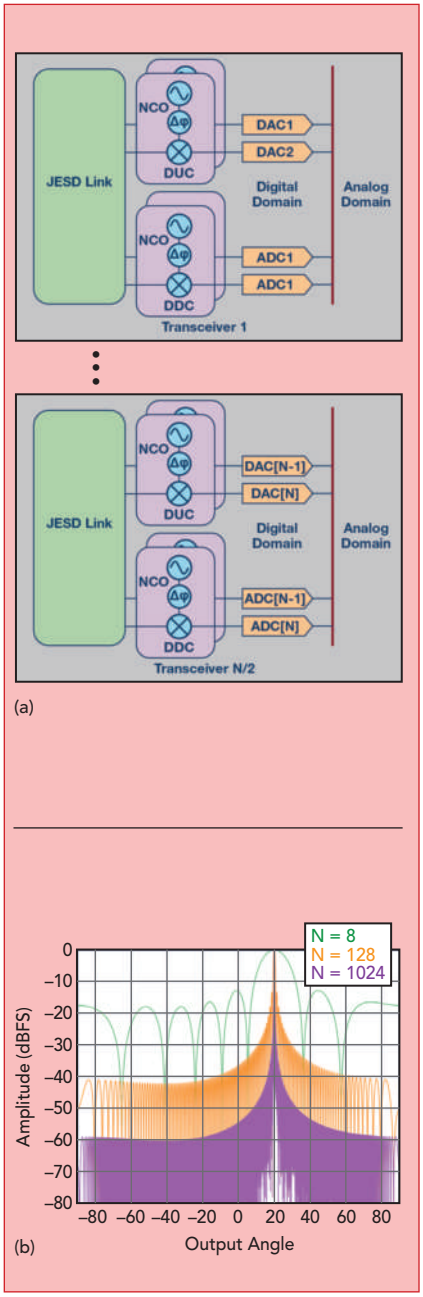
improvement can be enhanced as the number of channels increases.

Combining multiple integrated transceiver channels and aligning the phase can improve the phase noise of the array. The top three traces of ***Figure 5*** show improved phase noise when combining eight transmit channels using the internal LOs of four integrated transceiver ICs. Once again, with four distinct and uncorrelated LOs (N_{LO} = 4), the phase noise is improved by approximately 6 dB when increasing the number of Tx channels from one to eight. Increasing the channel count will further improve the phase noise of the radar. Alternatively, an external LO can be injected into each subarray of N transceivers to improve the starting phase noise of the subarray, shown by the lower trace in Figure 5. However, each element within the subarray will be correlated, and the subarray will not benefit from channel summing improvements, since the elements all share the same LO.

With its integrated DSP features such as NCOs, digital phase shifters, DUCs and DDCs, the transceivers enable baseband phase- and frequency-shifting in the digital domain, enabling digital beamforming in a multichannel phased array radar. By integrating these func-



▲ **Fig. 6 Increasing the channel count and using digital phase shifting (a) enables the theoretical system beamwidth to be narrowed.**

Phase Adjusters

Part Number	Connectors	Frequency Range (GHz)	VSWR max.	Insertion Loss max. (dB)	Phase Shift min. (°)	No. of Turns	Phase Shift Deg/ GHz/ Turn	Time Delay min. (psec.)	Time Delay max. (psec.)	Temperature (°C)	Weight max. (g)
LS-0002-YYYY[1]	div.	DC - 2	1.2:1	0.3	85	37	1.15	393	516	-65 to +125	98-220[2]
LS-0103-6161	Nf	DC - 3	1.15:1	0.4	540	cont.		1826	2328		700
LS-0203-6161				0.9	1080			3693	4694		1200
LS-0012-YYYY[1]	div.	DC - 12	1.3:1	0.8	520	37		406	530		114-234[2]
LS-0112-XXXX[3]	SMA	DC-12.0	1.25:1	0.4	230	16.5	1.2	238	293	-65 to +125	70
LS-A112-XXXX[3]											47
LS-0212-1121											70
LS-A212-1121											47
LS-0118-XXXX[3]		DC-18.0		0.6	350						70
LS-A118-XXXX[3]											47
LS-0218-1121											70
LS-A218-1121											47
LS-0118-5161	N							300	355	-65/+70	105
LS-U118-5161										-65/+165	
LS-0018-YYYY[1]	div.	DC - 18	1.5:1	1.0	770	37	1.15	406	530		98-220[2]
LS-0121-XXXX[3]	SMA	DC-26.0	1.30:1	0.8	500	16.5	1.2	238	293	-65 to +125	70
LS-A121-XXXX[3]											47
LS-0221-1121											70
LS-A221-1121											47
LS-0321-1121			1.31:1		500	35	0.6	236.7	290.5		30
LS-0170-1121			1.26:1	0.26	127	13.5	0.36	109.2	122.8		9
LS-S008-1121			1.50:1	0.4	155	10	0.6	118.6	135.1		20
LS-P140-KFKM	2.92 mm	DC-40.0	1.2:1	0.6	590	12	1.2	168	208	-65 to +65	51
LS-0140-KFKM			1.4:1								49
LS-P150-HFHM	2.40 mm	DC-50.0	1.3:1	0.8	400	7		172	195		55
LS-0150-HFHM			1.5:1								53
LS-P165-VFVM	1.85 mm	DC-63.0	1.4:1	0.8	600	8		167	195		55
LS-0165-VFVM			1.5:1								53

[1] div.: Connector Configuration available: SMA, male and female; N, male and female; TNC male and female
[2] Weight depends on connector configuration
[3] SMA Connector Configuration available: male/female; male/male; female/female; female/male

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tions on a single IC, a transceiver-based system can support the required antenna lattice spacings for many phased array applications. Increasing channel count with more transceivers generally results in narrower beams, at the expense of increasing system footprint. However, with the multiple functions integrated in a single monolithic IC, the increase in footprint is smaller than could be achieved previously.

Simulating radiation patterns using MATLAB®, ***Figure 6*** shows how increasing N from 2^3 (8) to 2^{10} (1024) channels narrows the beam with a deeper lobe amplitude, although the achievable power nulls will be dictated by the actual antenna design.

CONCLUSION

The integration of multiple digital and analog functions within a single, small transceiver IC simplifies phased array design and accelerates development and manufacturing. These transceivers enable both digital beamforming and hybrid beamforming, depending on system specifications. This article has demonstrated the performance that can be achieved with Analog Devices' transceiver. The ADRV9009 supports a variety of system architectures, serving multiple applications with the same hardware.■

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1. J. Harris, "What Is JESD204 and Why Should We Pay Attention to It?," *Analog Devices Technical Article*, MS-2374, October 2013, pp. 1–4.
2. P. Delos, M. Jones and M. Robertson, "RF Transceivers Enable Forced Spurious Decorrelation in Digital Beamforming Phased Arrays," *Analog Devices Technical Article*, August 2018.

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67 GHz Signal Generator Delivers High Output Power with Low Phase Noise and Harmonics

Rohde & Schwarz
Munich, Germany

Rohde & Schwarz has extended the frequency range of the R&S SMA100B signal generator from 20 to 67 GHz, with intermediate options of 31.8, 40 or 50 GHz to best fit the application. The 40 GHz option, for example, covers all major radar bands in development and the 5G bands to 39 GHz. With the 67 GHz option—and over-range operation to 72 GHz—the instrument supports emerging satellite links at Q- and V-Band and the unlicensed 60 to 71 GHz bands used by IEEE 802.11ad and IEEE 802.11ay.

