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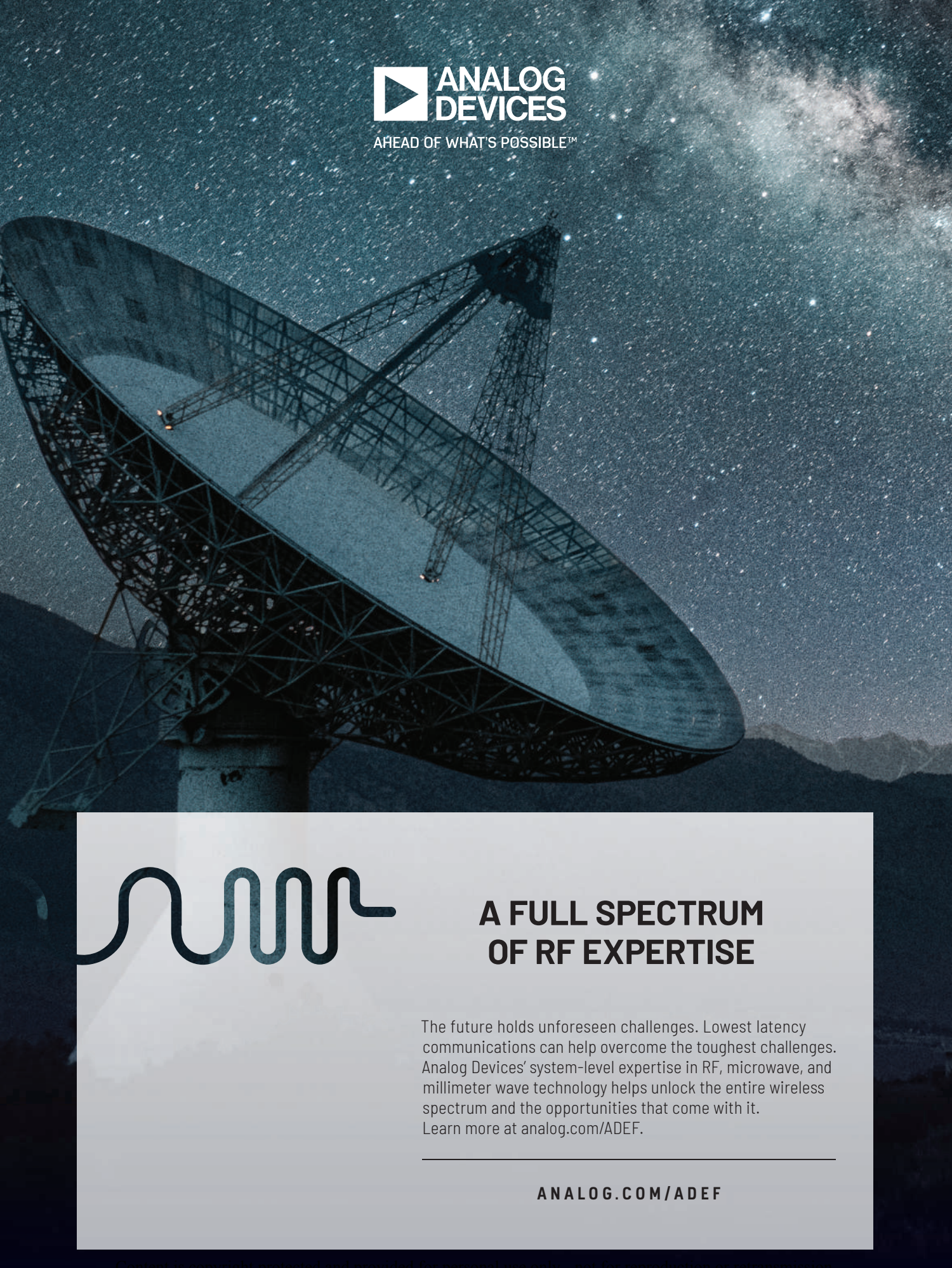

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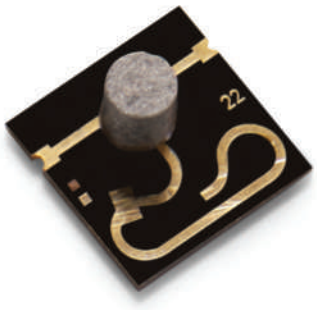

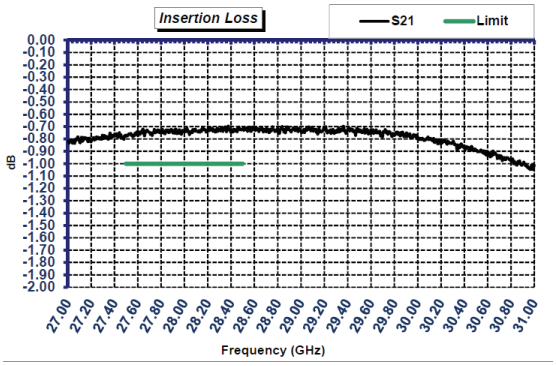

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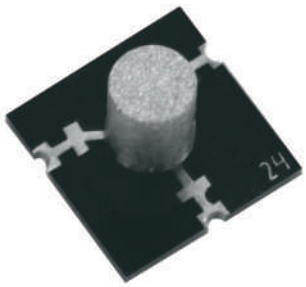

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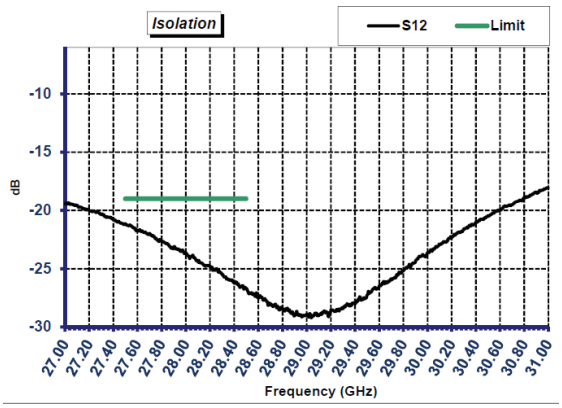

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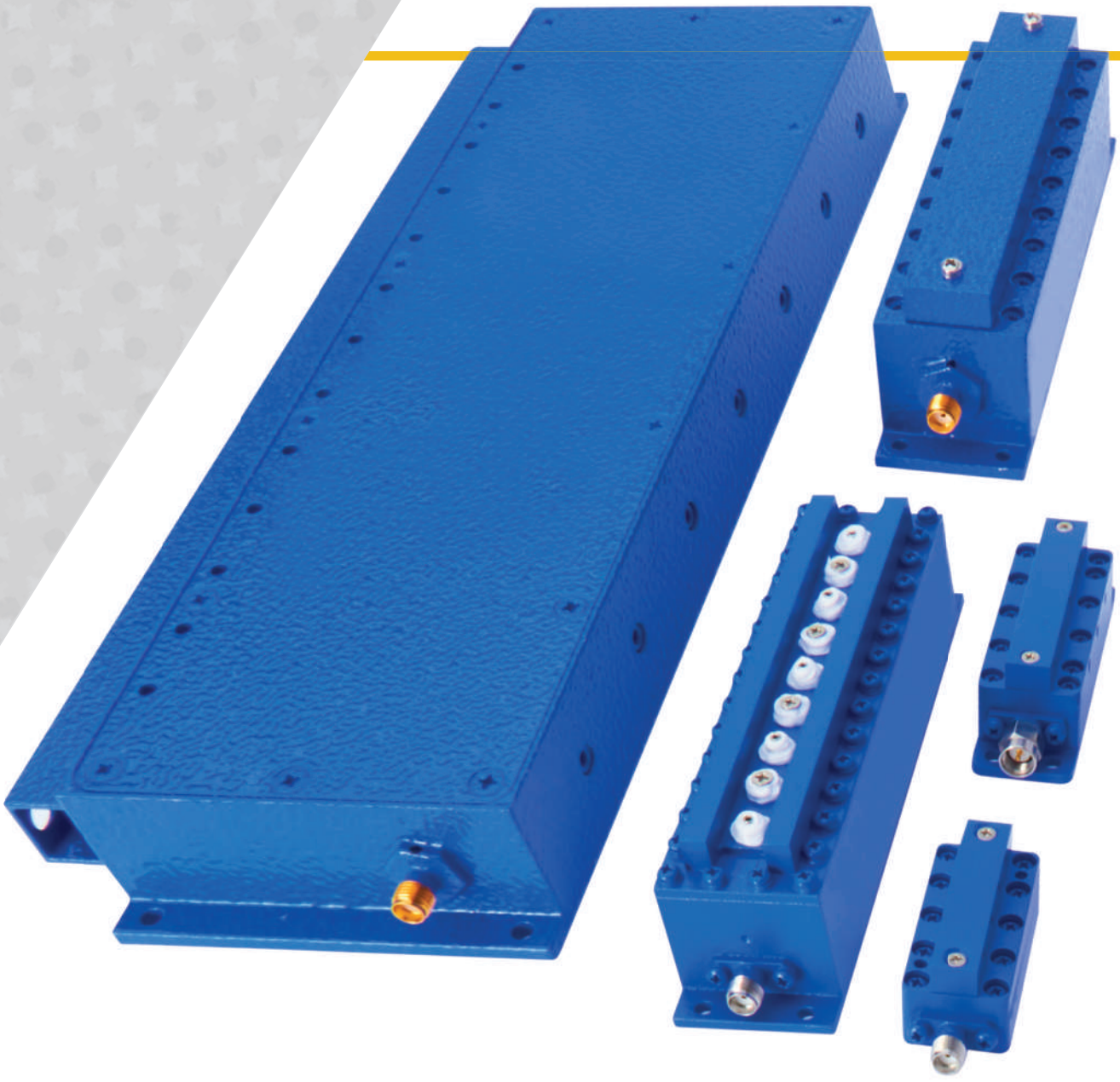

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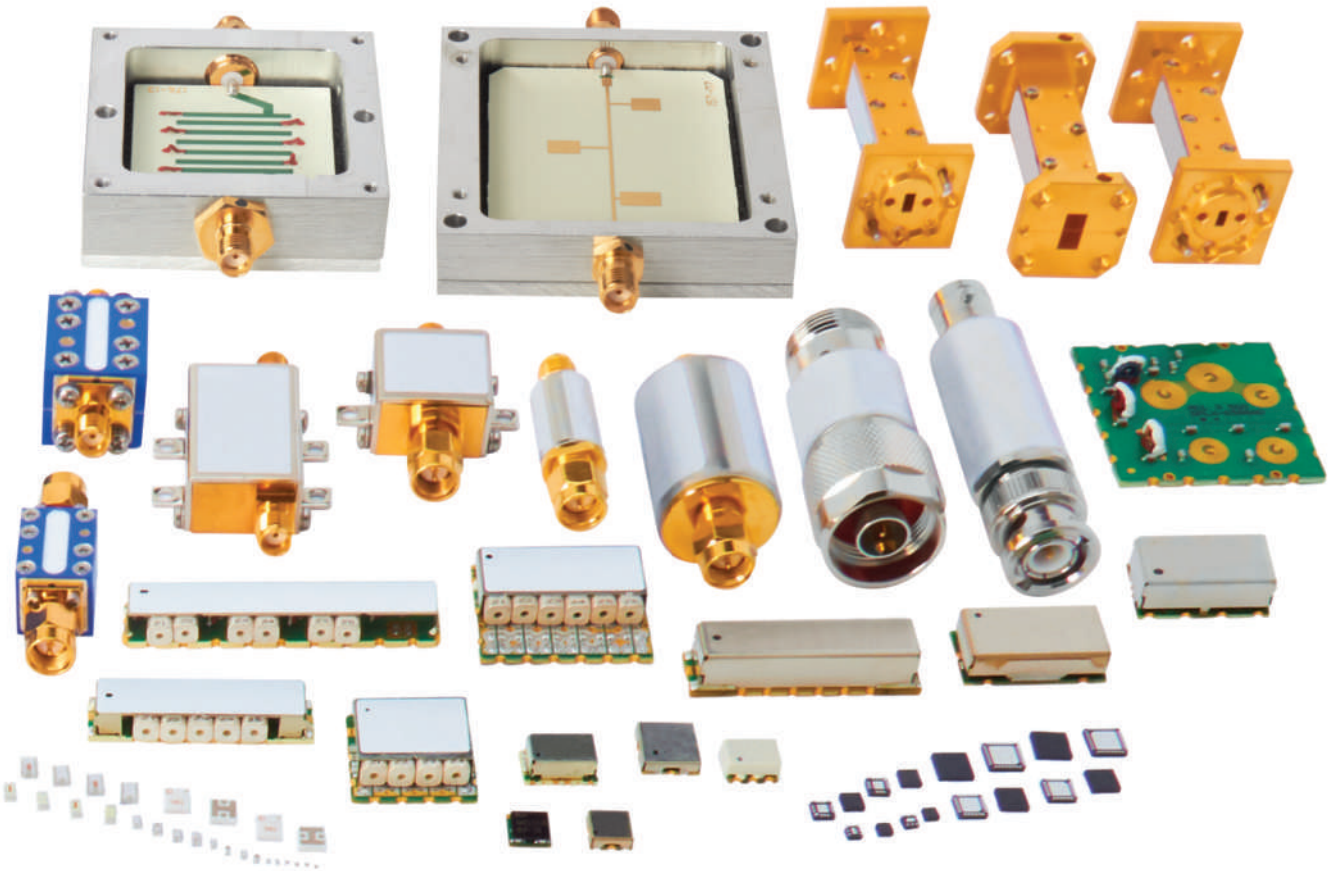

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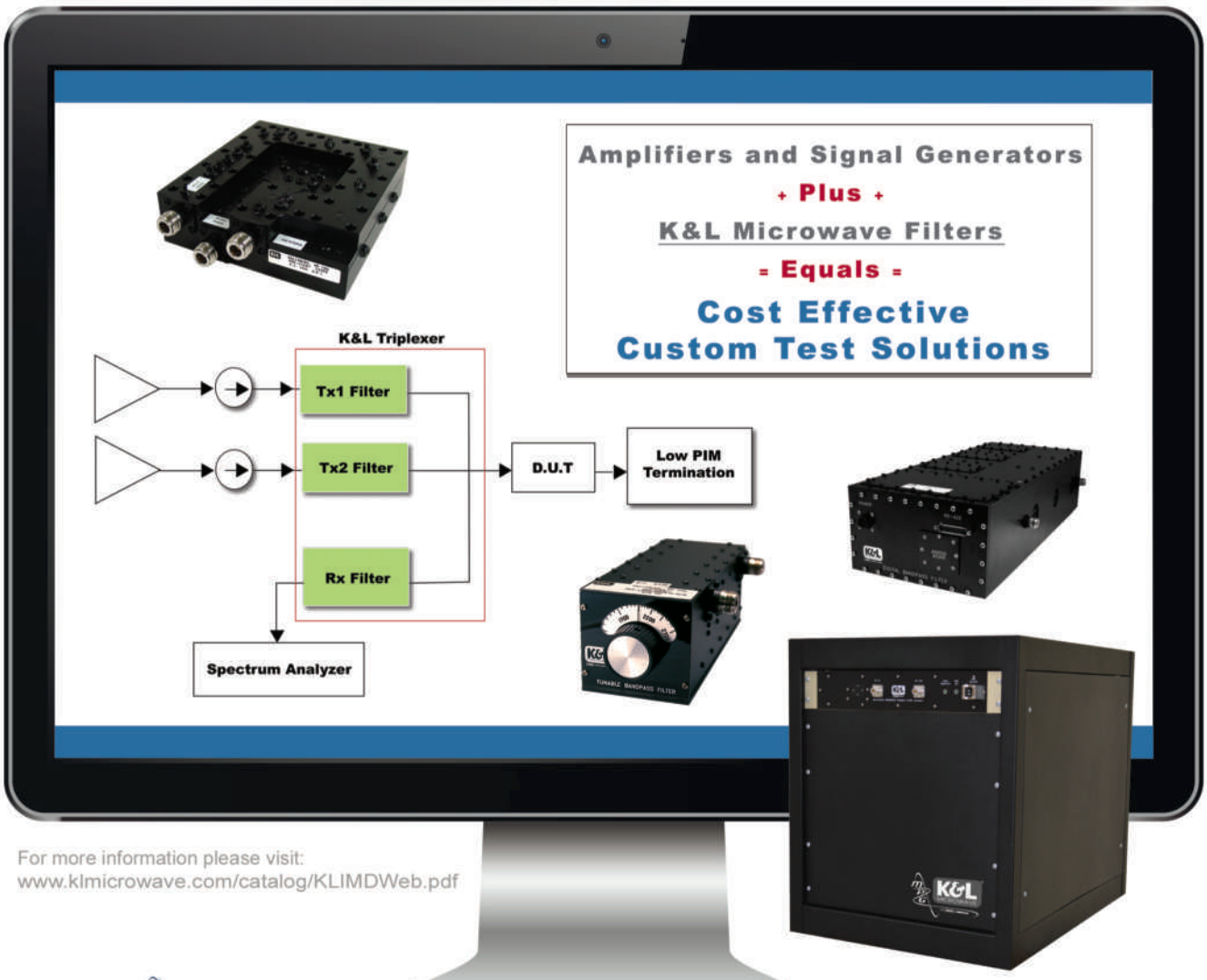