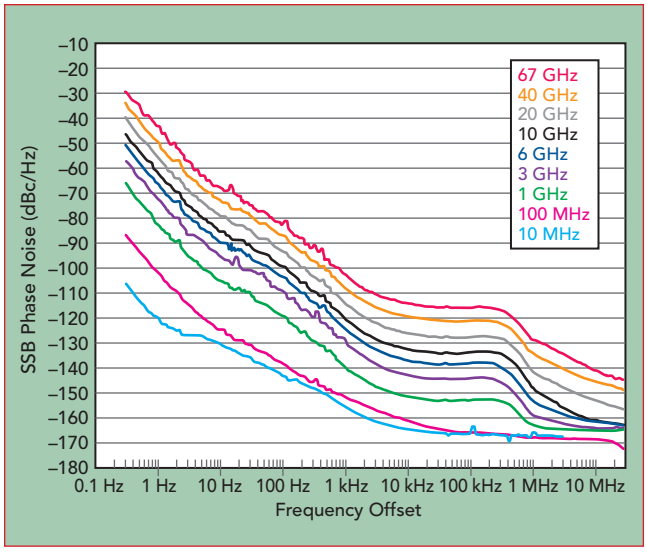

Fig. 1 Measured single sideband phase noise vs. output frequency with the ultra-low phase noise option.

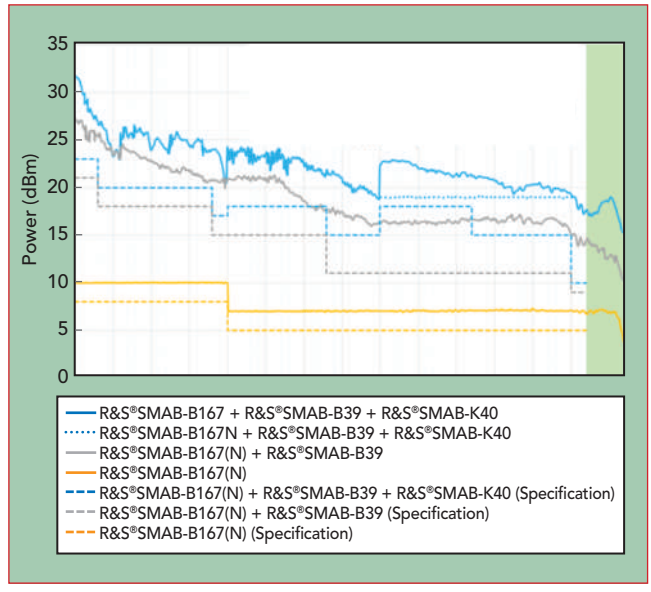

Fig. 2 Measured output power vs. frequency with the high output power options.

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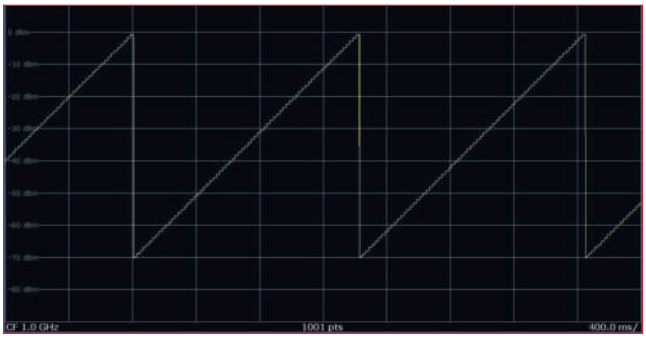

Fig. 3 The continuous power sweep has 70 dB dynamic range.

The R&S SMA100B is the only analog signal generator available with a large spurious-free dynamic range that can simultaneously generate high output levels with low harmonics, phase noise and wideband noise—even with the extended frequency range. The signal generator also has a continuous level sweep with a 70 dB dynamic range and the capability to generate chirp signals.

EXTREMELY PURE

The R&S SMA100B is well suited for generating low noise local oscillator signals for radar applications, where extremely low phase noise is crucial. With the ultra-low phase noise option, the generator achieves a measured phase noise of −120 dBc/Hz at 20 kHz offset from a 40 GHz carrier (see ***Figure 1***). As sampling rates increase with each generation of analog-to-digital and digital-to-analog converters, pure RF carriers with extremely low phase noise and low wideband noise are required to measure component and system performance. Complementing its ultra-low phase noise, the R&S SMA100B achieves low wideband noise: −150 dBc/Hz at 40 MHz offset from a 30 GHz carrier.

In practical test setups, the attenuation from cables and adapters can limit the measurement range. With the ultra-high output power option with integrated harmonic filters, the R&S SMA100B can compensate for most cable losses (see ***Figure 2***), considerably simplifying test setups by eliminating the need for external amplifiers and harmonic filters. With this option, the R&S SMA100B can measure the saturated output power and compression characteristics of power amplifiers, particularly those using GaN devices. GaN amplifiers typically have higher saturated output power than GaAs-based amplifiers and, depending on the amplifier's gain, may require higher input power to reach the 1 dB compression point and saturation.

To measure an amplifier's full transfer function with an analog signal generator, the level sweep must cover a large dynamic range without interruption. Blanking the input power can cause an unpredictable reaction in an amplifier's automatic level control, which should be avoided. The R&S SMA100B has an uninterrupted RF level sweep range of more than 70 dB without blanking or spikes (see ***Figure 3***).

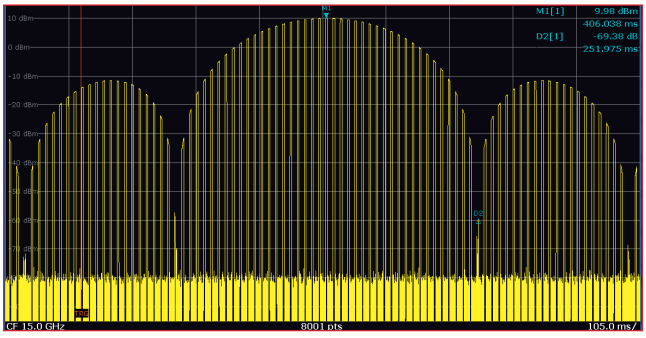

Fig. 4 Amplitude modulated pulsed signal. The amplitude envelope is generated with an external source.

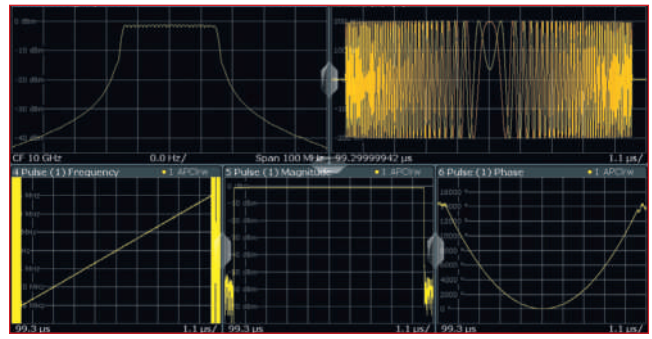

Fig. 5 Chirp signal (10 µs duration, 30 MHz bandwidth) generated with the R&S SMA100B.

AM MODULATION AND FREQUENCY CHIRPING

Received pulsed radar signals often have superimposed amplitude modulation, representing radar transmitters with rotating antennas and narrow lobes. In such cases, the receivers only receive short input signals. To simulate this scenario when testing, the ScanAM option of the R&S SMA100B can generate pulsed signals with superimposed amplitude modulation, with a modulation depth greater than 70 dB (see ***Figure 4***).

Some radar systems, such as weather and long-range surveillance radars, use pulse compression, where each pulse is "chirped," i.e., modulated with a linear frequency modulation. This improves range resolution, the ability to distinguish between two objects close to each other. The R&S SMA100B can generate chirp signals with adjustable chirp duration and bandwidth, even superimposing impairments such as AM noise and AM drift to simulate the influence of the receiver's hardware (see ***Figure 5***).

With new frequency options, the R&S SMA100B extends its frequency range to above 67 GHz and provides extremely low phase noise, high output power and low harmonics. These features make it well suited for testing radar receivers, other defense systems, mmWave telecommunications and RF semiconductors supporting these markets.

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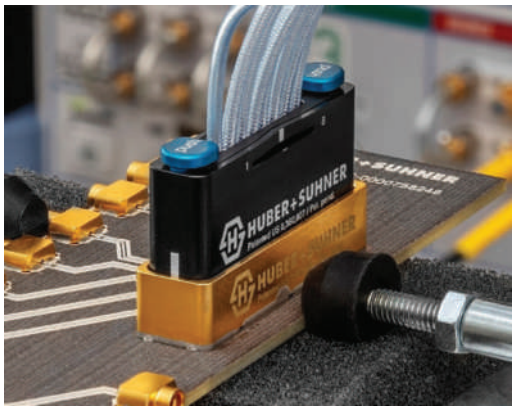

Multicoax Board-Mounted Connector Performs to 70 GHz

HUBER+SUHNER AG
Herisau, Switzerland

Responding to the market's advance to mmWave frequencies for wireless and data rates approaching 100 Gbps for data communications, HUBER+SUHNER has developed a multicoax connector for circuit boards, enabling low reflection transitions from the cable assemblies to the PCB. Designed with the goal of achieving an electrically transparent connection, the MXPM70 provides performance through 70 GHz—optionally > 90 GHz—and is available in configurations including single and dual rows of eight coax cables with 2.54 mm center-to-center pitch. A magnetic locking mechanism maintains repeatable and precise connections between the socket and cables, ensuring consistent signal integrity. The gold-plated brass socket and aluminum connector housing were designed to be low-cost while achieving the stringent performance requirements.

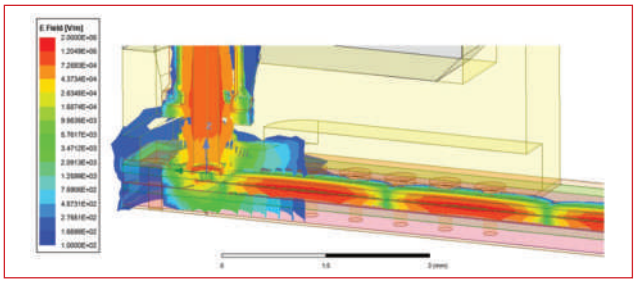

Fig. 1 The transition, which converts the TEM wave in the coax cable to a planar wave propagating on the board, can introduce unwanted reflections if not properly designed.

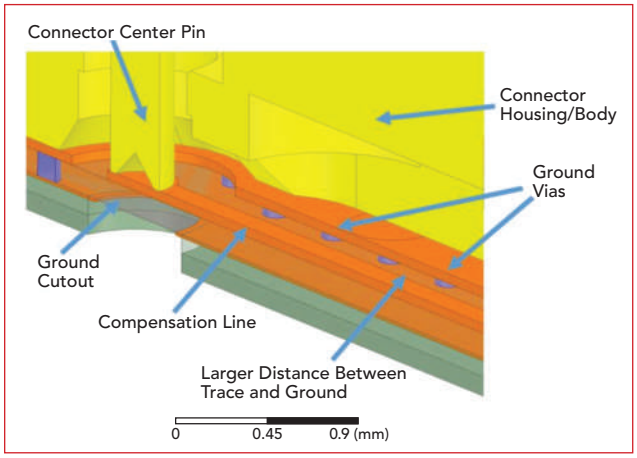

Fig. 2 MXPM70 connector-to-board transition optimized for high frequency performance.

BOARD TRANSITION DESIGN

RF board connectors are challenging to specify, as their electrical performance depends on the design of the PCB footprint or transition to the interconnecting lines on the board. Selecting the best board connector requires understanding the design of the interface used by the connector manufacturer to determine the specified performance. Insertion loss, return loss and crosstalk are only valid for the same footprint and board configuration used by the manufacturer. Achieving this performance in the user's application requires the same design or a new, carefully designed transition. Any changes in the dielectric material, substrate thickness and metallization thickness can have a significant impact on the actual performance of the user's board. The transition, which converts the TEM mode of the coaxial cable to a planar mode propagating on the board, is the most sensitive part of the design, po-

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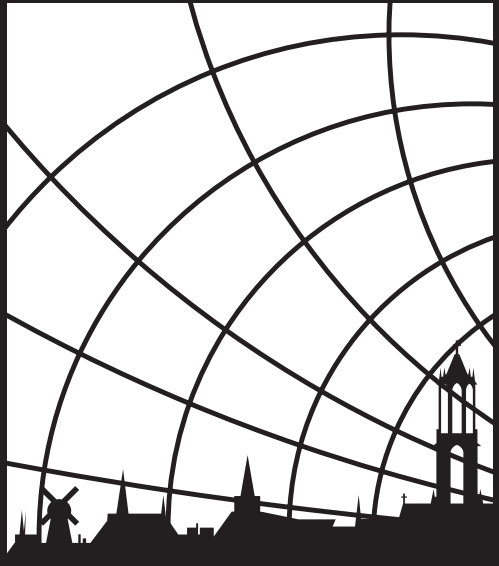

TABLE 1 BOARD CONFIGURATION

Layer Number	Material	Layer Type	Thickness (µm)
L1	Cu with ISIG Plating*	Signal	17 + 33
	RO3003 (Dk = 3)	Core	127
L2	Cu	Ground Plane	17
	RO3003 (Dk = 3)	Prepreg	100
	RO3003 (Dk = 3)	Prepreg	100
	FR4 (Dk = 3.48)	Core	1500

*ISIG = Imersion Ag, Imersion Au

tentially creating reflections with attendant suck-outs in insertion loss, particularly near the upper end of the operating frequency range (see ***Figure 1***).

To achieve the specified performance using the MXPM70 board connector, HUBER+SUHNER recommends using electromagnetic (EM) simulation to optimize the user's board footprint for the connector. Begin by choosing the transmission media on the board—typically microstrip, stripline or grounded coplanar waveguide (GCPW)—and the board structure, i.e., board material and thickness, number of layers, metallization and thickness. Design an initial layout of the footprint, analyze the performance of the interface and iterate the layout to optimize performance. To illustrate, the design of a transition to GCPW using the board stack-up of ***Table 1*** was optimized, resulting in the footprint shown in ***Figure 2***.