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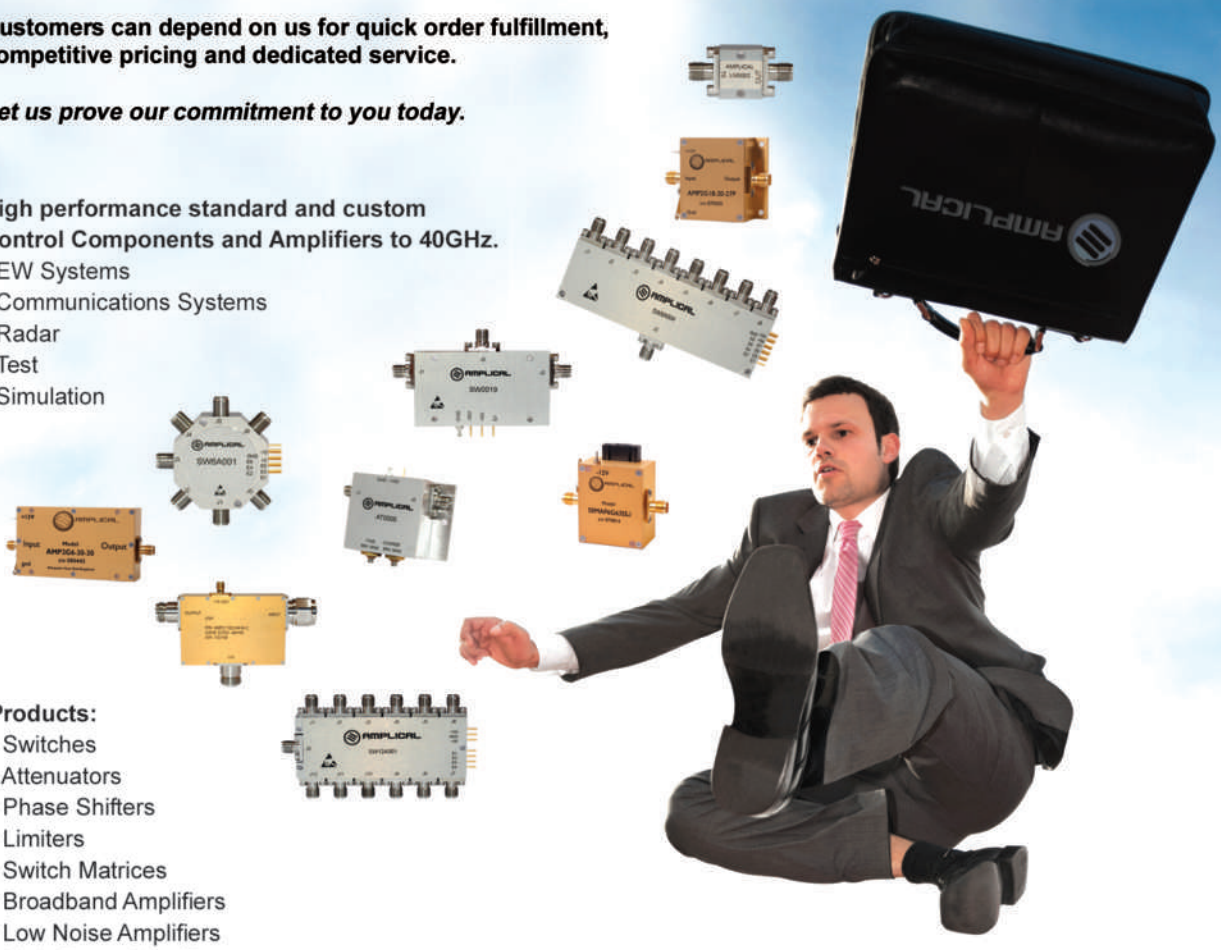

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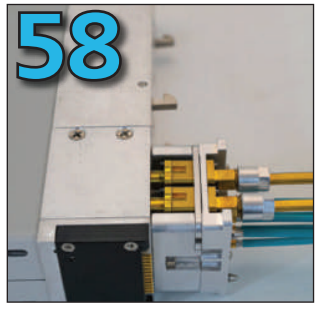

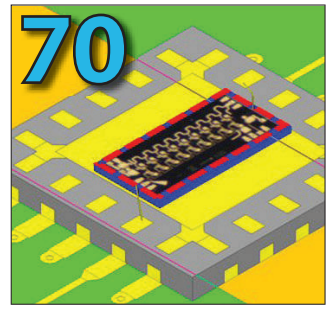

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Microwave Journal (USPS 396-250) (ISSN 0192-6225) is published MARCHly by Horizon House Publications Inc., 685 Canton St., Norwood, MA 02062. Periodicals postage paid at Norwood, MA 02062 and additional mailing offices.

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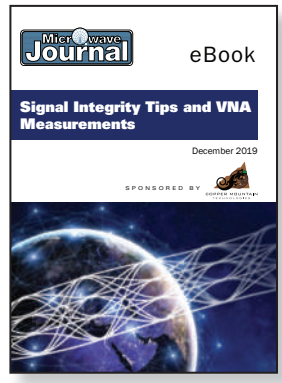

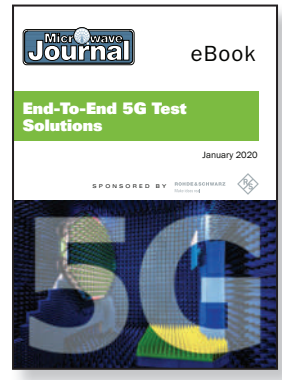

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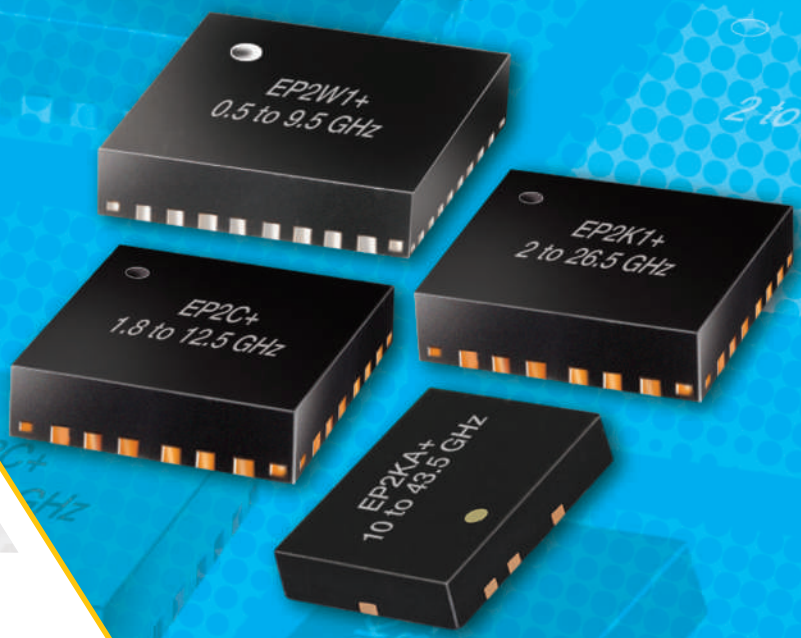

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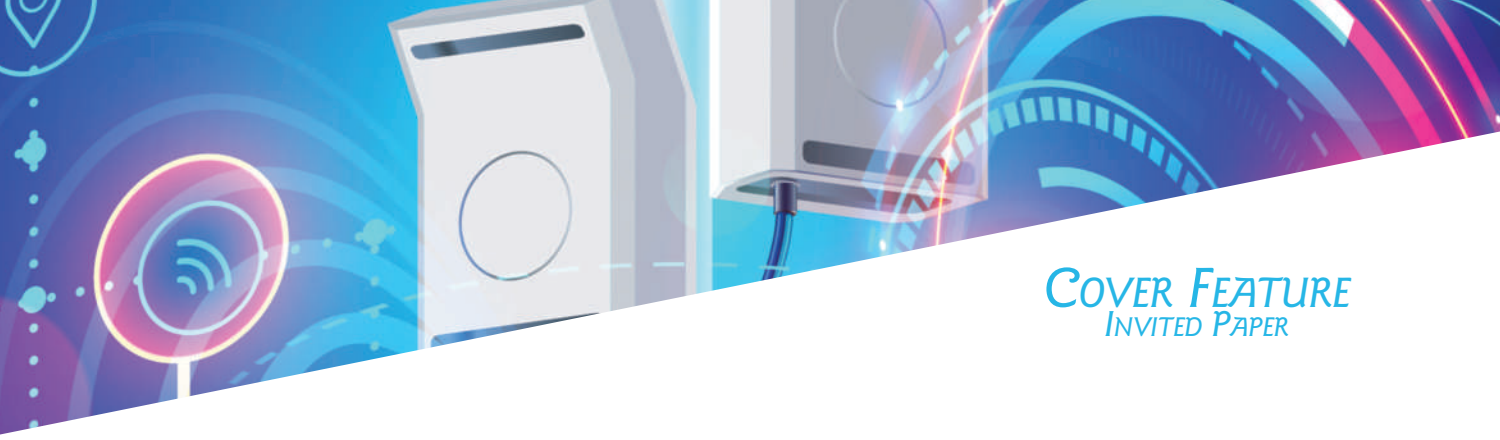

COVER FEATURE
INVITED PAPER

Significant Test Time Reduction and Equipment Utilization in 5G RF Production Testing

Sascha Laumann
Rohde & Schwarz
Munich, Germany

5G base station and infrastructure manufacturing is currently one of the hottest areas in communication technology as deployments are accelerating. Success among competitors is generally measured by traditional metrics such as cost of production and integration, productivity and time-to-market. Yet, delivering products in large quantities becomes more important as regulatory bodies start to pave the way to mass installations and delivery bottlenecks may cause significant loss of business. The question is, "How can we manufacture products faster, given the known technical and financial conditions?" There are probably many answers to this question, but in the context of testing of units in production, the answer is likely: "In a given period of time, increase the number of units properly produced and successfully tested, according to the specification."

Improving the 'speed of test' has been an ongoing subject since the dawn of testing endeavors. The ever-increasing frequency of product releases, shorter time-to-market cycles and budgetary constraints call for new ideas on how to improve one of the fundamental metrics particularly important in production environments: test throughput.

Test throughput is essentially a reciprocal figure to the speed-of-test. Besides indicating how fast a single test can be executed, test throughput can additionally address cases where multiple tests are accomplished in parallel. Achieving higher throughput almost always demands some degree of concurrent operation, particularly in cases where speeding up a single test is either technically not possible or too expensive. Forms of parallelization may range from simple duplication to a configuration of independently executed tasks and subtasks that allow fully asynchronous test execution. The speed of test is either difficult or impossible to measure in such a highly parallelized testing environment. In contrast, test throughput remains a valid metric with an increasing significance.

Parallelization of tests must be well thought out; higher throughput rates must not lead to deterioration of quality-related metrics. The more tests that are being executed asynchronously, the more care needs to be put into ensuring that test results remain valid and consistent. Solutions designed for sequential execution are not necessarily suitable for parallel operation. Luckily, technological advancements in the domain of software architecture render such a shift in testing paradigms possible without sacrificing test quality and reproducibility. Solutions supporting parallelized operation are already commercially available.

PROBLEM DESCRIPTION

In the context of emerging 5G infrastructure business, ensuring a high production throughput rate is crucial for success and competitiveness. Clearly, test throughput is one of many factors that influences the production throughput; yet, it is comparatively easy to improve this metric in specific environments if few prerequisites are met.

Traditionally, the execution of 5G production tests is done close to or in conjunction with the product assembly line. Once the product is assembled, a manual or automated set of a multitude of tests, including an RF test, is performed. After test execution and results retrieval, the system decides if the device-under-test (DUT) has fulfilled the testing requirements or not. Lastly, the tested product is sorted accordingly. This is a typical representative of a sequential and synchronous test execution; the following task waits

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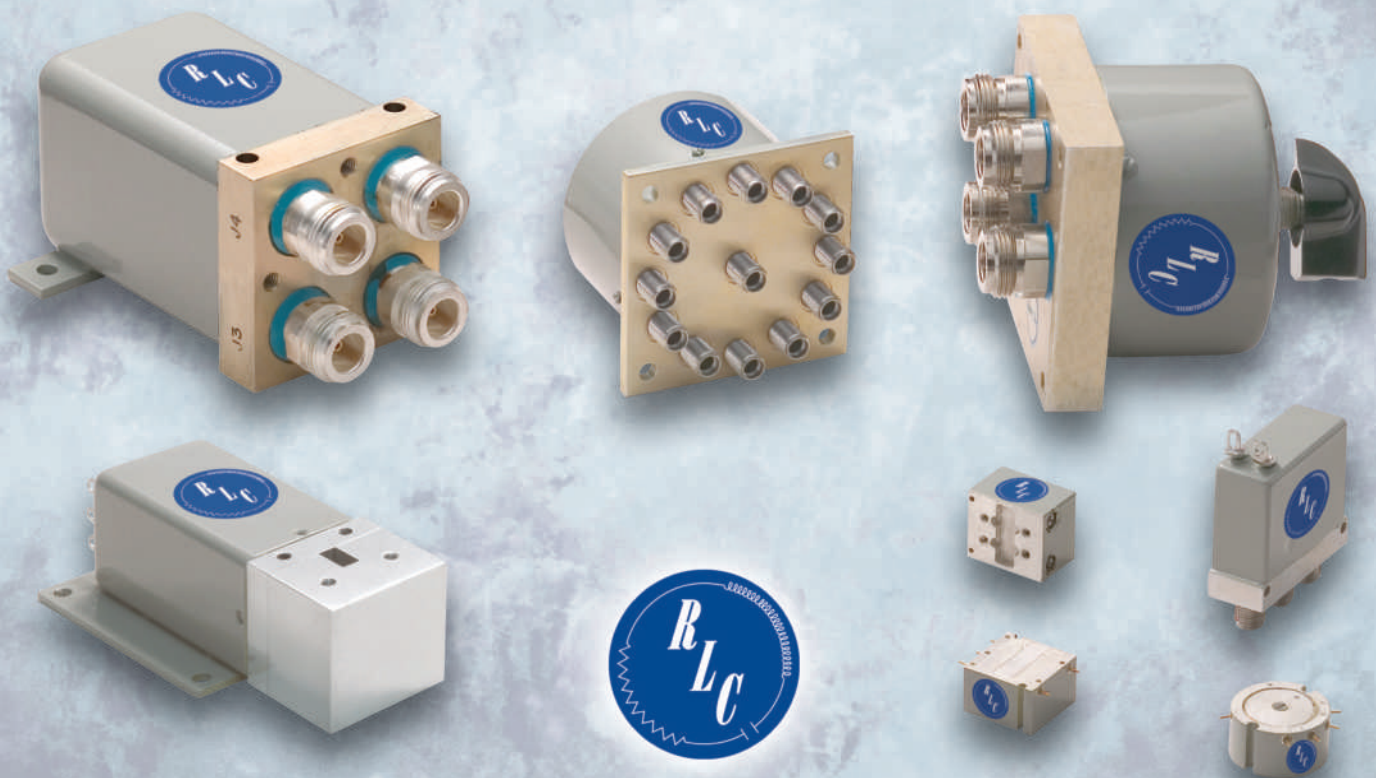

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until the previous task has finished, and its result is available. Although RF tests generally do not have a large impact on the overall performance, the complexity of the analysis of the test data increases with tighter testing conditions and thus may render testing throughput worth improving.

While the sequential execution in its simplicity is acceptable for many applications, it also bears one potentially significant impediment: it generally does not scale well. Here, increasing throughput calls for either the installation of one or multiple duplicates of the production and testing equipment, which is expensive, or reduction of testing complexity. The latter may result in a poor overall yield or higher failure rates of devices in operation.

Coming back to the 5G infrastructure manufacturing and testing use case, the 3GPP TS 38.141 specification requires multiple metrics to be evaluated. Error Vector Magnitude (EVM), Operating Band Unwanted Emission (OBUE) / Spectral Emission Mask (SEM) and Adjacent Channel Leakage Power Ratio (ACLR) are the commonly used measurements to specify if a DUT can pass a test or not. All tests are jointly performed in several frequency and output power ranges; the depth and number of tests depend on the product category and its specifications.

Executing a typical production line test on a 5G macrocell base station can take up to several minutes to conduct. Speeding up this process can significantly improve the throughput rate in production. Repetitive characterization test may require multiple hours of testing scenarios. It is safe to say that by analyzing the complex process of production and testing of devices, one may find a few tasks or subtasks that are executed sub-optimally. Depending on the product and the testing specification the device needs to be tested against, this could be either test data acquisition time or analysis time. Clearly, upcoming higher requirements in 5G FR2 testing (and beyond) will likely result in more complex analyses and thus longer processing times.

BACKGROUND

The concept of parallelization in the context of technology or productivity optimization is nothing new; in the last few decades, the development has been boosted by an increasing number of available parallel processing units (multicore CPUs) and the simplified access to those resources from both programming and operational standpoints. Asynchrony or asynchronous operation has gained more attention in recent years due to the rise of distributed systems. It forms a fundamental construct allowing non-deterministic operation mainly found in communication technology.

The rise of parallelization as a technology aspect paved the way to new problem-solving techniques: instead of focusing on improving individual execution performance, parallelization renders new levels of scalability. By looking at cloud-based technologies available nowadays, it should be clear that speed performance is simpler to implement within a framework allowing parallel processing.

The demands from an economic perspective arise as well; more than ever, it has become important to optimize the cost of usage of assets, such as test equip-

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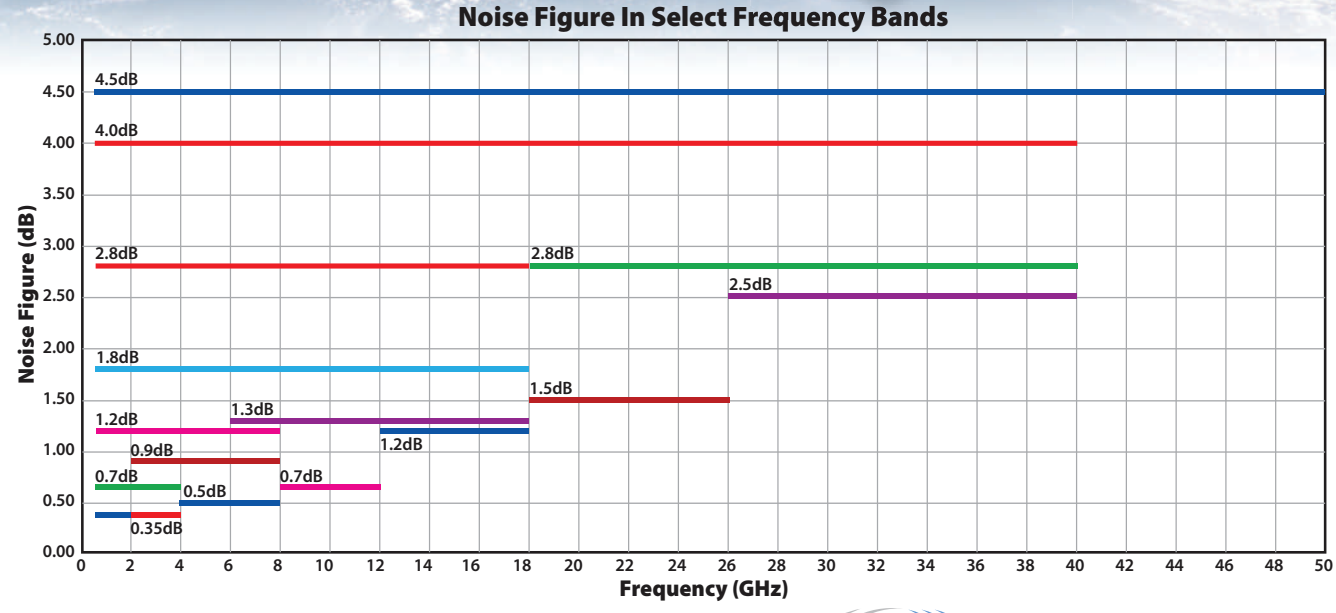

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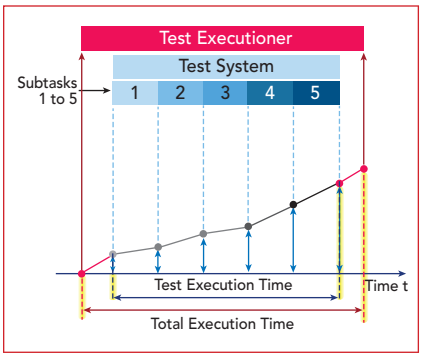

Fig. 1 **Sequential test scenario.**

ment, especially in cases where substantial investment is required; metrics such as Return-on-Investment (ROI) or Total Cost of Ownership (TCO) have gained importance. Lastly, new business and cost models such as Operational Expenditures (OPEX) asks for lower upfront spending and thus call for different commercial solutions. This, in turn, increases the importance of a qualified equipment usage metric which allows usage-based business models (such as pay-per-use) to be attractive for both the solution providers and their customers.

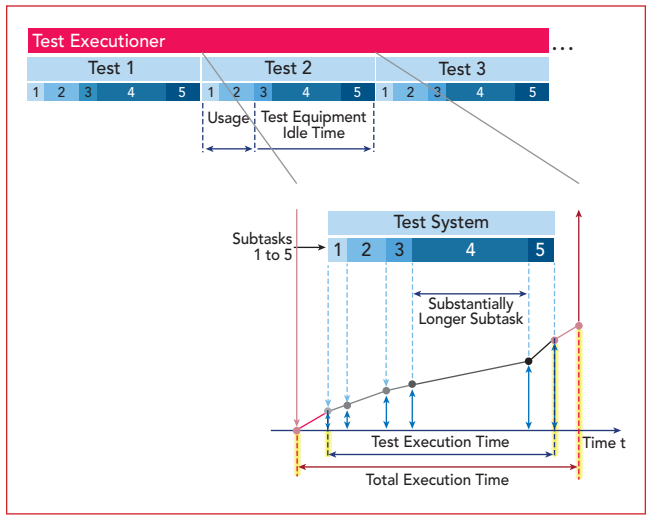

Fig. 2 **General overview of a test sequence.**

APPROACHES

Sequential Operation

Consider the following scenario: a DUT requires a specific set of tests to be performed upon it to ensure its functionality. Let us imagine each individual test sequence consists of five subtasks: test preparation and equipment setup, stimulus generation and data capture, test data retrieval (transmission), data processing/analysis, and test result delivery as shown in ***Figure 1***. The test sequence is repeated either with a different set of testing parameters or through provisioning of another DUT.

In a sequential approach, subtasks are executed one after the other since the degree of dependency between two adjacent subtasks is high; it makes no sense to start data acquisition before test equipment has been instructed what exactly to capture. Equivalently, analysis of test data cannot happen before the data has been successfully transmitted.

Each subtask has its own execution time. In many cases it is a largely consistent number across test se-

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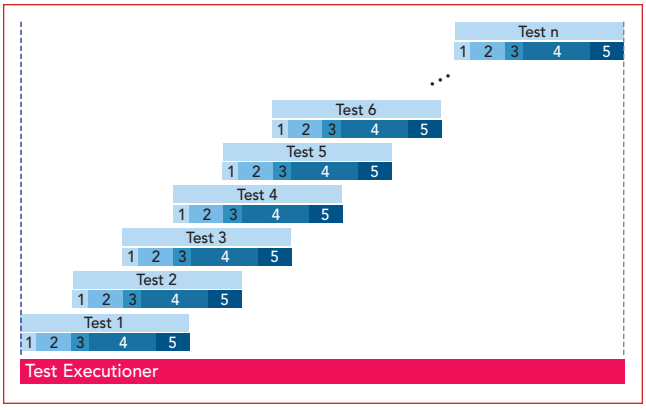

Fig. 3 **Weak parallel test execution.**

quences, but it may exhibit some degree of uncertainty and jitter (e.g. in cases of non-deterministic data transmission). In sequential testing, the overall test execution is the sum of individual task execution times. Thus, improving the overall test duration is only possible by accelerating any respective subtask within that test sequence. Some 'expensive' subtasks may be subject to optimization but in general there will always be technical (e.g. CPU clock speed) or procedural (e.g. handling or settling time) boundaries which do not allow further execution speedup.

By looking at ***Figure 2***, one can easily identify a further implication: test equipment used in subtasks 1 and 2 returns to idle mode when the respective subtasks

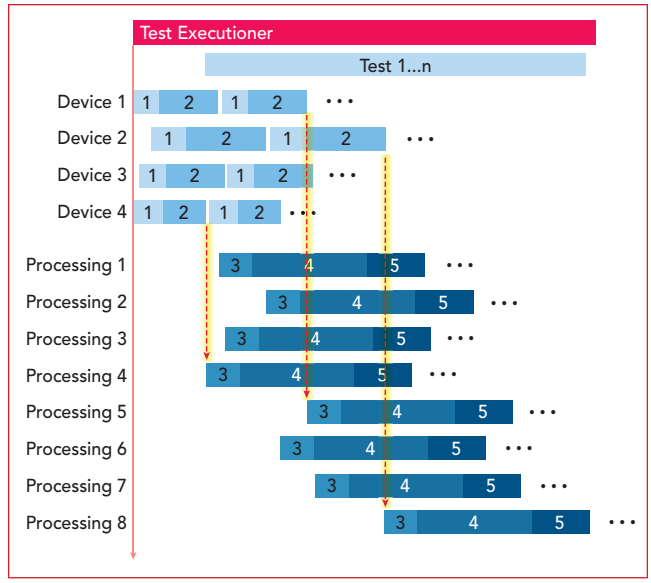

Fig. 4 **Strongly parallelized operation with decoupled subtasks. Arrows depict the arbitrary selection of processing units for the handling of incoming capture data.**

have finished and becomes operational only when next test sequence is executed. The period between the two subsequent test sequences determines the utilization ratio; the shorter the period is, the higher the ratio. This is generally favorable; yet, improving this number in pure sequential operation is equally challenging.

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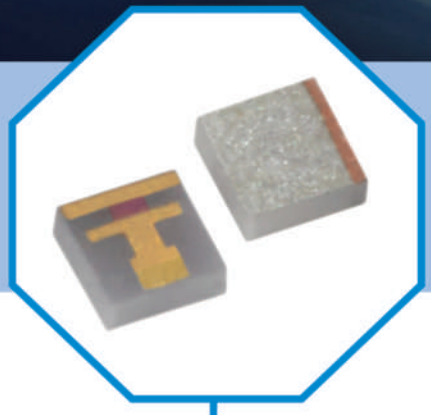

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Weakly Parallelized Operation

An alternative to a sequential implementation is to consider parallel execution of subtasks, or a set thereof, wherever possible. This may be an interesting approach in cases where individual subtasks require significant time for completion with a certain degree of decoupling rendered possible; any such 'expensive' subtask that bears a lower degree of dependency on adjacent tasks is potentially suited for migration to parallel operation.

Consider again the same test sequence of five subtasks needed to complete a test of a single DUT. In subtask 4, data processing and analysis, execution is likely to be computationally expensive, requiring a substantial amount of time to accomplish the task. This is generally found in 5G NR applications given the complex yet tight 3GPP specification requirements the production tests must fulfill. Clearly, parallelization of the execution of this and the following subtasks results in higher throughput.

In most cases, isolating a processing task is possible; subtasks of test preparation, stimulus generation and test data capture do not need to wait for the analysis to be finished and thus can be restarted. Depending on the parallelization capabilities of the processing unit, this process could be set up such that it allows complete decoupling of the expensive subtask, allowing other tasks to be performed much quicker.

This process can be named weak (or incomplete) parallelization since not all subtasks are eligible for parallel execution. As depicted in ***Figure 3***, subtask 2 (capture) must wait for subtask 1 (preparation) to complete. However, once subtask 2 has completed, the subtask 3 (data transmission) can be executed while subtask 1 of the next test iteration is started immediately. In contrast to the sequential execution, the interval where testing equipment idles is also minimized or even eliminated given the immediate reuse for next test.

Strongly Parallelized Operation

In the previous case, performance is limited by two factors: the number of parallel processing units available and the speed of execution of subtasks 1 and 2. While enabling additional parallel processing capabilities nowadays is a relatively simple technical modification or upgrade, accelerating capture time is rather difficult—unless parallelization of the capturing process becomes viable. This is generally done by adding more capture devices to the setup. In that case, the test execution may be considered a strongly (or complete) parallelized operation; this is the case when a high degree of decoupling of subtasks is given.

Consider the ideal case depicted in ***Figure 4***. There are 4 devices available independently delivering capture data, whereas the analysis of the test data can be done by 8 parallel processing units.

In such a case, any arbitrary pro-

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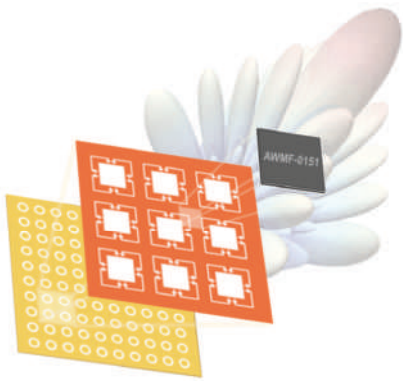

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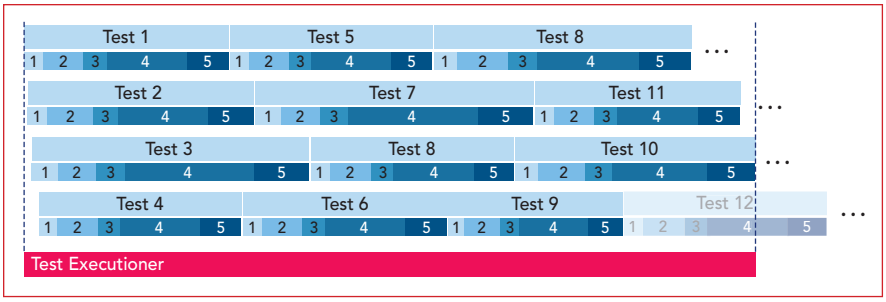

Fig. 5 **Strongly parallelized operation with 'sorted' operators.**

cessing unit that is 'free' at a given time can fetch and handle the available data coming from any of the devices. The next available unit does the same, resulting in an asynchronous operation. In addition, each device may have a specific capture duration, resulting in slower or later provisioning of the capture data. This has no significant impact on the overall performance since the processing units are rather agnostic towards 'who delivers data when'; they simply process any capture data available independently of its source.

While asynchrony is difficult to depict, ***Figure 5*** shows a qualitatively similar graph where the aforementioned processing units are assigned to each devices' 'capture stream'; by looking at the number of executed test iterations, one sees that the throughput has significantly improved when compared against both previous cases. However, this does not necessarily mean that the processing of the capture data coming from a specific device is also handled by a specific processing unit.

It should be mentioned that parallel data delivery is not always possible: in cases where single DUTs are tested, it may not be possible to add multiple capture devices (such as spectrum analyzers) due to complex RF connectivity or instrumentation.

TEST RESULTS

To verify the benefits of parallel test execution, a realistic scenario often found in 5G applications was set up and executed in multiple test configurations. The setup allowed two modes, a sequential and a weakly parallelized operation. The specific test system consisted of the signal generator (R&S SMBV100B), spectrum analyzer (R&S FSVA3000) and R&S server-based testing (SBT) unit, a processing platform capable of processing 16 data sets in parallel. The SBT was configured so that EVM, ACLR and SEM metrics were calculated in each test iteration. The generator was set up in such a way that the stimulus output power was stepped across 59 different levels. The analyzer was set up so that data was captured and transported as I/Q data files. The connectivity between devices was given through a

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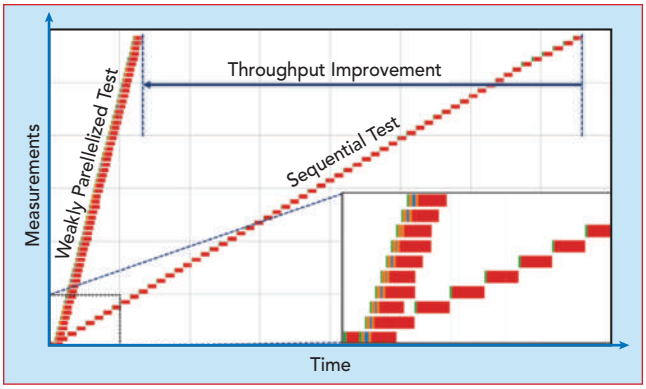

Fig. 6
Comparison of sequential (right) and weakly parallelized (left) test execution. Lower right shows the first few steps.

local gigabit Ethernet with no special hardware used to interface the participating devices. All calculations were compared to ensure validity of the results.

Figure 6 depicts the qualitative results of the two scenarios. It confirms that the performance in a sequential operation (shown in Figure 6 on the right) is limited by individual test step execution time. The lower right diagram is a zoom-in into the first few test steps executed, depicting the difference between sequential (flat) and parallel (steep) approaches. A breakdown into individual subtasks within each step is irrelevant since all test steps have a largely consistent duration. Total test time for all 59 steps is simply the sum of individual test execution periods.

The left part of the diagram depicts the weakly parallelized operation with a single analyzer being operated as the sole capture data source. The zoomed-in view on the lower right shows the first 10 iterations of the parallel and 8 iterations of the sequential test. It illustrates how each individual test step, divided in subtasks, is being executed. The parallel execution of analysis task is reflected by the overlapping red bars. One can also notice that the single-device operation results in the test preparation and data capture subtasks effectively determining the systems performance. This is a result of having both fast data transfer capabilities and enough parallel processing units available.

By quickly inspecting the difference between the two scenarios in total test execution time in Figure 6 (dashed vertical lines), one clearly sees that the performance gain in the second scenario is substantial; the weakly parallelized setup performs almost six times faster than the sequential test. This can be considered a significant improvement for any scenarios requiring acceleration of repetitive test execution. In contrast, the ratio of used equipment is almost at 100% for the duration of the test. The ratio in sequential execution is lower than 10% on average for the complete test sequence.

A general view at the system's performance can be seen in ***Figure 7***.