To minimize parasitic capacitance, a ground cutout was incorporated on layer L2 under the signal pad on layer L1, since the size of the signal pad cannot be reduced. The minimum size of the signal pad is set by the connector center pin and positioning tolerances to ensure electrical stability and mechanical robustness. While the cutout increases losses slightly at lower frequencies, it improves the high frequency performance significantly and has minimal effect on the crosstalk between connectors. One caution: the ground cutout should be evaluated to ensure it does not allow parallel modes within the stack. A second design choice to minimize the parasitic capacitance was extending the distance between the signal line and its ground on L1.

To improve impedance matching and signal transfer to the GCPW transmission line, a compensation line was added to L1. PCB traces are commonly designed with impedances of 46 to 48 Ω to minimize losses and compensate for the etching process during manufacturing. Etching reduces the transmission line width, increasing the impedance—which can cause mismatch with connectors designed for 50 Ω. The compensation line provides a gradual impedance transition, yielding lower insertion loss and minimizing capacitive effects.

EM modeling this design shows $|S_{11}|$ better than −15 dB through 80 GHz (see ***Figure 3***). Simulating the time domain response of the transition shows the impedance is between approximately 49.5 and 52.5 Ω (see ***Figure 4***). To show the performance improvement achieved by optimizing the footprint, the $|S_{11}|$ and time domain responses are also plotted for the non-optimized board design.

SUMMARY

While a generic footprint design can be used during the early phase of development, to place the connectors and route the RF or data channels on the board, the footprint must be optimized for the specific board configuration to achieve the highest frequency and data rates. While the footprint design may seem straightforward, not analyzing and optimizing the transition can significantly degrade test results and the overall performance of a high cost system.

With appropriate board design, HUBER+SUHNER's MXPM70 multi-coax connector is well suited for RF and high speed data applications, providing low reflection coax-to-board transitions with performance to at least 70 GHz—pretty close to electrically transparent.

VENDORVIEW

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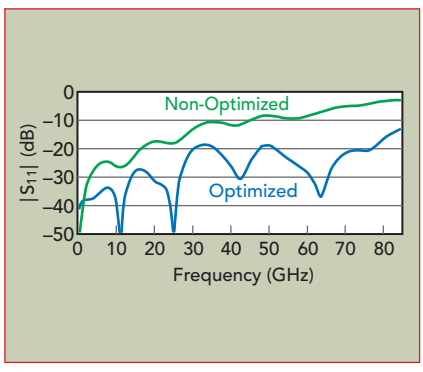


Fig. 3 Simulated $|S_{11}|$ of the MXPM70-to-board transition.

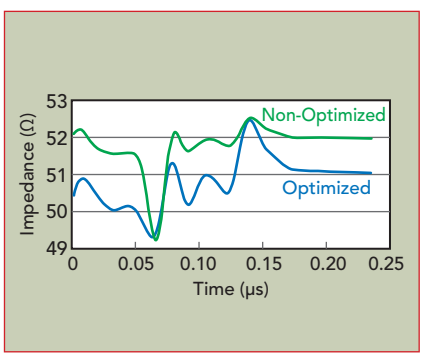
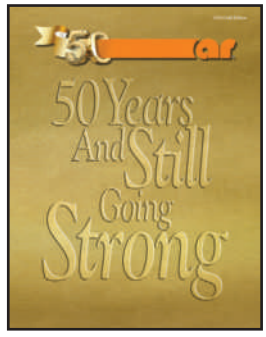


Fig. 4 Simulated time domain response of the MXPM70-to-board transition.

50 Years and Still Going Strong

VENDORVIEW



This one, comprehensive catalog includes virtually everything necessary for RF and EMC testing. You will find important information on everything from RF/microwave amplifiers to antennas, probes, analyzers, accessories and integrated test systems that make testing quicker, easier and more accurate. You will discover innovative new products like MultiStar Field Analyzers and Test Systems that use groundbreaking technology to perform multiple tasks simultaneously, reducing test times from days to hours. The latest developments in hybrid power modules and dual band technology are also represented here.

AR RF/Microwave Instrumentation
www.arworld.us/

Your Partner in Space

K&L Microwave has been a key supplier to space programs since the Apollo 17 lunar sounder experiment in 1972. K&L has supported customers with high-reliability filter products for integration into flight equipment, providing bandpass, highpass, lowpass and bandstop configurations. As a supplier of custom filter products, K&L has the expertise and resources for determining how best to meet customer space flight requirements. A highly trained engineering staff utilizes specialized in-house and purchased software tools to identify and realize advantageous designs. Download their new brochure and find out how K&L can be "Your Partner in Space."

K&L Microwave
www.klmicrowave.com

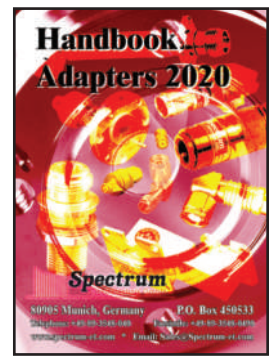
New Product Guide – Q3 2019

VENDORVIEW

Mini-Circuits has released over 400 new models to their catalog in 2019 year to date. The Q3 2019 new product guide highlights some of the latest additions including MMIC LNAs up to 43.5 GHz, ultra-wideband coaxial LNAs, over 50 new LTCC products, new reflectionless filters, the company's innovative 3D mmWave imaging and sensing evaluation kit and more.

Mini-Circuits
www.minicircuits.com

The 2020 Adapter Handbook



The new handbook shows, at over 450 pages, in detail 34 adapter categories, standard MIL- and DIN-products, as well as the Spectrum Elektrotechnik developments, In- and In-between Series. Waveguide, WR and WRD to coax adapters with a variety of connector types are shown in a special section. This most complete handbook is in each section headed by a reference table, indicating the contents of the section and referencing related products. Specification sheets show the electrical, mechanical and environmental performance of the series with interface dimensions.

Spectrum Elektrotechnik GmbH
www.spectrum-et.com

30th Anniversary Edition Catalog

VENDORVIEW

Spectrum Instrumentation presents its catalog 2020, which is the 30th anniversary edition. The catalog contains a detailed 30 years history of the company, as well as all the information about the current product range of 130 different digitizers and 55 different AWGs, available as PC-cards (PCIe and PXIe) and standalone Ethernet (LXI) instruments. You will find the PDF version of the catalog on the starting page, bottom right, of the website.

Spectrum Instrumentation
www.spectrum-instrumentation.com

Rev. II of 2019 Lab Brick RF Test Devices Product Guide

VENDORVIEW

Vaunix announced the release of rev. II of their 2019 product guide covering over 60 standardized Lab Brick test devices. Functions include digital attenuators up to 20 GHz, signal generators up to 20 GHz (40 GHz coming soon), switches up to 6 GHz and phase shifters up to 12 GHz. All standard Lab Bricks included in the guide are available from stock to one week and can be purchased for immediate delivery directly from our website via credit card.