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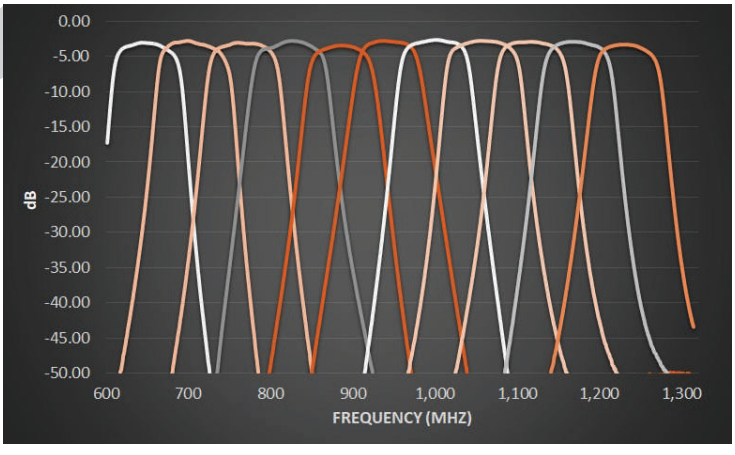

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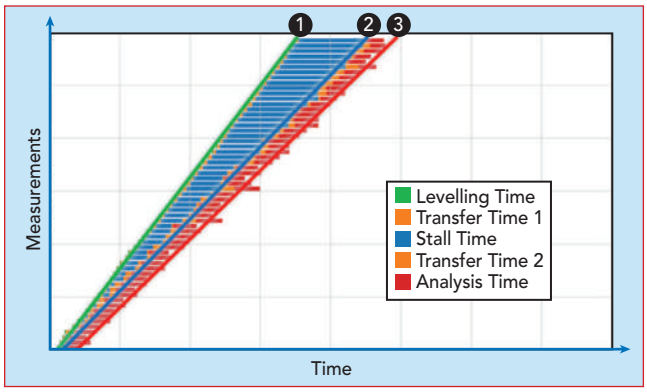

Fig. 7
Throughput subtask segmentation and the respective effect on the overall systems' performance.

Here, a system was purposely configured with a low number of parallel processing units and used to run the same test. The system's throughput performance data was recorded, with the separation of individual phases in each test step. First phase (green) is the analyzer preparation time where input levelling is performed; second phase (orange) is the data capture and transfer time to a centralized buffer. Third phase (blue) is a file server that is utilized as a buffer. Fourth phase is the data transfer to the processing unit, whereas phase 5 (red) is the actual processing of the capture.

By observing the diagram, one can identify three segments that have an effect the performance:

Segment 1, identified by the green gradient No 1 in Figure 7, defines how fast data is delivered. Speed improvement is done by both acceleration of data delivery and parallelization of data sources where applicable. This is a large factor to the speed of the system but is often limited by the test setup or physical boundaries.

Segment 2, which is the area between gradients 1 and 2, reflects how much a system must wait (or buffer) due to a lack of parallel processing capabilities. In cases where enough processing units are available at the system's disposal, the blue area is minimized. This segment can be considered as both the biggest contributor to overall performance and the easiest to tune, if the underlying platform supports such scalability. In this test case, SBT is specifically designed to support an arbitrary number of processing units running on single hardware unit (e.g. server) or across multiple units.

Segment 3, the red area between gradients 2 and 3, defines how fast individual processing units can execute the analysis task. Optimizing a single processing time has a comparatively small effect on the overall system's performance and can be generally deemed as an expensive tuning factor.

In additional tests, strong parallelization was approximated by a simulation of an arbitrary number of capture devices, effectively resulting in an almost-immediate availability of capture data. The latter use case

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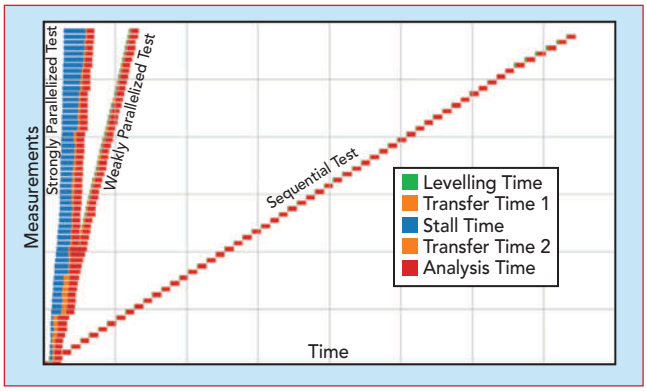

Fig. 8
Performance of strongly and weakly parallelized tests vs sequential test.

functions as a setup allowing an estimation of best possible performance of the processing platform. It shall be considered a borderline, yet real scenario, where enough data capturing devices is available. ***Figure 8*** shows the strongly parallelized test simulation in comparison with the other two scenarios.

CONCLUSION AND OUTLOOK

As expected, the strongly parallelized test performs the best. Due to the system's configuration of 16 parallel processing units, the blue segment shows where buffering takes place since data is almost instantaneously available for processing. Adding further processing units would have minimized the overall throughput time to a minimum, effectively rendering improvement factors of 10 and more versus sequential testing.

Note that data-transfer phases in both Figures 7 and 8 (in orange) have a little impact on the system's performance despite some variance in the duration. This is a typical observation when a non-deterministic transfer protocol (such as TCP over Ethernet) is used. Yet, the asynchronous, non-blocking operation can support such an execution mode.

The asynchrony is enabled through the utilization of system components that are commonly used in scalable IT systems. The recent rise of cloud-based systems, both public and on-premises, render the usage of such building blocks possible for system designs beyond the original use case. Here, the SBT solution tested is built around such scalable components. Yet, it is a purely localized deployment with no external connectivity requirements.

The benefits of such a solution with a focus on throughput improvements are manifold: apart from the discussed faster overall test speed or throughput, parallelization renders better equipment utilization ratios possible and allows a high ROI. Eventually, new usage-based commercial models become more attractive in cases where lower upfront investment in high-value equipment is desired.■

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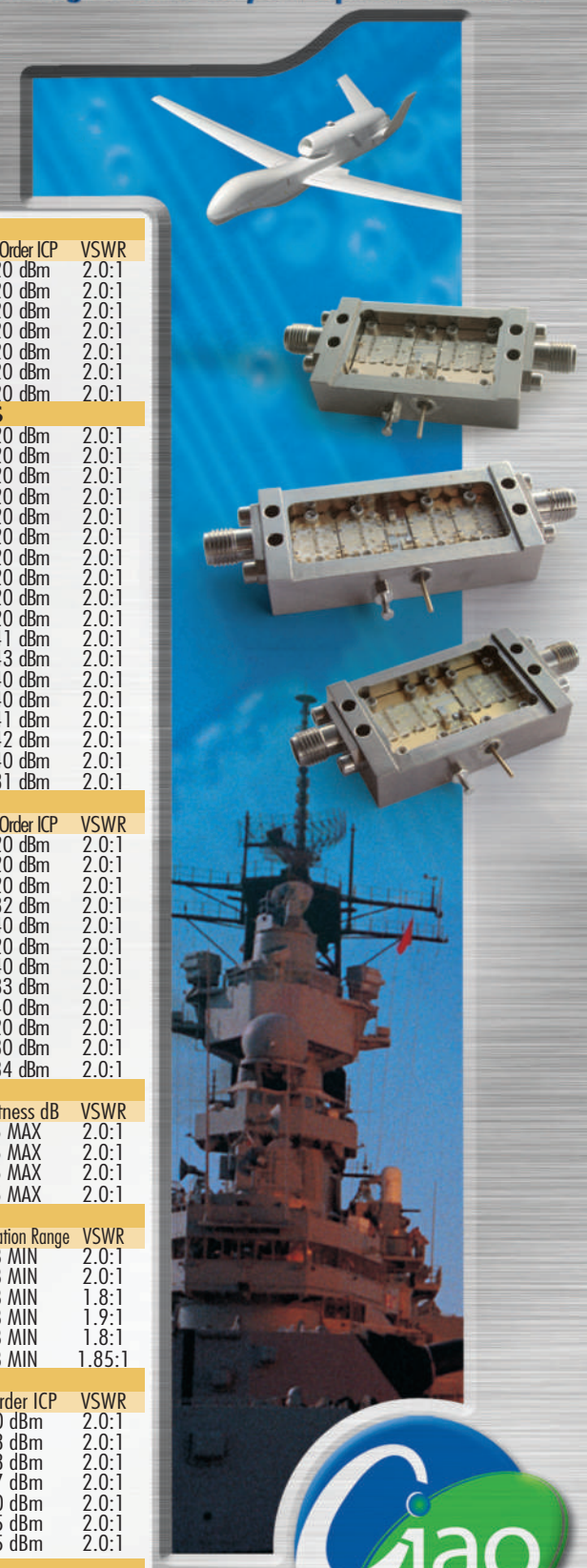

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CA12-2110	1.0-2.0	30	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA24-2111	2.0-4.0	29	1.1 MAX, 0.95 TYP	+10 MIN	+20 dBm	2.0:1
CA48-2111	4.0-8.0	29	1.3 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA812-3111	8.0-12.0	27	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA1218-4111	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

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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

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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

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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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Protecting Wideband RF Systems in Congested Electromagnetic Environments

Today's electromagnetic (EM) spectrum is a scarce resource that is becoming increasingly congested and contested as friendly, unfriendly and neutral entities vie for available spectrum resources at any given time, location and frequency. Within the DoD, RF systems, such as communications networks and radar, must operate within this congested environment and contend with mission-compromising interference from both self- and externally generated signals. A desire to support wideband EM spectrum operations also adds to the burden, as current approaches to mitigating wideband receiver interference are suboptimal and force compromises around signal sensitivity, bandwidth usage and system performance. Further, in the case of self-interference, traditional mitigation approaches such as antenna isolation alone are often insufficient for protecting wideband receivers.

"Protecting our wideband digital radios from interference and jamming in the unpredictable EM environment is critical to our defense capabilities and has prompted the exploration of wideband tunable circuit architectures to support cognitive radio technology," said DARPA Program Manager, Dr. Timothy Hancock. "Unlike narrowband radios that rely on switching between pre-planned filtering and narrowband signal cancellation, today's wideband radios lack the RF front-ends that could help mitigate harmful signals before they reach the sensitive receiver electronics."

The Wideband Adaptive RF Protection (WARP) program seeks to enhance protections for wideband receivers operating in congested and contested EM environments. The goal is to develop wideband, adaptive filters and analog signal cancellers that selectively attenuate–or cancel–externally generated interference signals (from adversarial jamming, for instance) and self-generated interference signals (like those created by a radio's own transmitter) to protect wideband digital radios from saturation. Saturation occurs when the power level of a received signal exceeds the receiver's dynamic range–or the range of weak to strong signals it can handle. When exposed to interference or jamming, the target WARP components will sense and adapt to the EM environment through the intelligent control of adaptive hardware.

To address external interference, WARP will explore the development of wideband tunable filters that can continuously sense the EM environment and adapt to maintain the receiver's dynamic range without decreasing signal sensitivity or bandwidth. The research will look at innovative filter architectures supported by state-of-the-art components and packaging to achieve the program's target metrics.

"With the WARP filters, the goal is to reduce the effect of large signals without attenuating smaller signals. By attenuating the large signals, a wideband RF system is better able to listen to both weak and strong signals over a wide bandwidth," noted Hancock.

WARP will also address self-generated inference with the development of adaptive, analog signal cancellers. "Sometimes a system's own transmitter is the biggest interferer to the receiver. To avoid this issue, transmitting and receiving at different frequencies has traditionally been commonplace, aided by a frequency duplexer to keep the two bands separate. However, for defense systems there are benefits to transmitting and receiving on the same frequency, such as doubling spectrum efficiency and increasing network throughput. This concept is referred to as same frequency simultaneous transmit and receive (STAR)," said Hancock.

The use of same-frequency STAR has been limited due to few available means of ensuring the transmitter leakage does not interfere with the receiver. To combat this, WARP will explore analog cancellers that will reduce the transmit leakage before the wideband digital receiver, such that any residual leakage will be sampled and further cancelled in the digital domain.

Raytheon to Help USAF Modernize Missile Warning Architecture

Raytheon Company will help the U.S. Air Force modernize its missile warning architecture with a new system that will collect and fuse data from an array of sensors to provide a comprehensive picture of launch activity under a 5 year, $197 million contract.

To help with this mission, Raytheon Intelligence, Information and Services has developed a completely open framework—which the Air Force calls the Future Operationally Resilient Ground Evolution (FORGE) Mission Data Processing Application Framework (MDPAF)—that will be capable of processing Overhead Persistent Infrared (OPIR) satellite data from both the U.S. Air Force's evolving Space Based Infrared System (SBIRS) constellation and the future Next Gen OPIR constellation, as well as be capable of processing data from other civil and environmental sensors.

"The U.S. government's global satellite network produces a constant flood of data—petabytes and petabytes of it every day," said Dave Wajsgras, president of Raytheon IIS. "The Air Force wants to open that network up so they can use as much of that data as possible. That is a huge transformation not just for the service, but for the whole government."

This is a significant departure from previous satellite ground control programs. Typically, companies would develop a system that collects and exploits data from specific types of satellites or sensors. FORGE changes this model as it is able to collect data from nearly any type of satellite or sensor, and then helps operators

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make sense of that data quickly.

"Essentially, this is a smartphone model," said Wajsgras. "We've built an operating system that everyone can build applications for—from Raytheon to the Air Force to universities to small companies. These applications allow the system to process specific types of data."

One of the key benefits of incorporating new applications is that the system can be used beyond its intended mission. For example, an application could be built that would allow civil agencies to use the same satellite data to help detect forest fires, volcanic activity, agricultural changes, even surges in electric power consumption.

Further departing from the traditional ground control development model, Raytheon built the prototype system in less than a year and it is capable of processing real data today. The company leveraged development work on several past programs, especially its Advanced Weather Integrated Processing System, to design the framework.

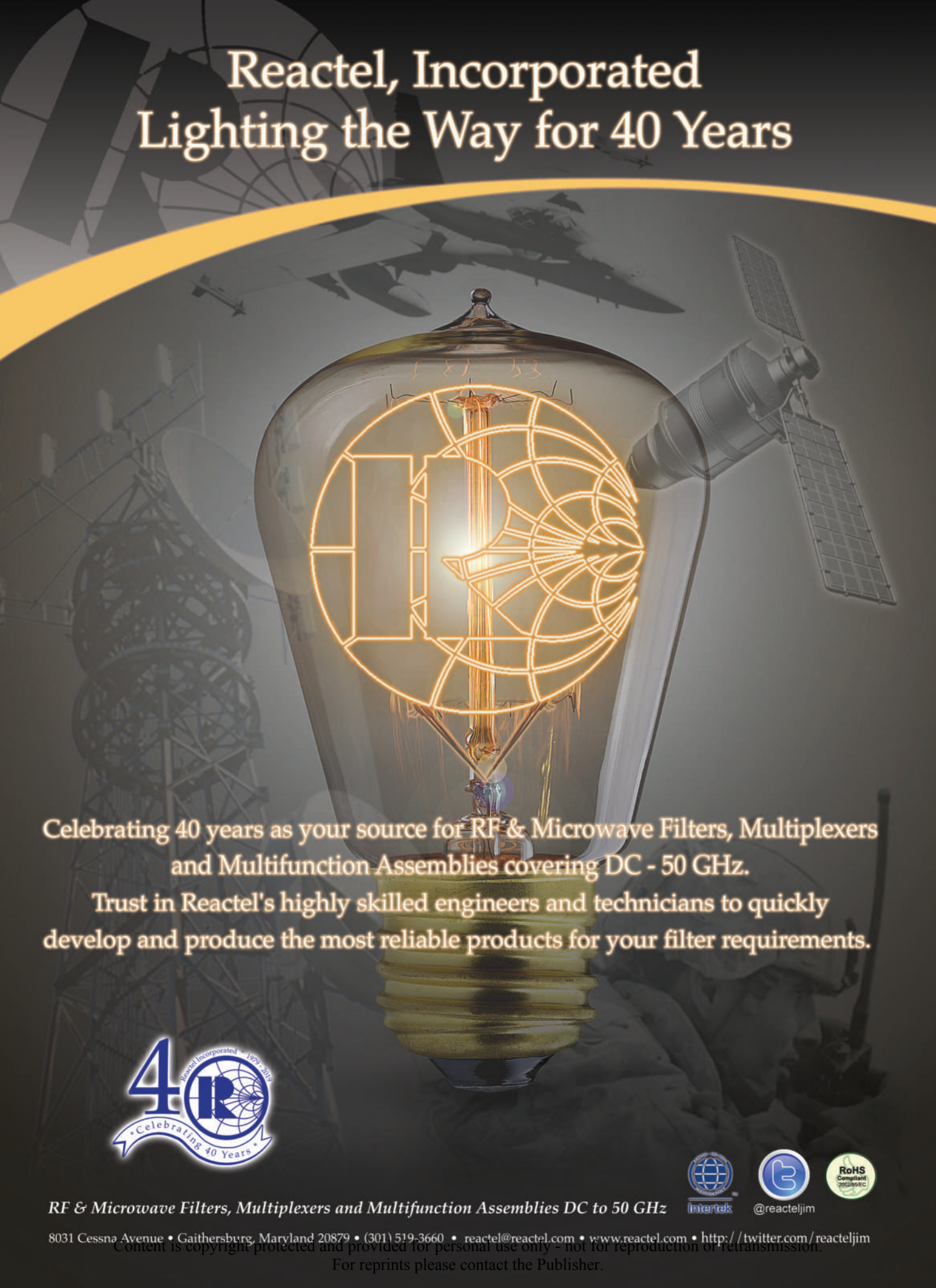
US Army and Air Force Team up for Multi-Domain Operations

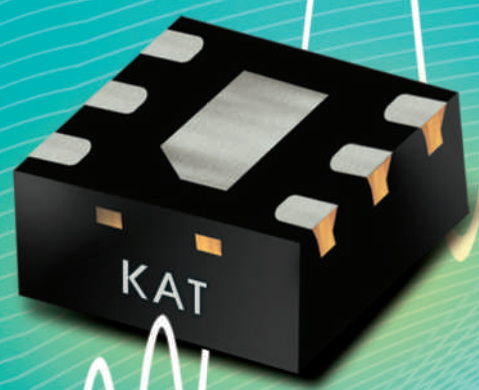
Two U.S. Air Force F-35s were recently integrated with the U.S. Army Integrated Air and Missile Defense Battle Command System (IBCS), providing an airborne sensor capability to successfully detect, track and intercept near simultaneous air-breathing threats in a test at White Sands Missile Range, New Mexico. This test marked the first time F-35s were used as sensors during an IBCS live fire test against multiple airborne targets.