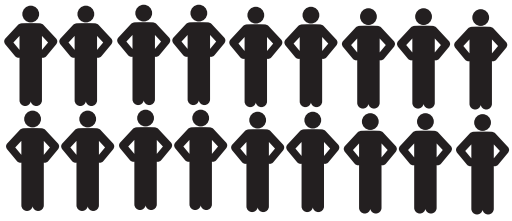
Vaunix
https://vaunix.com/

EDI CON 2020

Electronic Design Innovation Conference
电子设计创新大会

Come celebrate innovation in RF, microwave, EMC/EMI, signal integrity, and power integrity design at EDI CON China 2020.

Learn more about sponsoring and exhibiting at ediconchina.com. Here's a summary of the 2019 event:

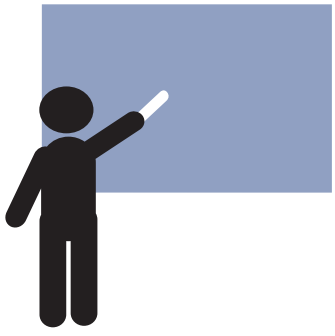


2,943 Unique Attendees

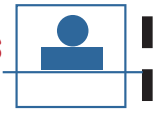
66 Technical Sessions

45% returned for a second day

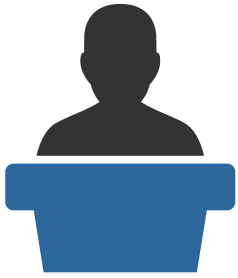
37 Workshops



Nearly 100 Exhibitors



2nd Annual EDI CON Product Innovation Awards



14 Frequency Matters Theater Talks

Book your sponsorship for May 12-13, 2020

Integrated Passives Shrink Circuit Footprints Up To 80%

Designers are turning to integrated passive components (IPC) to help meet the continuing demand to miniaturize wireless devices while ensuring the reliability of RF circuits, such as filtering, impedance matching, coupling and baluns. IPCs combine multiple discrete passive components into a single surface-mount device—a passive subsystem which complements an RFIC. Manufactured using low temperature cofired ceramic (LTCC) technology, which enables passive components to be layered in 3D, IPCs can integrate the functionality of 10 to 40 individual L/C components. With an IPC, the entire front-end between the RF chipset and antenna can be realized in a single, ultra-low profile package—0.35 to 1 mm thickness—less than 20 percent the total size of the same circuit using discrete components.

Using a proprietary LTCC manufacturing process, Johanson Technology has developed a line of small, highly reliable IPCs for RF systems. These components operate from 300 MHz to 14 GHz and cover the cellular, Wi-Fi, Bluetooth, Cat-M1, NB-IoT, 5G and GPS bands. Johanson IPCs are available for almost any type of passive circuit, including lowpass, highpass and bandpass filters; diplexers and triplexers; power dividers; couplers, baluns and balun-filter combinations; including EMI filter arrays. IPC solutions have been developed for many of the chipsets from the major semiconductor manufacturers, such as Analog Devices, Nordic Semiconductor, NXP, Qualcomm, Silicon Labs, Texas Instruments and others. If a catalog solution is not available, Johanson can develop a custom design with low development cost.

Using the same LTCC technology, Johanson offers chip antennas for many wireless applications, including 780 to 960 MHz ISM, GNSS, LTE, Bluetooth, 2.4 and 5 GHz Wi-Fi and ultra-wideband (UWB). LTCC chip antennas provide good gain in a very small footprint, well suited for portable wireless devices.

Johanson Technology
Camarillo, Calif.
www.johansontechnology.com

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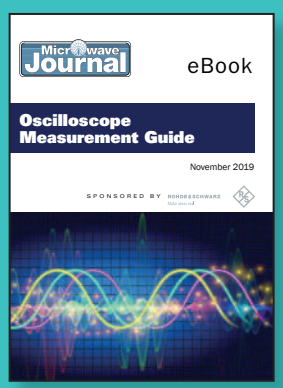

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NEW PRODUCTS

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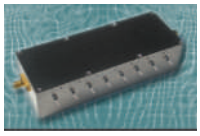
COMPONENTS

Electromechanical Programmable Attenuator



BroadWave Technologies model 651-031-127 is a voltage controlled programmable attenuator originally developed for test applications. This 50 Ω attenuator has a frequency range of DC to 2200 MHz. Attenuation range is 1 to 127 dB in 1 dB steps with attenuation accuracy ±0.5 dB. Insertion loss is 4.5 dB max while VSWR is 1.5:1 max. Input power is 1 W average with supply voltage +12 VDC at 30 mA nominal per section.
BroadWave Technologies Inc.
www.broadwavetechnologies.com

Hi-Rel Frequency Dividers

Fairview Microwave Inc. has introduced a new line of frequency divider modules that cover broadband frequencies from 0.1 to 20 GHz. A comprehensive offering of 28 different models features fixed divide-by-ratios from 2 to 40. These compact prescalers are ideal for use in frequency synthesizer and phase locked loop (PLL) circuit designs, as well as test instrumentation systems. These rugged frequency dividers are typically used in applications such as SATCOM, VSAT, aerospace and defense, test & measurement and point-to-point radio networks.
Fairview Microwave Inc.
www.fairviewmicrowave.com

Low PIM Thermally Compensated Loads

MECA's low PIM (–161 dBc typ.) 30 W loads feature industry leading PIM verified at 1900 MHz at –155 dBc min. and are thermally compensated to handle full rated power to 85°C. Covering 0.38 to 2.7 GHz available in Type N, 4.1/9.5, 4.3/10 and 7/16 DIN interfaces. VSWR's of 1.1:1 typ./1.2:1 min. (0.698 to 2.7 GHz) and 1.15:1 typ./1.25:1 max (0.38 to 0.698 GHz). All in a compact package of 6 × 2.25 in. Made in the U.S. with 36-month warranty.
MECA Electronics Inc.
www.e-MECA.com

Broadband Resistors

PPI 2010 Case Size Broadband Resistors are specifically designed to operate at frequencies up to 50 GHz. With special microwave laser-trimming used to ensure a tight tolerance at high frequencies, these broadband resistors are wire bondable, solderable and can be used in a flip-chip configuration.
Passive Plus Inc.
www.passiveplus.com

High-Power Attenuators

VENDORVIEW

Pasternack, an Infinite Electronics brand, has launched a new line of 10, 25, 50 and 100 W RF attenuators with operating frequencies up to 18 GHz depending on the configuration. Pasternack now offers 31 high-power, fixed attenuators which offer attenuation levels of 3, 6, 10, 20, 30 and 40 dB. Additionally, in-series connector gender interfaces are available in male-female configurations with both SMA and Type-N connector options.
Pasternack
www.pasternack.com

Bi-Phase Modulator

VENDORVIEW

PMI Model No. BPM-1840-180-292FF is a Bi-Phase Modulator operating over the 18 to 40 GHz frequency range. This model offers insertion loss of 8 dB typ. while maintaining a typical amplitude balance of ±4 dB. This compact housing measures 1 × 1 × 0.5 in. and is outfitted with 2.92 mm female connectors.