Linking F-35s to IBCS via the Multifunction Advanced Data Link (MADL) provided enhanced situational awareness and weapons-quality track data to engage airborne targets. The proof of concept demonstration used experimental equipment developed by Lockheed Martin, including the Harvest Lightning Ground Station and IBCS adaptation kit (A-Kit).

"The F-35's advanced sensors and connectivity enable it to gather, analyze and seamlessly share critical information with the joint fighting force to lead the multi-domain battlespace," said Greg Ulmer, Lockheed Martin vice president and general manager of the F-35 program. "This test validated the F-35's capability to serve as an airborne sensor and extend the range of critical Integrated Air and Missile Defense interceptors."

"This test represents a major milestone for multi-domain operations by leveraging airborne assets to detect and track threats that can then be countered with ground-based effectors. This demonstrates a tremendous capability to defeat threats that are terrain masked or beyond ground-based sensor detection capabilities due to terrain and curvature of the earth," said Jay Pitman, vice president, Lower Tier Integrated Air and Missile Defense at Lockheed Martin Missiles and Fire Control.





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5G Fixed Wireless Broadband CPE Market Set to Reach Nearly 7 Million Units in 2024

Fixed wireless broadband services based on Long Term Evolution (LTE) technology have been widely deployed globally, mostly focusing on areas with a poor fixed network infrastructure. Today, 5G technology opens more opportunities for the fixed wireless broadband segment. As operators continue to roll out 5G networks, the commercial launch of 5G fixed wireless broadband services will accelerate in the next few years. This will ultimately drive the 5G fixed wireless Consumer Premise Equipment (CPE) market. ABI Research forecasts that shipments of 5G fixed wireless broadband CPE will hit more than 2 million units in 2020.

5G fixed wireless access (FWA) brings several benefits to both operators and consumers. The deployment of 5G fixed wireless broadband networks in place of last-mile fiber connectivity will save costs and time to install fiber-optic lines while providing Gigabit capacity broadband access. "Interestingly, except for China and a few other developed markets, fiber-to-the-home penetration is still limited to less than 20 percent of total households worldwide. This creates a huge opportunity for the whole 5G fixed wireless broadband market," notes Khin Sandi Lynn, Industry Analyst at ABI Research.

After the initial launch in four U.S. cities in 2019, Verizon is now planning to expand its 5G Home broadband service in areas with a 5G mobile network footprint. T-Mobile is also planning to commercially roll out a 5G broadband service to home users with its nationwide 5G network launch. Vodafone, Three UK, EE in Europe, and Rain in South Africa are some of the operators that have rolled out a 5G FWA service. Several service providers worldwide are also working toward the commercial launch of 5G fixed wireless broadband services.

Chipsets and device makers are also actively playing roles in the 5G FWA space. Qualcomm has announced it has partnered with more than 30 OEMs to develop 5G FWA CPE. At the same time, device makers such as Huawei, NetComm, Nokia and Samsung have already introduced 5G FWA CPE. As the 5G FWA ecosystem evolves, there will be additional commercial launches of 5G FWA services and CPE. The 5G FWA CPE market will increase at CAGR 71 percent to reach just under 7 million units in 2024.

Depending on the deployment scenario, 5G FWA services will need different forms of CPE, the selection of indoor or outdoor, mmWave or Sub-6GHz, etc. Device makers should make sure to support various form factors and specifications to meet service provider requirements. The integration of advanced Wi-Fi features, the ability to connect to smart home devices, and in-home Wi-Fi management solutions can add value for end-users as well as create differentiating factors for service providers.

MOSHEMT: Innovative Transistor Technology Reaches Record Frequencies

Scientists at the Fraunhofer Institute for Applied Solid State Physics (IAF) have developed a novel transistor with an extremely high cutoff frequency. Named a metal oxide semiconductor high electron mobility transistor (MOSHEMT), the device uses an oxide instead of the Schottky barrier of a conventional HEMT, yielding a transistor that has already demonstrated a record oscillation frequency of 640 GHz.

The high frequency characteristics of HEMTs have steadily improved as the gate length has been reduced to 20 nm. However, the current transistor geometry of a conventional HEMT has reached its scaling limit. At such small sizes, HEMTs encounter a problem: the thinner the barrier material of InAlAs, the more electrons leak from the channel through the gate. These gate leakage currents hurt the efficiency and durability of the transistor, making further downscaling infeasible.

Faced with similar challenges, silicon MOSFETs have an oxide layer that prevents unwanted leakage currents more effectively than the traditional HEMT structure. So researchers at Fraunhofer IAF combined the advantages of III-V semiconductors with silicon MOSFETs, replacing the Schottky barrier of the HEMT with an isolating oxide layer. The resulting MOSHEMT is a new structure.

"We have developed a new device which has the potential to exceed the efficiency of current HEMTs by far. The MOSHEMT allows us to downscale it even further, thus making it faster and more efficient," said Arnulf Leuther, a researcher in the field of high frequency electronics at Fraunhofer IAF. With the new transistor technology, Leuther and his team have succeeded in achieving a record maximum oscillation frequency of 640 GHz. "This surpasses the global state of the art for any MOSFET technology, including silicon MOSFETs," said Leuther.

To overcome gate leakage, the scientists used a material with a significantly higher barrier than a conventional Schottky, replacing the semiconductor material with a combination of isolating layers of Al2O3 and HfO2. "This enables us to reduce the gate leakage current by a factor of more than 1,000. Our first MOSHEMTs show a very high development potential, while current field effect transistor technologies have already reached their limit," said Axel Tessmann, a scientist at Fraunhofer IAF.

The extremely fast MOSHEMT is designed for applications above 100 GHz, such as novel communication systems, radars and sensors. Future high power devices will enable faster data transmission across radio links, imaging radar systems for autonomous driving and higher resolution, precision sensor systems. While it may be some years before the MOSHEMT is widely adopted, the researchers at Fraunhofer IAF have already demonstrated what they say is the first amplifier MMIC using InGaAs MOSHEMTs, operating between 200 and 300 GHz.

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The AR Cloud Promises High Value, Future Proof AR Use Cases

The Augmented Reality (AR) cloud is often described as the world's digital twin, a digital copy of the real world that is accessible by any user from any device, from any location and at any time. It is expected that the AR cloud will play catalytic role in the way that users engage and search for information while at the same time, transform the way that businesses operate and communicate with customers and employees in both physical and digital forms. The AR Cloud has the potential to directly impact most of the AR value chain, which ABI Research forecasts will reach almost US$102 billion by 2024.

"The journey toward scaled deployment of the AR Cloud has begun and numerous companies from tech giants to start-ups are starting to build 'mini AR clouds' and contributing to building a cloud-based 3D map of the real world. The synergy of numerous technologies, including computer vision, Simultaneous Localization and Mapping (SLAM), and connectivity are required to precisely localize devices in the environment and deliver sharable and persistent AR content," says Eleftheria Kouri, Research Analyst at ABI Research.

One of the most advanced AR cloud-based apps is Google's AR navigation, which leverages Google's Visual Positioning Service (VPS) and the AR cloud to enable device localization in the environment with a higher accuracy than that of GPS. AR indoor and outdoor navigation are among the most promising cloud-based use cases, requiring large scale mapping and persistent localization and digital content. One company, Sturfee, utilizes VPS and the AR Cloud for AR city navigation, while 6D.ai is a prime example of indoor navigation leveraging the AR Cloud. Scape Technologies, Visualix, YOUAR, and Ubiquity6 are also active in the space, offering software development kits for building cloud-based 3D maps of the physical world by utilizing mobile devices. Constantly updated environments and shareable and persistent AR experiences will revolutionize numerous industries and applications, from product design with collaboration to retail and gaming.

"5G connectivity, improved AR devices, and the further growth of connected devices will all contribute to the development and the wider adoption of AR cloud-based applications. At the same time, the digital twin of the real-world generates questions about user safety, security, and privacy. So, both policymakers and providers need to apply new legal frameworks and ensure user privacy. With the immense value, unique experiences, and the potential ROI that comes with ubiquitous and persistent augmented reality ecosystems, efforts must hasten to address the issues and realize the value," concludes Kouri.

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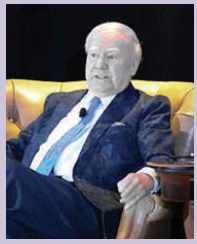
Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

IN MEMORIAM



Barrie Gilbert passed away on January 30, 2020. He was well known for his invention of numerous analog circuit concepts, holding over 100 patents worldwide, and for the discovery of the Translinear Principle. His name is attributed to a class of related topologies loosely referred to as the Gilbert cell, one of which is a mixer—a key frequency translation device—used in every modern wireless communication device. A similar topology, for use as a synchronous demodulator, was invented by Howard Jones in 1963. In 1979, Analog Devices allowed Gilbert to create the first remote design center for the company, in Oregon, to persuade him to rejoin the company as their first Fellow. This center developed into the Northwest Labs. To read more, visit mwjournal.com/gilbert.

MERGERS & ACQUISITIONS

Qorvo announced it will pay some $500 million to acquire two companies: **Decawave**, a technology play in ultra-wideband (UWB) for mobile applications, and **Custom MMIC**, a complementary addition to its defense segment. Qorvo CFO Mark Murphy said more than three-quarters of the $500 million will be for Decawave, the remainder for Custom MMIC. Qorvo will pay for them with cash.

COLLABORATIONS

Keysight Technologies Inc. announced an extended collaboration with **Samsung Electronics' LSI Business**, to validate dynamic spectrum sharing technology used in the smartphone maker's new 5G modem. Samsung has used Keysight's 5G network emulation solutions to accelerate the development of its RF solution, Exynos RF 5510, as well as its newest 5G modem, Exynos Modem 5123, which supports DSS technology.

DuPont Electronics & Imaging and **SCHMID Group** announced that they have entered into a nonexclusive joint development agreement to explore new PCB plating applications to bring advanced innovations to its global customers. The partnership will benefit high-end printed circuit board manufacturers by delivering next-generation interconnect products and metallization processes that can create faster, smarter and more reliable devices for the 5G era. The new solutions which will include equipment and chemistry are expected to be launched in late 2020. The new equipment and chemistry solutions are expected to address the challenges from advanced circuit board designs that require enhanced performance and reliability, and improved cost of ownership for production.

ConcealFab has collaborated with **Radio Frequency Systems (RFS)** to enable ConcealFab's 5G Radio Concealment Shroud to efficiently package a sizable amount of 5G mmWave radio equipment, 4G radios, and interconnection cables while ensuring optimal RF performance. As 5G can utilize high-frequency energy to transmit and receive voice and data, ConcealFab's proprietary shroud materials had to optimize signal strength while protecting the equipment from weather and environmental exposure in a compact and easy to service configuration. Empirical testing has proven maximum RF performance from ConcealFab's proprietary clearWave™ radome material.

ZTE Corp. and **China Telecom**, have developed China's first 5G remote diagnosis of the new coronavirus pneumonia. 5G, featuring high bandwidth and low latency, makes medical diagnosis and treatment more efficient and convenient. The 5G remote diagnosis involves West China Hospital and the Chengdu Public Health Clinic Center of Sichuan University. ZTE has used its CPE equipment to commission 5G services by means of outdoor 5G signals while constructing indoor coverage points. On January 25, 5G indoor base stations were built and interconnected, and the conference room for remote diagnosis and treatment in the West China Hospital was first connected to the remote diagnosis and treatment system.

NEW STARTS

Rohde & Schwarz announced the company is changing its industry-first promotion to provide customers a new, extended offering titled, "This Changed Everything." The extended promotion, which runs January 1, 2020 to June 30, 2020, includes 10 value bench instrument solutions for customers to choose from. Rohde & Schwarz's "This Changed Everything" promotion, continues to support customers' long-term viability and eliminate the add as you go component, presenting the opportunity to purchase all the bandwidth, channels, inputs, memory interfaces and signal generation design engineers may ever need at one unrivaled package price.

Triad RF Systems, a designer and manufacturer of high-performance RF/microwave amplifiers and integrated radio systems, has announced the launch of a new brand identity and website. Visitors to their new website will discover Triad's track record of creating RF/microwave amplifier products that push the limits of size, features, efficiency and linearity. They will also recognize Triad's earned reputation for achieving the perfect balance between solving issues of transmission distance, data rate, linearity and signal purity.

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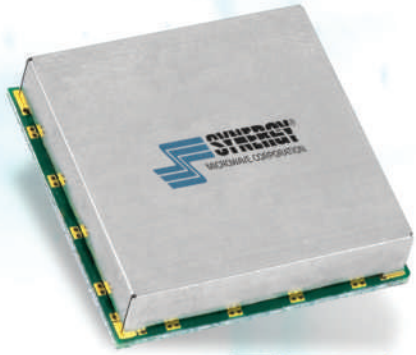

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HFSO745R84-5	745.84	0.5 - 12	+5 VDC @ 35 mA	-147
HFSO776R82-5	776.82	0.5 - 12	+5 VDC @ 35 mA	-146
HFSO800-5	800	0.5 - 12	+5 VDC @ 20 mA	-146
HFSO800-5H	800	0.5 - 12	+5 VDC @ 20 mA	-150
HFSO800-5L	800	0.5 - 12	+5 VDC @ 20 mA	-142
HFSO914R8-5	914.8	0.5 - 12	+5 VDC @ 35 mA	-139
HFSO1000-5	1000	0.5 - 12	+5 VDC @ 35 mA	-141
HFSO1000-5L	1000	0.5 - 12	+5 VDC @ 35 mA	-137
MSO1000-3	1000	0.5 - 14	+3 VDC @ 35 mA	-138
HFSO1200-5	1200	0.5 - 12	+5 VDC @ 100 mA	-140
HFSO1600-5	1600	0.5 - 12	+5 VDC @ 100 mA	-137
HFSO1600-5L	1600	0.5 - 12	+5 VDC @ 100 mA	-133
HFSO2000-5	2000	0.5 - 12	+5 VDC @ 100 mA	-137
HFSO2000-5L	2000	0.5 - 12	+5 VDC @ 100 mA	-133

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Around the **Circuit**

ACHIEVEMENTS

Anokiwave Inc. was named a hot tech innovator by global technology market advisory firm **ABI Research** in its 2019 QTR 4 report, "Hot Tech Innovators" for Cellular and 5G Antenna Technologies. Advances in phased array antennas for use at mmWave frequencies are essential for the rollout of new 5G, cellular and other applications. In naming Anokiwave as a hot tech innovator in this area, ABI Research said that the company's pioneering hybrid beamforming technology not only enables the development of high-performance antennas, it also provides the additional benefits of low cost, low complexity, and ease of reconfigurability for even the largest designs.

Fabless RFIC company **Sivers IMA** announced four design wins for the company's 57 to 71 GHz RFIC, the TRX-BF01. The company said the wins, with third-tier manufacturers, will not increase near-term revenues appreciably, estimating the time from design win to volume production in the range of 9 to 18 months. Sivers IMA has now secured 16 design wins, representing a 20 percent conversion from supplying an evaluation kit to winning a design.

WUPATEC, a supplier of high performance mixed-signal and RF solutions for wireless communication, announced the closing of a 3M€ financing with IRDI Soridec, Aquiti Gestion and InnoEnergy. Founded in 2016 and located in Limoges, France, Wupatec has developed unique IPs to significantly decrease the power consumption of RF front end. With the ever increasing need for broadband data (LTE/5G handset, LTE/5G eMBB, Public Safety Network ...), the power hungry and narrowband Radio Front End Amplifier is a major roadblock to finally unleash all of the benefits of true Software Defined Radio (SDR), and the deployment of 5G networks with his large Massive MIMO Antenna System.

Anritsu Co. has announced that Eurofins E&E North America, the first Nationally Recognized Test Laboratory (NRTL) and part of the Eurofins Electrical and Electronics (E&E) global network of laboratories, has purchased several Anritsu 5G and Wi-Fi testing and analysis solutions. The Anritsu technology will be integrated into the Eurofins E&E testing facility in Santa Clara, Calif., and will support Eurofins E&E's 5G testing protocols, as well as the new CTIA test requirements associated with IEEE 802.11ac. The Anritsu test instruments will allow Eurofins E&E to provide comprehensive certification testing on Wi-Fi 802.11ac devices, as well as 3G/4G/5G user equipment (UE).