Planar Monolithics Industries Inc.
www.pmi-rf.com

New**Products**

Bias Tees

RLC Electronics manufactures both narrowband and broadband bias tees from 5 MHz to 40 GHz that provide excellent performance over the full band. This unit is used to inject a DC current or voltage into an RF circuit without affecting the flow of RF through the main transmission path. Typical applications include biasing amplifiers, DC return, DC blocking, as well as other various digital and analog uses, including in air-borne applications.
RLC Electronics Inc.
www.rlcelectronics.com

Coaxial Lowpass Filter

Model SCF-55375330-2F2M-L1 is a coaxial lowpass filter with a passband from DC to 55 GHz. The typical insertion loss of the passband is 1.5 dB. The rejection band is from 75 to 110 GHz with a typical rejection value of 30 dB. The RF connectors of the filter are male and female 2.4 mm connectors. The passband typical return loss is 15 dB. Other configurations, such as different connectors for input and output, are available under different model numbers.

SAGE Millimeter
www.sagemillimeter.com

Non-Isolated DC-DC Converters

Sager Electronics is now stocking TDK-Lambda's i6A4W non-isolated DC-DC converter series. Capable of operating from a wide input voltage of up to 9 to 53V, TDK's i6A4W step-down converters deliver an output voltage that can be adjustable from 3.3 to 15 or 3.3 to 40 V. The i6A4W series can operate from existing 12, 24, 36 or 48 V system voltages to generate additional high-power voltages in medical, communications, industrial and test & measurement equipment.
Sager Electronics
www.sager.com

2-Way Power Divider

The DSK-729S is a 2-way power divider operating in the frequency range of 800 to 2000 MHz. This power divider can handle 10 W max of input power in splitter mode with an insertion loss of 0.5 dB max above the theoretical split loss. Other product features include 22 dB typical isolation, 0.4 dB max amplitude unbalance and 2 degrees max phase unbalance. This combination of high performance with wide bandwidth makes this power divider ideal for signal splitting and low power combining.
Synergy Microwave Corp.
www.synergymwave.com

Inductors

Vishay Intertechnology Inc. introduced three new commercial IHLP®low profile, high current inductors with high operating temperatures up to +155°C in the 3.3 × 3.3 mm 1212 case size—the company's smallest to date. Designed to save space in computer and telecom applications, the Vishay Dale IHLP-1212AZ-51, IHLP-1212AB-51 and IHLP-1212BZ-51 offer extremely low profiles down to 1 mm. The devices released are optimized for energy storage in DC/DC converters up to 5 MHz.
Vishay Intertechnology Inc.
www.vishay.com

CABLES & CONNECTORS

FAKRA Connectors

QuickBuild RF™, a partnership between Amphenol RF and Amphenol Custom Cable, announce the introduction of FAKRA connectors into its

robust portfolio. FAKRA connectors are the latest addition to the continuously expanding connector offerings contained within the custom RF cable configurator which launched earlier this year. Customers will immediately be able to utilize FAKRA connectors in the universal Z key code to build custom RF cable assemblies. The connectors are available in a variety of straight and right-angle configurations with both jack and plug options.
Amphenol RF
www.amphenolrf.com

Johnson™ SMA/SMP Adapter Series

Cinch Connectivity Solutions, a Bel group company, announced the Johnson SMA/SMP series of adapters. This new series of high frequency adapters continues Johnson's development of products in support of 5G standards. Cinch Connectivity Solutions' SMA/SMP adapters are available in combinations of plug to plug, plug to jack, jack to plug and jack to jack and are designed for use in most high frequency applications.
Cinch Connectivity Solutions
www.belfuse.com/cinch

Microwave Cable Assembly

MIcable C29S superbend cable assembly is low-profile designed for internal and point to point connections, it eliminates the need for costly right angle connectors and offers excellent mechanical and electrical performance up to 50 GHz with low loss, low VSWR, high shielding effectiveness, good phase stability, high retention force and long repeated bending life. The VSWR is 1.15 at 26.5, 1.2 at 40 and 1.3 at 50 GHz typically.

Fuzhou MIcable Electronic Technology Co. Ltd.
www.micable.cn

Coaxial Cable Assemblies

L-com, an Infinite Electronics brand, announced that it has introduced a new series of coaxial cable assemblies that feature 402SS cable that can be used in place of semi-rigid coax in applications requiring increased flexibility. L-com's new LCCA Series 402SS Cable Assemblies provide an excellent alternative to 0.141 Semi-Rigid (RG402) style cables. These assemblies offer flexibility without compromising performance and exhibit performance characteristics very similar to semi-rigid coax.
L-com
www.L-com.com

AMPLIFIERS

Solid State Power Amplifier Module

COMTECH PST introduced a new ultra-wideband high-power solid-state RF module. COMTECH's latest development continues to expand on its proven innovative integrated RF GaN power amplifier designs by further increasing the bandwidth and power density. Consistent with its planned technology development roadmap, COMTECH introduces the latest in GaN-based 4 to 18 GHz RF amplifier. This highly integrated design is ideal for use in communication, electronic warfare and radar transmitter systems where space, cooling and power are limited. This unit is ideal for UAV/Airborne, ground mobile, surface and shipboard applications.
COMTECH PST
www.comtechpst.com

GaAs Distributed Amplifier

VENDORVIEW

Custom MMIC introduced a new GaAs distributed amplifier operating in the popular DC to 20 GHz frequency range, targeting Instrumentation and EW applications. The CMD244K5 offers very flat gain and low noise figure across the band. This MMIC also has high P1dB and IP3, yielding a high dynamic range. All this performance is neatly integrated in a small 5 × 5 mm plastic air-cavity surface mount QFN package. This new, high performance distributed amplifier continues Custom MMIC's aggressive efforts to deliver the best performing GaAs and GaN MMICs in the industry.

Custom MMIC
www.CustomMMIC.com

10 kHz to 100 MHz, 150 W Amplifier

VENDORVIEW

Exodus Advanced Communications introduced a high-power 10 kHz to 100 MHz 150 W amplifier. Exodus AMP2080B-1 produces 150 W min., > 200 W nominal power. The min. power gain is > 52 dB with excellent gain flatness. Optionally Exodus offers monitoring parameters for forward/reflected power, VSWR as well as voltage, current and temperature sensing for optimum reliability and ruggedness for all applications. Nominal weight is 35 lb, and dimensions of 19 × 22 × 5.25 in.

Exodus Advanced Communications
www.exoduscomm.com

Tiny MMIC Gain Slope Equalizers

VENDORVIEW

Mini-Circuits' EQY-5-24+ is an absorptive MMIC gain equalizer with a negative 5.1 dB slope versus frequency from DC to 20 GHz. Fixed slope MMIC equalizers are useful for flattening negative gain slope in wideband amplifiers, receivers and transmitters in applications from wireless communications to broadband/optical, satellite, defense and more. This model is capable of handling up to +34 dBm RF input power and provides 20 dB typical return loss across its full bandwidth. Fabricated using highly repetitive GaAs IPD technology, this equalizer provides outstanding repeatability of performance, making it suitable for volume production. It comes housed in a 2 × 2 mm 8-lead QFN package,

New**Products**

saving board space and minimizing the effect of parasitics. EQY-series MMIC gain slope equalizers are available with a wide range of slope values to meet your needs.