34 satellites for the **OneWeb** constellation are ready for launch from Baikonur, Kazakhstan. The satellites which arrived in two shipments, have been tested, and were fitted into the dispenser of the Soyuz-2.1b rocket. The satellites, which are manufactured at 1/50th of the cost of a traditional spacecraft, are all fitted with plasma thrusters enabling them to reach their correct position in low Earth orbit at 1,200km.

Altum RF, a supplier of high-performance mmWave to digital semiconductor solutions for next generation markets and applications, announced registration to ISO 9001:2015 for its quality management system. The certification demonstrates Altum RF's focus on the quality, reliability and performance of its design and development of semiconductor products. The ISO 9001:2015 certification was awarded by TÜV Nederland, part of the international TÜV NORD GROUP, a global company located in 70 countries that has more than 100 years of experience with quality systems certification.

Metawave successfully demonstrated its award-winning SPEKTRA analog beam-steering radar. SPEKTRA is one of the most accurate and intelligent automotive radars available and can clearly detect vehicles beyond 300 meters and pedestrians beyond 200 meters with a high angular resolution. Metawave has filed for 150+ patents to date and received its first issued patent in 2019. At the heart of SPEKTRA are Metawave's MARCONI 77 GHz phase controllers and mmWave integrated circuits, which, when used with their proprietary calibration system, enable the transmit and receive beams to be precisely steered in steps of 0.1° in the range of ±22°.

L3Harris Technologies has reached a major milestone in the U.S. Air Force's Navigation Technology Satellite-3 (NTS-3) project—passing the preliminary design review that defines the spacecraft's path to delivery and allows the program to move to the next phase of development. NTS-3 is an experimental program examining ways to improve the resiliency of the military's positioning, navigation and timing capabilities. It will also develop key technologies relevant to the GPS constellation, with the goal of future transition to the GPS IIIF program.

CONTRACTS

Leidos, a defense, intelligence, homeland security, civil and health solutions provider has been awarded a prime contract by the **Federal Aviation Administration (FAA)** to replace the agency's Mode S Beacon Systems under the Mode S Beacon Replacement System (MSBRS) contract. The contract has a four-year base period of performance followed by four two-year option periods, at an approximate value of $450 million, if all options are exercised. Work will be performed in Gaithersburg, Md., Eagan, Minn. and Chesapeake, Va. The Mode S Beacon System is a secondary surveillance radar (beacon) capable of providing surveillance and specific aircraft information necessary to support Air Traffic Control (ATC) automation in all traffic environments.

Defense solutions pioneer, **Raytheon**, has received a $403 million contract from the **US Navy** for the next phase of Next Generation Jammer Mid-Band (NGJ-MB) program. The SDTA (System Demonstration Test Articles) pods for the advanced electronic warfare system will be delivered to the fleet once developmental and operational testing is complete.The NGJ-MB provides

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- Solderable SMT Terminations
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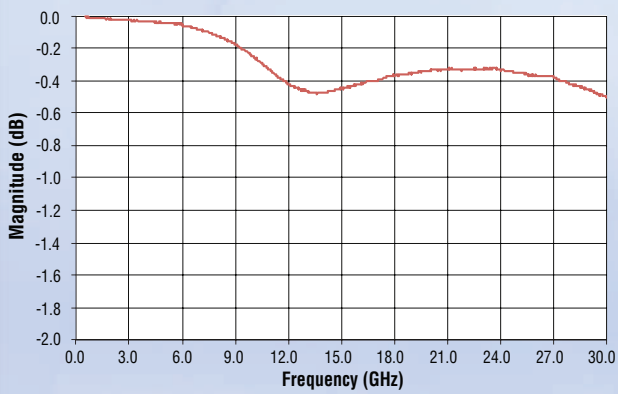
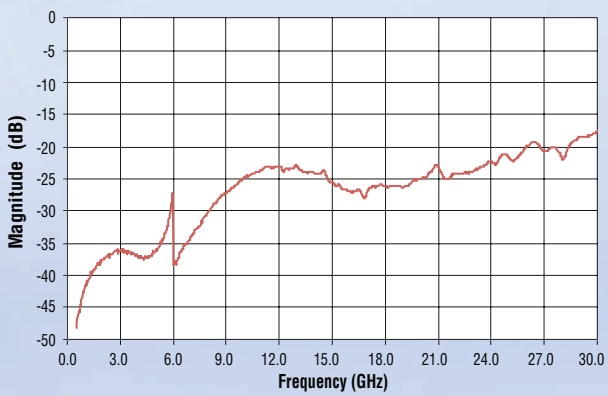
531Z Insertion Loss (S21)



531Z Return Loss (S11)



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significantly improved radar and communication jamming performance and capacity, as well as improved reliability and maintainability, for EA-18G Growler crews. Commanders will use NGJ-MB to deny, degrade and deceive the enemy's use of the electromagnetic spectrum through advanced jamming techniques.

BAE Systems' Intelligence & Security sector has received two separate contracts of $104.7 million and $212 million from the **U.S. Navy's Naval Air Warfare Center Aircraft Division (NAWCAD)** to integrate and sustain its critical communication systems. The company will design, acquire, integrate and test radio systems for newly constructed Guided Missile Destroyers (DDG) and other U.S. Navy and U.S. Coast Guard ships. Along with the $212 million contract, the company has also received a separate $104.7 million contract from **NAWCAD** to provide engineering and technical services to support production, lifetime-support and in-service engineering for the radio communications C5ISR systems.

Sentar Inc., specializing in advanced cybersecurity and intelligence services and technologies, announced the award of the $164 million task order from the **Naval Information Warfare Center (NIWC)** to provide the Defense Health Agency (DHA) with Cybersecurity Risk Management Operations Support (RMOPS) services. If fully executed, this contract will extend Sentar's support to the DHA through the next four years. Under the new contract, Sentar will continue to work closely with NIWC Atlantic in its support to the DHA in addressing various cyber security initiatives, processes and compliance requirements.

Mercury Systems Inc. announced it received a $24 million order from a leading defense prime contractor for SWaP-optimized RF modules ready for integration into an advanced electronic warfare system. The order was booked in the company's fiscal 2020 second quarter and is expected to be shipped over the next several quarters. Mercury is accelerating innovation for its customers as they bridge the gap between commercial technology and defense applications to meet the industry's current and emerging needs.

BAE Systems was awarded a contract from the **Defense Advanced Research Projects Agency (DARPA)** to develop the next generation of mixed-signal electronics that could enable new DoD applications including high capacity, robust communications, radars, and precision sensors, and lead to solutions that enhance situational awareness and survivability for the warfighter. As part of the $8 million contract, BAE Systems FAST Labs™ research and development team—working closely with program foundries—will design and develop wafer-scale technology on a silicon foundry platform that can enable U.S.-based production of next-generation DoD electronics.

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BRIDGING THE THz GAP JUST GOT SMALLER.

VDI's VNA Extenders provide high performance frequency extension of vector network analyzers from 26GHz to 1.5THz. These modules combine high test port power with exceptional dynamic range and unmatched stability.

VDI's mini-modules are reduced in size, but yield the same industry leading performance as our original designs. The compact form factor and simplified power supply make them the recommended solution for most applications.

Mini-modules are currently available in standard waveguide bands for 26GHz to 500GHz with higher frequency bands under development.

Waveguide Band (GHz)	WR28 26-40	WR15 50-75	WR12 60-90	WR10 75-110	WR8 90-140	WR6.5 110-170	WR5.1 140-220	WR4.3 170-260	WR3.4 220-330	WR2.8 260-400	WR2.2 330-500	WR1.5 500-750	WR1.0 750-1,100
Dynamic Range (BW=10Hz, dB, typ)	120	120	120	120	120	120	120	115	115	100	110	100	65
(BW=10Hz, dB, min)	110	110	110	110	110	110	110	110	105	80	100	80	45
Magnitude Stability (±dB)	0.15	0.15	0.15	0.15	0.15	0.25	0.25	0.3	0.3	0.5	0.5	0.4	0.5
Phase Stability (±deg)	2	2	2	2	2	4	4	4	6	6	6	4	6
Test Port Power (dBm)	13	13	13	18	6	13	6	-2	1	-10	-3	-25	-30

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Around the **Circuit**

Comtech Telecommunications Corp. announced that during its second quarter of fiscal 2020, its New York-based subsidiary, Comtech PST Corp., which is part of Comtech's Government Solutions segment, received a $3.1 million contract for high-power amplifier systems from a major domestic prime contractor. These amplifiers, which utilize the latest in solid-state GaN transistor technology, are key transmit elements in a data communication system. They are in addition to an installed base of Comtech solid-state high-power RF amplifiers previously delivered to this major domestic prime contractor.

Filtronic plc announced contract wins for two separate advanced mmWave design and development contracts that have strategic importance to the development of the company and its technology roadmap. The first contract, covers the design, development and delivery of high-performance, mmWave modules for incorporation within their next generation over-the-air equipment. The order is structured around incremental development milestones over a period of approximately 16 months, for a full contract value approaching $1 million (approximately £0.8 million). The second contract covers the design, development and delivery of next generation, high-performance transceiver modules. The order is structured around incremental development milestones over a period of approximately 18 months, for a full contract value approaching $0.6 million (approximately £0.5 million) with revenue predominantly recognized in FY2021.

Comtech Telecommunications Corp. announced that during the second quarter of fiscal 2020, its Santa Clara, California-based subsidiary, **Comtech Xicom Technology Inc.**, which is part of Comtech's Commercial Solutions segment, received a $1.3 million follow-on order from a domestic integrator for Traveling Wave Tube Amplifiers (TWTA) for a U.S. Government Satellite Communications application. The Ka-Band TWTAs ordered for this challenging Army application are part of Comtech Xicom Technology's high efficiency TWTA product line and will be delivered in 2020.

Akoustis Technologies, an integrated device manufacturer (IDM) of patented bulk acoustic wave (BAW) high-band RF filters, has received its first volume commercial order for 5G small cell network infrastructure filter solutions. This is a significant achievement for Akoustis as it marks the first volume order for its proprietary and patented XBAW™ RF filters targeting the fast-growing 5G infrastructure market. The order is from a tier-1 network infrastructure customer for high-frequency BAW filters targeting a key 5G band in the sub-6 GHz, ultra-high frequency (UHF) spectrum for the Asia market.

GaAs MIXERS

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Part Number	Freq. Range	Description
CMD258C4	7.5 - 13 GHz	High IP3 I/Q Mixer
CMD313	6 - 45 GHz	Fundamental Mixer
CMD310C3	20 - 32 GHz	Sub-harmonic Mixer

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Around the **Circuit**

PEOPLE

▲ *Dave Shepard*

Marki Microwave announced that **Dave Shepard** has joined the company as COO, reporting to Chris Marki, CEO. In this role, Shepard will manage all non-engineering functions with the goal of scaling those functions to meet the rapidly increasing demand created by the innovative products coming out of engineering. Shepard brings to Marki a wealth of general management experience in both large and small companies spanning a broad set of products and markets in the semiconductor industry. Prior to Marki, he held general management positions at IDT, Peregrine and Texas Instruments.

▲ *Chris DeMartino*

Modelithics Inc. welcomed **Chris DeMartino** to the company as sales and applications engineer. In this role, DeMartino will be responsible for technical support and application development for Modelithics products and services. He joins the Modelithics team from Informa PLC (formerly Penton Media), where he served as the editor of Microwaves & RF magazine. At this position, his responsibilities included generating technical content to serve the needs of the RF/microwave engineering community. Prior to assuming the role of editor of Microwaves & RF in May 2015, he was able to gain valuable experience in RF/microwave design and testing.

▲ *Shmuel Auster*

Shmuel Auster has been elected as the IEEE Israel Section Chair. He has been with IAI/Elta Systems since August 2006 as R&D coordinator and Liaison manager. He previously served as Chief Scientist at Elbit/Elisra Electronic Systems Ltd. (1980-2006). From 1993 to 2000 he represented Elisra as a Director of the Israeli GaAs/MMIC Consortium and served as the Chair of the Technical (R&D) Committee at this Consortium. Auster has served as the IEEE Israel Section's treasurer and BoD member since 2018.

Executive Interviews

With **Qorvo** completing the acquisition of **Custom MMIC**, Microwave Journal wanted to understand how Custom MMIC will merge into Qorvo. Roger Hall, general manager of Qorvo's High Performance Solutions (HPS) business, and Paul Blount, the founder of Custom MMIC, graciously responded to our questions at microwavejournal.com/articles/33482.

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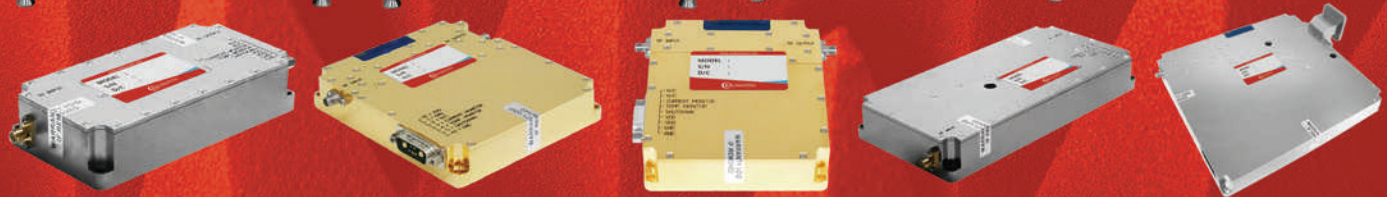

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Advancing ATE Strategy For mmWave Mass Market Production

Mark Roos
Roos Instruments, Santa Clara, Calif.

The automated test and measurement (ATE) landscape is rapidly changing, progressing beyond the capabilities of traditional bench-top and most legacy ATE systems. Varying and diverse performance requirements, testing speeds and frequencies used by modern cellular architectures (5G), Internet-of-Things (IoT) devices, and the latest feature dense systems-on-chip/systems-in-package (SoC/SiP) necessitate a different approach. This leverages a modular configuration focused on precise calibration, low loss device connections and high measurement accuracy with a small footprint and low capital expense. Modular architectures can provide future proof features and enable ATE systems to be faster and more accurate with less development. Not all modular ATE systems are created equal, however. At mmWave frequencies, test system configuration requires insight into the differentiating features between ATE systems as well as the bench-top units they typically replace.

Automated testing of mmWave devices has been subject to increasingly complex standards, methods and requirements over the past few years. This trend is likely to progress as fifth generation cellular mobility (5G), IoT, and system-on-chip (SoC) technologies continue to advance, leaving research and development and moving past engineering volumes to production.[1] Current mmWave automated testing relies on dedicated test (bench-top) instruments or custom designed/developed ATE purpose-driven for a specific type of device, standard or set of specifications.

This is an era of rapid technology advancement, shifting standards, and the use of the upper-microwave and mmWave spectrum for mainstream applications (see ***Figure 1***). It is unlikely that general purpose bench-top instruments or custom/application-specific ATE systems will be able to cope with the onslaught of new requirements. Hence, an engineering team selecting production test equipment must be mindful of current and future requirements. Organizations cannot risk purchasing capital equipment that may become rapidly obsolete or provide diminishing value due to complex setup and optimization requirements. There is a need for modular test systems that reach well into the mmWave frequency range, support multi-domain synchronized testing, have software-based configurability and can accommodate the shifting standards of modern cellular, Wi-Fi, IoT and other emerging technologies.