Mini-Circuits
www.minicircuits.com

1200 V SiC Power MOSFETs

Richardson RFPD Inc. announced the availability and full design support capabilities for a new family of 1200 V SiC power MOSFETs from Wolfspeed, a Cree Company. Based on third-generation planar MOSFET technology, the new devices include a rugged intrinsic body diode that allows for third-quadrant operation without the need for an additional external diode. According to Wolfspeed, the new product family includes the lowest Rds(on) at 1200 V in a discrete package with a flat Rds(on) over temperature.

Richardson RFPD
www.richardsonrfpd.com

SOURCES

N623 Series VCXO

The new N623 VCXO, available at 100 MHz, features a 9 × 14 mm SMD package, sinewave output and supply voltage of +5 VDC, with other frequencies and options available. Phase noise floor is –173 dBc/Hz max. Greenray Industries is a supplier of high precision, quartz-based oscillators for use in wireless, wired telephony, aerospace, military, satellite and other communications applications.

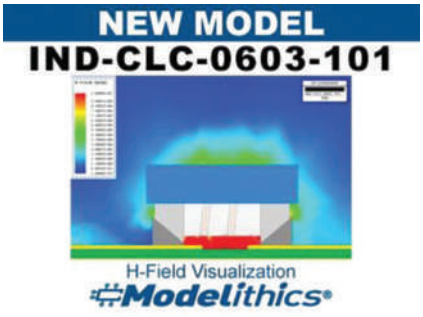
Greenray Industries Inc.
www.greenrayindustries.com

New**Products**

SOFTWARE

3D Geometry Model for 0603CS Inductor Series

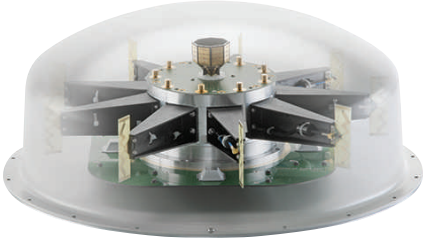
VENDORVIEW



Modelithics has introduced a new set of full-wave EM capable 3D geometry models for Coilcraft's 0603CS surface mount air coil inductor series. The model is now available within Modelithics COMPLETE+3D Library for ANSYS HFSS™. Individual 3D models are available from 1.6 to 390 nH and are validated against multi-substrate measured S-parameters through 20 GHz and equivalent series resistance (ESR), as well as against the corresponding Modelithics CLR Global Circuit model.
Modelithics Inc.
www.Modelithics.com

TEST & MEASUREMENT

Automatic DF Antenna



Connected to Narda's powerful SignalShark Real-Time Receiver, ADFA 2 enables the device to automatically localize signals between 10 MHz and 8 GHz precisely and reliably. The ADFA 2 delivers extraordinarily stable measurement results in seconds—insensitive to reflections. It is unique in combining an extremely broad spectrum with a minimum of equipment. This makes the ADFA 2 particularly interesting for regulatory authorities, mobile network providers and also for military applications.
Narda Safety Test Solutions GmbH
www.narda-sts.com

COMMUNICATIONS

WAYFARER Series

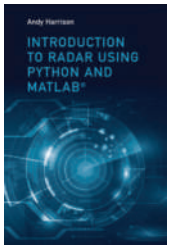
VENDORVIEW

The Norsat WAYFARER series includes two ultra-portable commercial fly-away satellite terminals, an easy-to-deploy drive-away antenna system and a fixed terminal solution.

Products in this series are ideal for a variety of commercial applications including broadcast, oil and gas, mining, forestry, emergency response and remote enterprises. With fast setup and tool-free installation, these weather-proof antennas are equipped with a 1.2 or 1.8 m composite reflector. A complete satellite solution, the WAYFARER Series includes everything to meet your communication needs.
Norsat
www.norsat.com

Ultra-Performance Receiver

The SIR-4000 uses the latest DSP technologies to meet the specific needs of the end user. Elcom recognized that in today's real-time threat environment one size does not fit all. The company goal was to provide the end user a tool that could cover a wider frequency range (up to 40 GHz) and instantaneous bandwidth (up to 2 GHz) critical to RWR applications.
Elcom
www.fei-elcomtech.com



Artech House Has a Blog: Take a Look at the Insider!

For more, visit https://blog.artechhouse.com/

Did you know Artech House has a blog? The Artech House Insider features news, author insights and a behind-the-scenes look at what is going on with our authors. Here is a sample post from author Andy Harrison:

"When Artech House first approached me in July of 2017 about authoring a text for the radar series, I relished the opportunity. I reflect now, a little over two years later, as this project is coming to an end and realize the time and effort that was put forth and the help I received along the way. I have found that finishing a book is the most difficult part of the journey. At the beginning, it is easier to find the energy and motivation which wanes as the weeks and months pass. I would not have been able to finish this text without the love and support of my wife, Lacon.

As part of this endeavor, I wanted to include a practical, easy-to-use set of radar design and analysis tools. Python was chosen as it is widely used in scientific and numeric computing and is an excelling language for education. I then decided to extend these tools with the addition of a very interactive GUI. To this end, Qt was used via pyqt for its cross-platform performance and overall appeal. MATLAB scripts were later added as there are many professional engineers that use this product. It is my hope that readers find this text and software a valuable tool in their pursuit of radar engineering."

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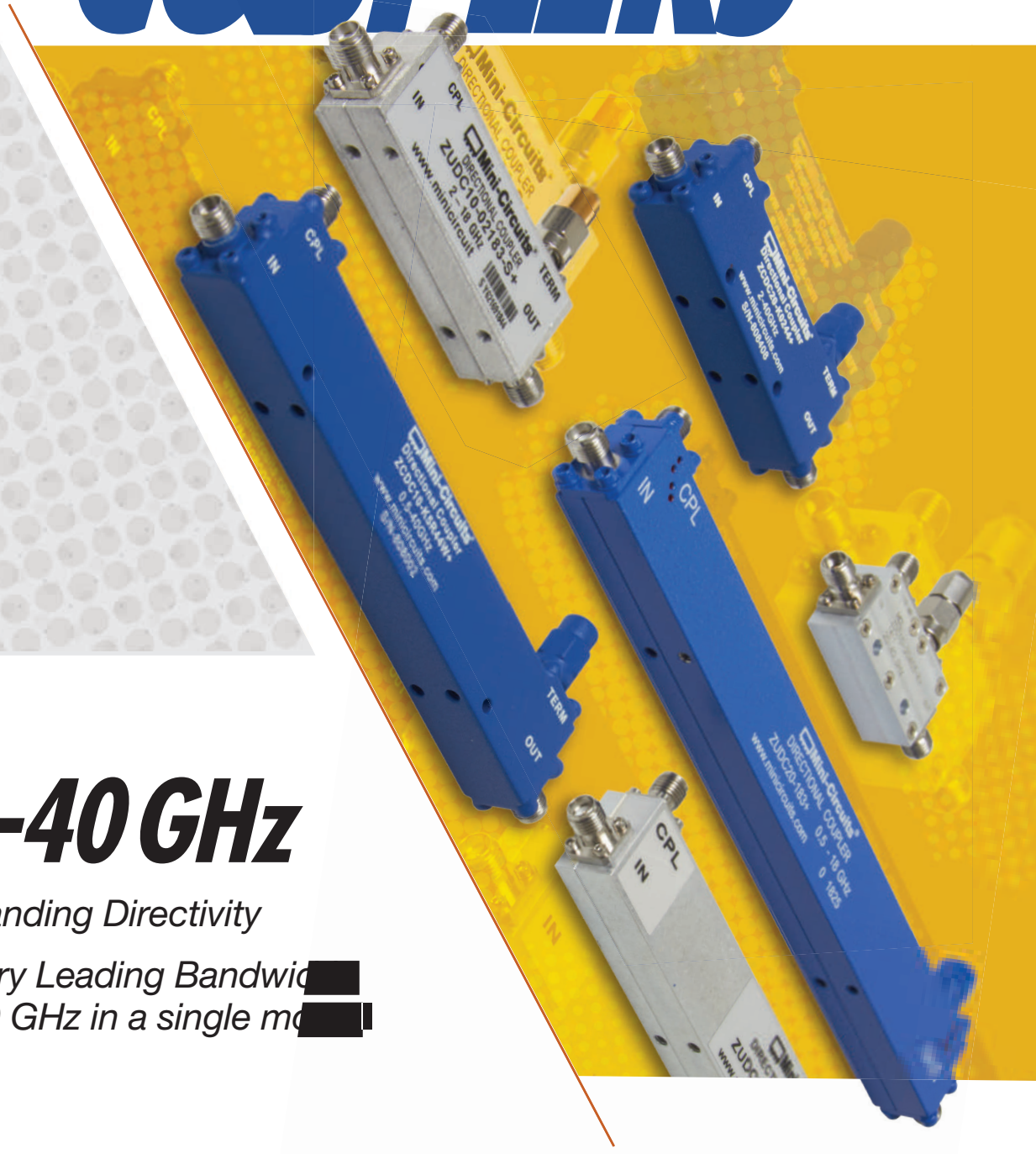