TRENDS & CHALLENGES

The emerging device trends responsible for the growth of mmWave production testing are: massive numbers of devices that operate at much higher frequencies (to nearly 100 GHz) with bandwidths reaching several hundred megahertz to a gigahertz, more complex and configurable RF devices with multiple RFICs, and testing scenarios that

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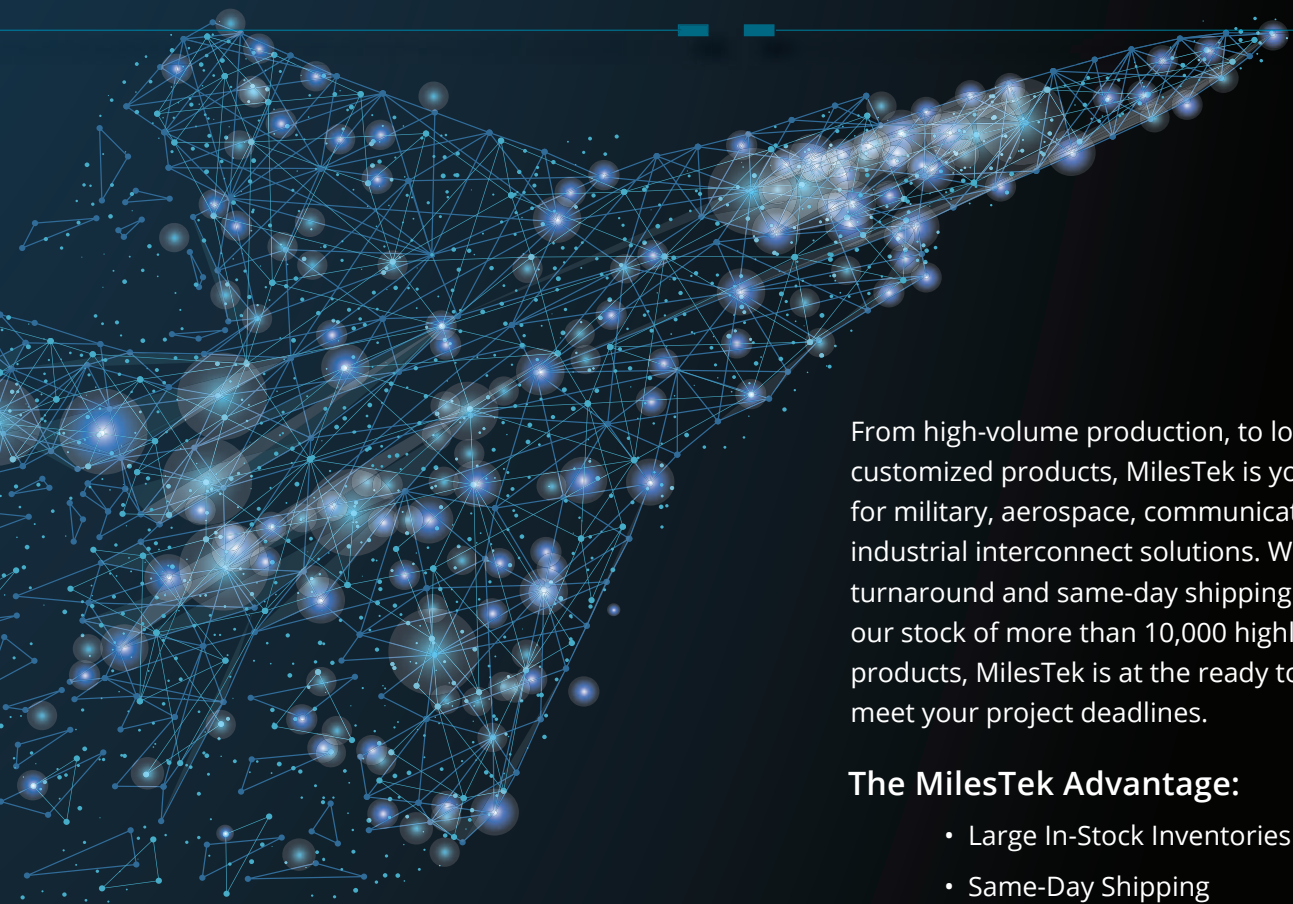

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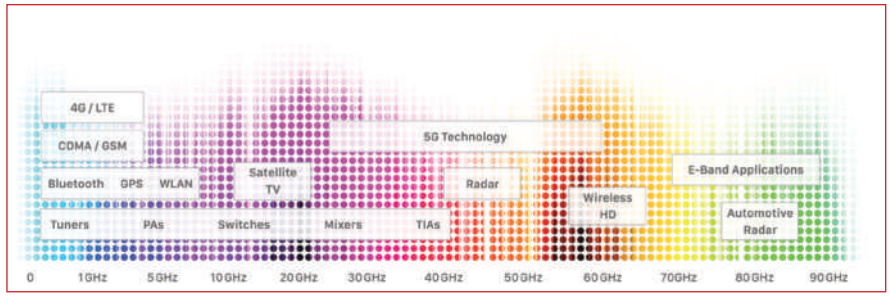


Fig. 1 Spectral mapping of applications.

TABLE 1
5G PARAMETERS

	Frequency Range 1 (FR1)	Frequency Range 2 (FR2)
Known As	Sub-6 GHz	mmWave
Frequency Range (U.S.)	450 MHz to 6 GHz	24.25 to 52.6 GHz
Duplex Mode	FDD, TDD	TDD
Subcarrier Spacing	15, 30, 60 kHz	60, 120 kHz
Bandwidth	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100 MHz	50, 100, 200, 400 MHz
MIMO	Downlink: 8 x 8; Uplink: 4 x 4	Downlink: 2 x 2; Uplink: 2 x 2
MIMO Method	Spatial Multiplexing for Higher Throughput	Beamforming for Better SNR
Radio Frame Duration	10 ms	
Subframe Duration	1 ms	
Modulation	π/2-BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	π/2-BPSK, QPSK, 16-QAM, 64-QAM
Access	Downlink: CP-OFDM, Uplink: CP-OFDM, DFT-s-OFDM	
Carrier Aggregation	16 Carriers Maximum	
Channel Coding	Polar, LDPC Codes	

require simultaneous and synchronized mixed-domain (power, RF, analog and digital) measurements and signal generation. Initial 5G user equipment (UE) and customer premise equipment alone are capable of operating in all 4G bands, new 5G sub-6 GHz bands (FR1) and new 5G mmWave bands (FR2), which in the U.S. can include frequencies beyond 50 GHz (see ***Table 1***). These are generally composed of highly integrated and tightly assembled digital, RF, analog and power devices, for which design and operation are dictated by standards that are prone to change over the next several years.

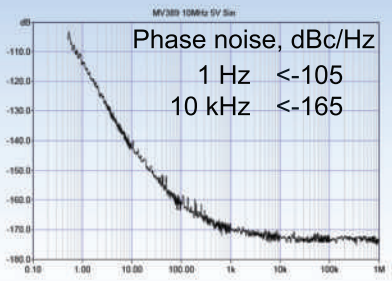
5G, as well as mmWave Wi-Fi (802.11ad), drive test complexity with other features such as multi-input multi-output (MIMO), beamforming and carrier aggregation (CA) that result in antenna systems capable of generating nearly infinite numbers of test cases and combinations of frequency bands (600+ carrier-aggregated combinations with 3GPP release 15).[2] This poses challenges for R&D characterization, quality and verification testing where there is little room for lengthy and complex measurements in an industry that is continuously driving down the bottom line in the face of rising competition. To prevent negative reception of early 5G products and services, the telecom industry and UE device manufacturers must also be aware of the market's low threshold for device failures, which underscores the need for rigorous testing and characterization.

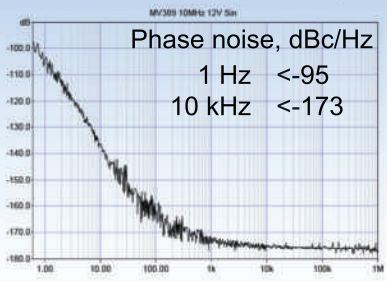
Ultra-Low Phase Noise OCXOs 10 and 100 MHz

MV389 10 MHz

Low Phase Noise Miniature OCXO with Low G-sensitivity

- √ Allan Deviation <5E-12 per sec.
- √ low G-sensitivity <6E-10/G (typical), options up to <3E-10/G
- √ package 25.8x25.8x12.7 mm





MV317 100 MHz

Miniature High Frequency Precision Low Phase Noise OCXO

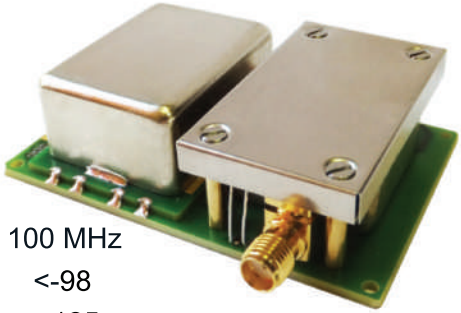
- √ low G-sensitivity <1E-9/G (typical), options up to <2E-10/G
- √ package 25x25x10.3 mm

Phase noise (typical), dBc/Hz, for	100 MHz
10 Hz	-102
100 Hz	-135
1 kHz	-164
10 kHz	-185
100 kHz	-190

MV359 10 and 100 MHz

Ultra Low Noise Dual Frequency OCXO

- √ Allan Deviation 5E-13 per sec.
- √ temperature stability ±1E-9
- √ package 67x44x18 mm



Phase noise, dBc/Hz, for	10 MHz	100 MHz
1 Hz	<-120	<-98
10 Hz	<-145	<-125
100 Hz	<-160	<-135
1 kHz	<-165	<-160
10 kHz	<-170	<-175
100 kHz	<-170	<-180

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WI-FI (802.11AD, 802.11AX) AND 5G CHALLENGES

The latest high throughput and high complexity SoCs/SiPs employ various styles of built-in-self test and test sequence automation to aid with chip-level testing and manufacturer verification. In some cases, these tests are performed rapidly, with some occurring within hundreds of microseconds. For RF test equipment to keep pace, equipment settling times must match or exceed these windows. Multi-domain testing, as well as direct circuit testing and over-the-air (OTA) testing must be done simultaneously with synchronized test equipment. For example, cellular handsets that have Wi-Fi, Bluetooth, 3G/4G/5G FR1 cellular and near field communications modules may require both OTA and direct circuit probing to test intersystem interference, which is compounded by new CA technologies where several cellular bands may be simultaneously used.

Wide dynamic range and frequency range OTA testing is also essential for characterizing and verifying MIMO/beamforming antenna systems. In the cases where each antenna element must be inspected, high dynamic range is necessary to determine the performance of each element, especially when some elements may exhibit much higher signal power levels than their defective neighbors. Discovering defective elements may be impossible without direct testing of each antenna element. For upcoming 64×64 MIMO 5G base station antenna systems, this testing may be impractical due to the time required, the cost and the setup complexity. To test large numbers of systems, test repeatability and optimization are crucial for 5G UE and base stations to be both economical and perform reliably in the field.

NEW ERA FOR PRODUCTION TESTING

Until recently, the mmWave arena has been dominated by the government and military for radar and satellite communications with a small amount of commercial backhaul products. MmWave products have historically been high cost and low volume where hand testing with traditional bench equipment was acceptable (see ***Figure 2a***). The high volume and low cost consumer market traditionally remained below 6 GHz. ATE systems evolved in the sub 6 GHz range to meet the fast, low cost test needs of consumer products. Now volume production is reaching into mmWaves and extending the need for fast low cost testing that maintains accuracy in frequencies where high accuracy has previously been impractical.

Production ATE systems also generally offer much more granular control over the operation of the

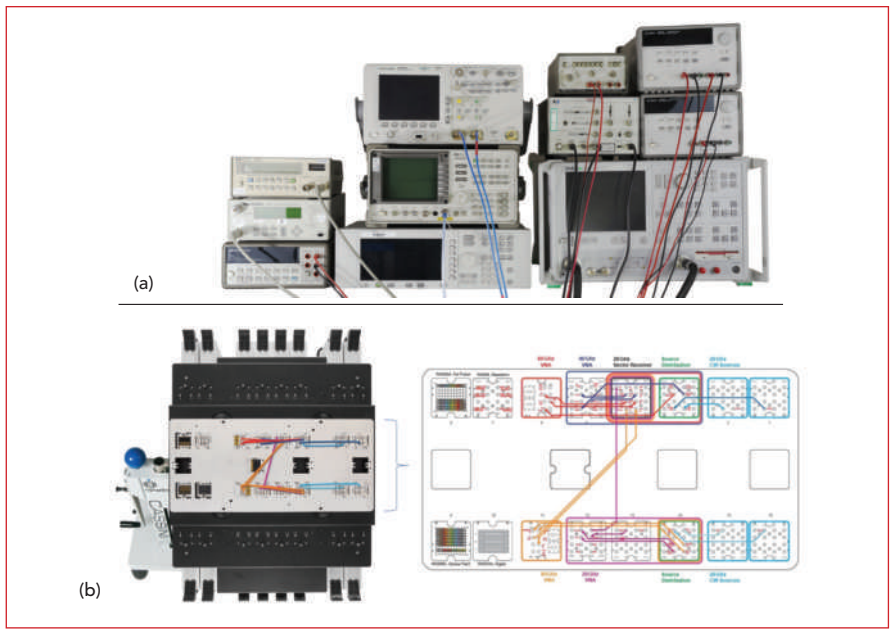

Fig. 2 Legacy bench-top (a) and modular production (b) test systems.

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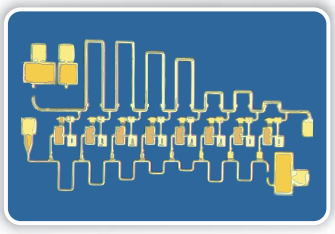
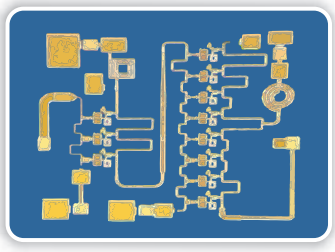
New Broadband GaAs MMIC offerings from AMCOM!

AMCOM's AM06013033WM-XX-R is a broadband GaAs MMIC which operates between 6 and 13 GHz with 28 dB gain and 33 dBm output power. This MMIC is available in both bare die form (AM06013033WM-00-R) and packaged form (AM06013033WM-EM-R).The EM package is a ceramic package with a flange and straight RF and DC leads for drop-in assembly. The MMIC input and output are internally matched to 50 Ohms.



AMCOM's AM00020026WM-00-R is a broadband GaAs MMIC Distributed Power Amplifier die which operates between DC and 20 GHz. This amplifier has 13.5 dB gain, and 26 dBm output power. The chip input and output are internally matched to 50 Ohms.



AMCOM's AM02018026WM-00-R is a broadband GaAs MMIC Distributed Power Amplifier die which operates between 2 and 18 GHz. This amplifier has 23.5 dB gain, and 26 dBm output power. The chip input and output are internally matched to 50 Ohms.

GaAs MMIC PAs

Model	Freq(GHz)	Gain(dB)	P1dB(dBm)	Psat(dBm)	Eff(%)	Vd(V)
AM003536WM-XX-R	0.01-3.5	23	35	36	20	20
AM002535MM-XX-R	0.03-2.5	24	34	35	25	20
AM012535MM-XX-R	0.03-2.5	20	33	33.5	20	20
AM009023WM-XX-R	0.05-9	21	21	23	20	12
AM008030WM-XX-R	0.05-10	18	30	31	20	12
AM012020WM-XX-R	0.1-2	30	16	17	8	8
AM011037WM-XX-R	0.2-1.0	31	37	37.5	40	8
AM103026MM-XX-R	0.9-3.2	22	25	26	10	14
AM132740MM-XX-R	1.3-2.7	26	38	39	30	14
AM142540MM-XX-R	1.4-1.8	25	39	40	35	14
AM153040WM-XX-R	1.4-3.4	18	37	38	30	12
AM143440WM-XX-R	1.5-1.8	20.5	38.5	39	35	12
AM143438WM-XX-R	1.5-1.8	20.5	37.5	38	30	12
AM153540WM-XX-R	1.5-3.5	18	39	39.5	35	14
AM183030WM-XX-R	1.6-3.3	30.5	30.5	31.5	20	8
AM183031WM-XX-R	1.6-3.3	31.5	31.5	32.5	25	8

GaN MMIC PAs

Model	Freq(GHz)	Gain(db)	Psat(dBm)	Eff(%)	Vd(V)
AM00010037WN-00-R	DC-10	13	37	25	28
AM00010037WN-SN-R	DC-10	13	37	23	28
AM003042WN-00-R	0.05-3	24	42	35	40
AM003042WN-XX-R	0.05-3	23	42	33	40
AM206041WN-00-R	1.8-6.5	32	42	27	28
AM206041WN-SN-R	1.8-6.5	30	41	23	28
AM408041WN-00-R	3.75-8.25	33	42	27	28
AM408041WN-SN-R	3.75-8.25	31	41	23	28
AM07512041WN-00-R	7.75-12.25	28	42	27	28
AM07512041WN-SN-R	7.75-12.25	27	41	22	28
AM08012041WN-00-R	7.5-12	22	42	20	28
AM08012041WN-SN-R	7.5-12	21	41	20	28

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test equipment RF components, which only some bench-top units offer; and, the ones that do generally require custom setups. Given the stringent requirements of mmWave testing, it is conceivable to use approaches that have largely been ignored or undiscovered by mainstream test and measurement device manufacturers who have mostly focused on either large format all-in-one bench-top instruments or highly integrated and limited field portable test units.

As a result, there is a growing number of test equipment manufacturers building modular test equipment platforms designed with components that can be configured in a variety of ways to meet unique test needs (see ***Figure 2b***). These are focused on sub-6 GHz technology to serve R&D, specialized and production test scenarios with low cost and configurability requirements. The general purpose modular test units often require customized setups and programming to build viable platforms and generally do not offer the same level of performance and reliability as traditional bench-top units.

MMWAVE MODULAR ATE FEATURES

There are many frequency dependent phenomena associated with RF testing, some of which become major test system design challenges at mmWave frequencies. Test systems that are not designed with these in mind may be much less accurate and may even yield misleading or inconsistent results at frequencies above several gigahertz. Some of these phenomena drive mechanical/electrical (physical) test system design, while others influence test system architectures.

Interconnects, Probes, Match and Loss

At mmWave frequencies the conductivity of metals decreases as a function of frequency and the dielectric loss of insulators increases. Moreover, the much smaller wavelengths of mmWave signals interact with geometric features that exhibit minimal impact at lower frequencies. For example, a quarter-wavelength in air at 1 GHz is 75 mm, while at 80 GHz it is less than 1 mm; hence, interconnects that work adequately at lower frequencies do not scale to mmWave.

The result of these phenomena is greater insertion loss through transmission lines, greater attenuation in connectors, poorer match between interconnects and less tolerance to misalignment in the connections between transmission lines. This is why, in many cases, waveguide interconnects are necessary for mmWave applications, as losses and mismatches are considerably less in waveguide compared to coaxial transmission media. It is also important to minimize transmission line lengths by placing the ATE system as close to the device under test (DUT) as possible.