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Sanan IC: Helping People Chase Their Dreams

Sanan Integrated Circuit (Sanan IC) built China's first 6-in. compound semiconductor platform wafer fab to offer foundry services for RF, photonics and power electronics applications. Founded as Xiamen Sanan Integrated Circuit Company in 2014 and funded with a 3 billion RMB ($500 million) capital investment, Sanan IC built a wafer fab on a 180,000 square meter site in the Xiamen Torch high-tech industrial district located in the Fujian province. Risk production began in October 2015, and Sanan began marketing to designers outside China in August 2018. With more than 90 percent of the equipment fully automated, the fab's GaAs capacity, among other process technologies, is 4,000 wafers per month, which can scale up rapidly as market demand grows.

Sanan IC provides MOCVD epitaxial wafers, wafer processing and wafer probe testing. The foundry has qualified three GaAs MMIC processes for RF/microwave applications—HBT, PHEMT and BiHEMT—complementing these with integrated passive device (IPD) and PIN diode processes. The 2 µm HBT node comprises five versions, each optimized for specific performance parameters: linearity, power-added efficiency, current gain, phase noise, ruggedness and operating voltage.

The PHEMT processes can be fabricated with 0.5, 0.25, 0.15 and 0.1 µm gate lengths, each with several versions for specific applications. The 0.5 µm process uses depletion mode (D-mode) FETs optimized for RF switching. Four, 0.25 µm versions offer a mix of D-mode and enhancement mode (E-mode) devices that can be used to design low noise amplifiers (LNA), power amplifiers (PA) and switches, with the option to add integrated logic. Four options are also offered with the 0.15 µm gate process, again a mix of E- and D-mode devices to address higher frequency LNA, PA and switch designs with on-chip logic. The devices have ft values from 64 to 85 GHz; to minimize gate length variation, the 0.15 and 0.1 µm gates are defined with e-beam lithography.

Sanan's BiHEMT process combines HBT and PHEMT transistors on a single MMIC, typically using the HBT device for a PA and the PHEMT for an LNA or switch. Two E-mode PHEMTs are available, with 0.25 and 0.5 µm gate lengths. The IPD process integrates passive circuits of resistors, capacitors and inductors. Sanan has also developed a GaN-Si process, which complements its SiC Schottky barrier diode and SiC MOSFET processes for power electronics.

To aid designers, the foundry offers process design kits (PDK) and design support for Keysight's Advanced Design System (ADS) software. Once a design is complete, Sanan uses a five-step process for design rule checking before releasing the customer's design for mask fabrication and wafer processing. Sanan's quality management system is certified to both ISO9001:2015 and IATF16949:2016 for automotive, and its information system meets the ISO27001:2013 certification for information security management.

Paraphrasing a Chinese expression, the world is full of people chasing dreams. Sanan's vision is to enable those dreams through wireless communication, lifting the constraints of space and time.

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Directional Couplers

Model	Type	Frequency (MHz)	Power (W CW)	Coupling (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
C8000	Bi	600-6000	100	30	0.40	SMA-Female	1.8 x 1.0 x 0.56
C10799	Dual	700-6000	100	40	0.20	N-Female	2.0 x 2.0 x 1.06
C10117	Dual	700-6000	250	40	0.20	N-Female	2.0 x 2.0 x 1.06
C10526	Dual	700-6000	300	40	0.20	N Female	2.0 x 2.0 x 1.06
C10364	Dual	700-6000	500	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10614	Dual	700-6000	500	60	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10996	Dual	700-6000	700	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C11555	Dual	700-6000	1,000	50	0.20	7/16-Female	2.15 x 2.0 x 1.36
C10695	Dual	700-6500	500	50	0.20	7/16-Female	2.15 x 2.0 x 1.36

0° (In-Phase) Combiners/Dividers

Model	Type	Frequency (MHz)	Power (W CW)	Isolation (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
D11911	2-Way	600-6000	100	15	0.60	N-F / SMA-F	2.00 x 2.0 x 1.00
D11959	2-Way	600-6000	100	Non-Isolated	0.40	N-F / SMA-F	2.00 x 2.0 x 1.00
D11958	4-Way	600-6000	100	18 (PI*)	0.60	N-F / SMA-F	4.00 x 2.0 x 1.00
D11149	4-Way	700-6000	300	Non-Isolated	0.60	N-Female	4.35 x 3.9 x 1.15
D11832	2-Way	700-6000	500	Non-Isolated	0.60	7/16-Female	5.50 x 2.4 x 1.06
D10803	2-Way	700-6500	300	Non-Isolated	0.60	N-Female	5.50 x 2.4 x 1.06

(PI*) references Partial Isolation

90° Hybrid Couplers

Model	Type	Frequency (MHz)	Power (W CW)	Amp. Bal. (±dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
QH11687	90°	500-6000	150	0.7	0.75	SMT	1.28 x 1.08 x 0.13
QH11443	90°	600-6000	150	0.8	0.70	SMT	1.30 x 1.30 x 0.13
QH10756	90°	700-6000	100	0.6	0.55	SMT	0.74 x 0.45 x 0.09
QH10541	90°	700-6000	150	0.6	0.50	SMT	0.86 x 0.66 x 0.09
QH10827	90°	1000-7500	100	0.7	0.65	SMT	0.86 x 0.61 x 0.09
QH10828	90°	1000-8000	100	0.7	0.90	SMT	0.65 x 0.50 x 0.07