For the final few centimeters at mmWave frequencies microstrip/stripline transmission lines are often used with IC load boards. Waveguide, although superior electrically, can suffer from its own mechanical issues. It is rigid and has physically large interconnects. For example, the UG387/u flange typically used between 60 and 90 GHz has a diameter of almost 20 mm. Some devices can have up to 24 mmWave ports on a single component. Physically routing waveguide through the interface layer for 24 ports can represent an impossible task. Several manufacturers are cre-

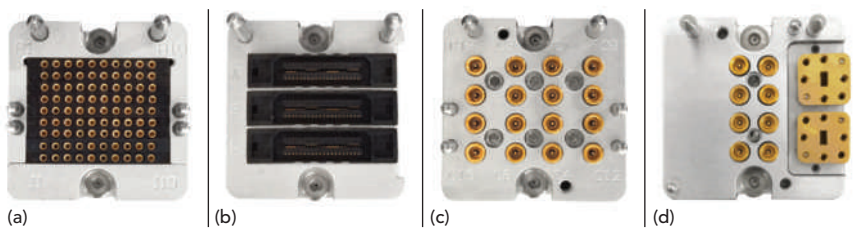

Fig. 3 **Modular interfaces for mixed-domain power (a), digital (b), RF/analog (c) and mmWave (d).**

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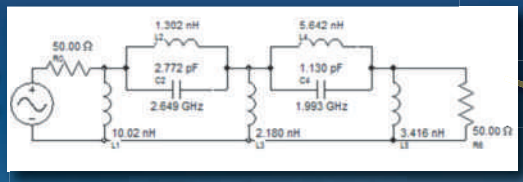

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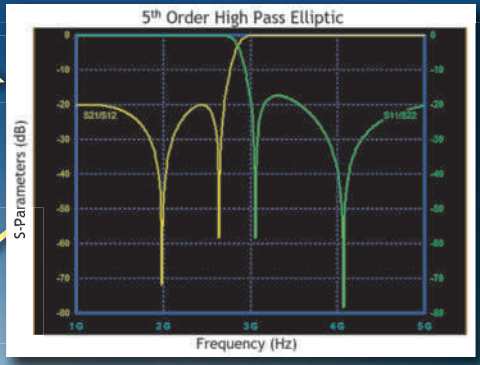

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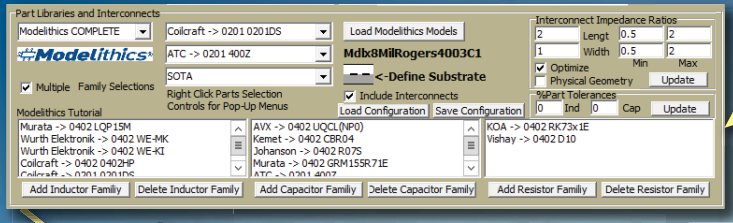

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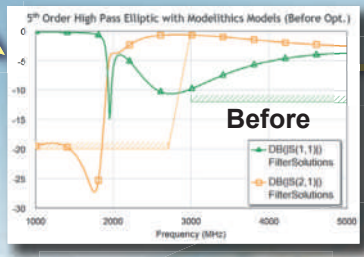

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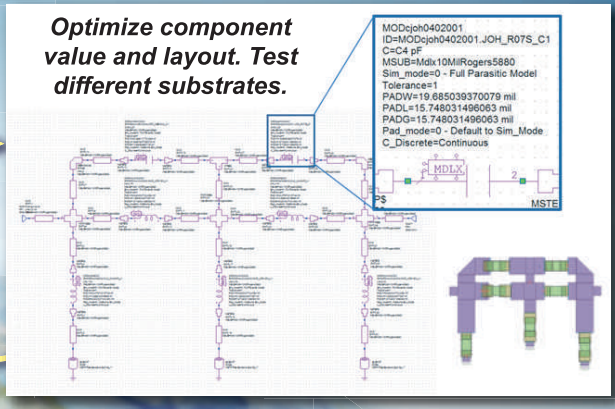

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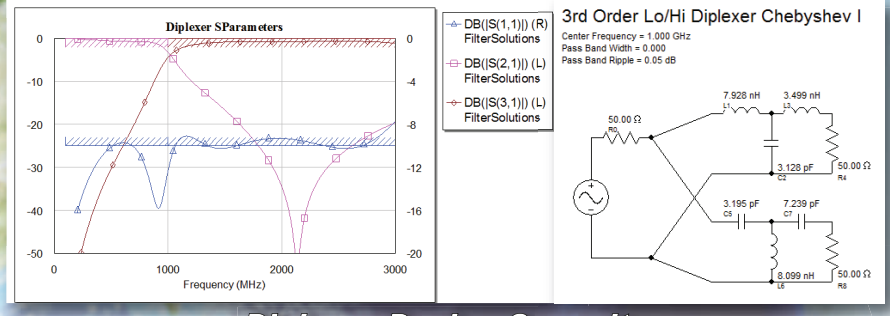

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ating custom small interface flanges to address the flange issue. Proprietary waveguide technology that is both thin-walled and conformable has also been developed that minimizes the routing challenges without sacrificing high frequency performance characteristics. Figure 2b illustrates a modular test system with a configurable mixed signal interface. ***Figure 3*** is a close-up view of the mixed signal interconnects.

Vector-Based Measurements for Accurate mmWave Calibration

The frequency dependent degradation in performance that emerges at higher frequencies also impacts test system architecture and calibration. Testing accuracy depends on ensuring that the calibration plane is extended to the DUT plane, i.e. the behavior of the interconnects and associated parasitics are part of the test environment.[3,4]

In production there is always interface hardware between the test instrument and the DUT. This may be as simple as a cable or waveguide or might include multiple active components. For accurate measurements, the hardware must be calibrated. At lower frequencies, it is often acceptable to calibrate only to the instrument interface. At mmWave frequencies, however, it is extremely difficult to achieve acceptable test results without calibration to the DUT. This requires on-wafer or in-socket standards, typically open/short/load and a vector measurement system to effectively de-embed test results from the testing environment.

In addition to individual instrument calibration, mmWave ATE must also include vector calibration of the interface layer and the ability to combine the calibration layers into a cohesive overall calibration. Some mmWave ATE systems provide up to three vector calibration layers. The instrument, the interface, and the probe card (or device interface board) have their own calibrations, which are coordinated by the system controller.

Modular Instruments

Fixturing is a major design consideration for most ATE systems and is much more critical at mmWave frequencies. In many cases, the fixture and interface cards that bridge the test equipment to the device must be custom designed for each device. This limits reusability and creates reliability and test issues by requiring a new interface card design for every DUT. Modular device interface cards and standardized modular fixturing designed with mmWave performance considerations provide better reusability of test system hardware as well as greater reliability and repeatability for high sensitivity measurements (see ***Figure 4***). Moreover, calibration is easier, as a modular device interface can be included in calibration procedures without additional custom calibration. Hence, additional vector error calibration can be performed for both the fixture layer and device interface board layer enabling system-wide vector error calibration down to the device plane.

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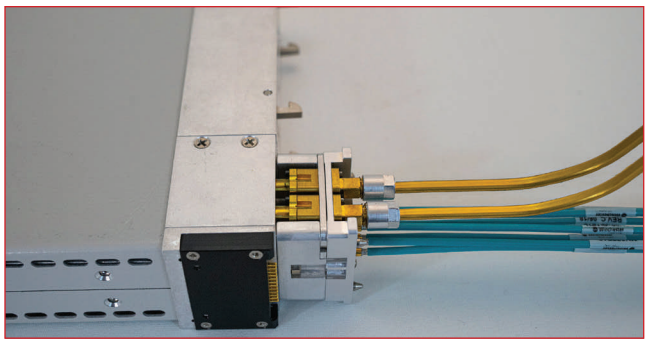

Fig. 4 Modular blind-mate interface and fixture.

Other important considerations at mmWave frequencies are control capability, software support and test system optimization features. With rack and stack systems made from bench-top instruments, there may be very limited flexibility and programmability available to the user and interfacing with the ATE manufacturer may be necessary for even relatively minor changes. In other cases, completely generic hardware and software configurations leave the user with the burden of programming an ATE system test routine from scratch. A more modern and user-friendly approach is to provide an extensively featured graphical user interface that can allow the user flexible control while minimizing design complexity and the potential for user error. It is also beneficial for these systems to allow for custom programming to enable additional features and customization to meet the latest standards and conformance testing.

CONCLUSION

mmWave testing is moving from the laboratory to mainstream production. The test industry is now facing challenges posed by both the production environment and highly sensitive and stringent mmWave testing requirements. Modular ATE is likely the only test system solution that can economically deliver production-grade mmWave and mixed-domain testing. 5G, as it goes up in frequency, is one of the first big market sectors entering this space. It forces the ATE industry to face the test challenges in making 5G a reality; much of the ATE industry will be working in the greater than 26 GHz frequency space for the first time.■

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INVITED PAPER

Moving Beyond S-Parameter Files: Advanced Scalable and 3D EM Models for Passive Devices

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Modelithics Inc.[2], Tampa, Fla.

S-parameter data files remain the most commonly available "model" for representing passive devices in the microwave industry. Physically motivated equivalent circuit models can be set up to scale accurately with part value, substrate properties and other parameters, such as solder pad dimensions. Still, such circuit models cannot generally account for electromagnetic (EM) coupling interactions between microwave components and between components and their surrounding shielding and interconnect environment. Consequently, full-wave EM analysis has become a crucial step at RF to account for such interactions. New technology, recently available in some EM simulators, allows for encrypting geometry and material details to protect vendor manufacturing IP and enable 3D EM models to be shared with a wider design community. These advances help designers reduce design risk and re-work and improve time-to-market for today's increasingly compact and complex product form factors.

For decades, measured S-parameter data files have been the most commonly available "model" for representing passive devices of all kinds in the microwave industry. S-parameter files, while useful, ubiquitous and very portable only represent the way a specific device behaves in the test fixture environment and the test conditions used for characterization. On the other hand, properly developed physically motivated equivalent circuit models can be set up to scale accurately with part value and substrate properties, as well as other parameters like solder pad dimensions.[1] This advance is a marked improvement that is used by many designers worldwide today. However, circuit simulation is not always sufficient in terms of pre-build risk management for microwave/mmWave designs that involve compact topologies and dense circuit implementations. Accordingly, full-wave 3D EM analysis has become a crucial step to account for possible EM coupling interactions between microwave components and between components and their surrounding shielding and interconnect environment. This unexpected coupling can result in performance degradation and, in turn, lead to costly and lengthened design cycles. Assembling the necessary geometry to complete full-wave analysis that includes representations of passive elements, such as packaged and surface-mount devices as well as packages and connectors, requires close collaboration between vendors and customers of vendors and model providers. In many cases, sharing of manufacturing geometry and material details is required. New

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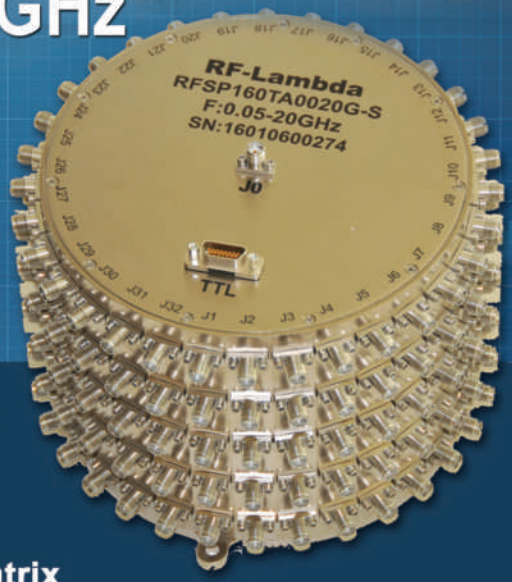

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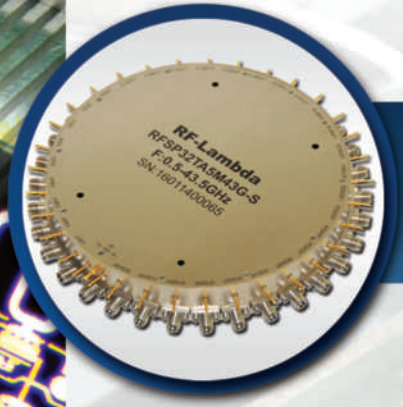

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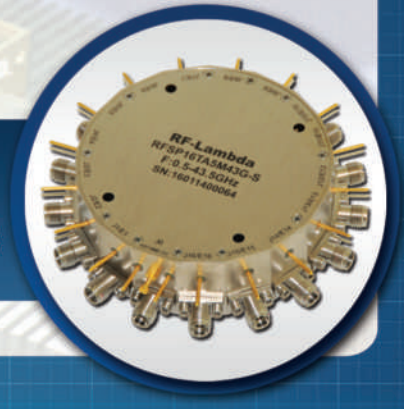

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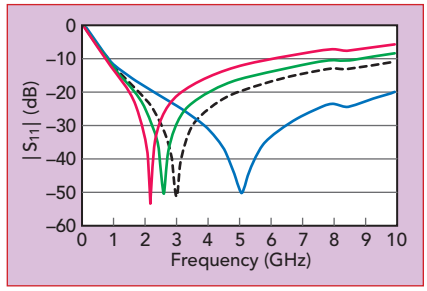
technology, recently available in some simulators like ANSYS HFSS, makes it possible to encrypt manufacturing details to better enable 3D EM models to be shared with a wider design community.[2,3]

S-PARAMETER FILES

S-parameter files are simply measurements of a device that are very commonly used as device "models" in high-frequency design simulations. S-parameter files are good representations of a device for simulation, provided the S-parameter measurement conditions match the design conditions. The properties of the test fixture and measurement conditions used to measure the S-parameters, such as substrate type, PCB pad dimensions and bias condition should be the same in the design to achieve the most accurate simulation. It is important to note that as frequency increases, parasitic effects become more and more significant. Thus, differences in design properties in comparison to measurement properties can lead to a less accurate simulation. ***Figure 1*** illustrates a capacitor's variation in S-parameter response solely due to the use of different substrates (part series, capacitance and pad dimensions are the same). While it is common for passive component suppliers to provide S-parameters for their devices, at best these represent only one possible mounting/usage scenario. In addition, measurements are typically performed in a standard coaxial-connectorized test fixture in which an air gap under the device may be present.

To evaluate different part values, pad arrangements or substrates in a design using S-parameter files as simulation models, different measurement files need to be used to represent each part value. As seen in Figure 1, the downloaded S-parameter file that represents device performance on a 20-mil substrate would less accurately predict the design response if a 10-mil substrate was used, especially for an application above 1 GHz. Another limitation to consider when using S-parameter files is that the simulation is only accurate within the measurement frequency range. Outside of the measurement frequency, an S-parameter file is generally invalid and may extrapolate to non-physical values depending on the simulator setup.



▲ **Fig. 1 Simulated $|S_{11}|$ of an AVX 0402xU 5.6 pF capacitor mounted on three substrates vs. AVX S2P data. Blue: 10 mil Rogers 4350B substrate; Green: 30 mil Rogers 4350B; Red: 60 mil Rogers 4003C. Dashed: AVX data, measured on 20 mil Rogers 4350B.**

S-PARAMETER FILE-BASED MODELS

A collection of S-parameter files can be packaged together into a single "S-parameter model" for added convenience. An S-parameter model represents multiple configuration options for a device or component series. For example, it can represent multiple part values of a passive component series or simulate different bias conditions for an active device, depending on the S-parameter files included. The model includes a parameter selection menu to select the properties of the S-parameter file that should be used for the simulation, all while keeping the same model element in the schematic.

S-parameter models can also be set up to work with tuning and optimization. Two S-parameter model examples are shown in ***Figure 2***. In Figure 2a, an S-parameter model for the Mini-Circuits EP2K+ splitter illustrates how models can be simulated on two different substrates and in Figure 2b the Gowanda C225FL conical inductor series model shows how multiple part values can be simulated without replacing the model.

Data-based or equivalent circuit models typically available often lack detailed information concerning how the measurements and/or models were developed, as well as usage information. We believe that such information is very important to designers. A model datasheet represents one way that this information can be presented.

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Such datasheets contain critical information concerning the model, including validation measurements along with details regarding reference planes, application/usage and more. Modelithics provides this type of detailed information for all models distributed and available for use by various circuit and system designers. The information varies based on the type of device or component represented by the datasheet; for example, different information is included in the model datasheets for the scalable equivalent circuit and 3D-geometry-based EM models discussed next.

SCALABLE EQUIVALENT CIRCUIT "GLOBAL" MODELS

A scalable equivalent circuit model represents a much more efficient and powerful type of component simulation model. These models are designed and validated using S-parameter data, and oftentimes other measurements, to build a comprehensive model for a device series that scales continuously over part value ranges and other design parameters. Modelithics uses the term "Microwave Global Models™" to represent its unique approach to scalable equivalent circuit models for microwave devices. In addition to part value, these scalable global models are set up to scale with pad dimensions, substrate properties (e.g., height and dielectric constant), and if applicable, temperature, bias and other properties. The unique and advanced scaling capabilities give them numerous advantages over previously discussed file-based models.

Compared to file-based S-parameter models that represent only a set number of simulation conditions, scalable equivalent circuit models represent an extremely broad range of possibilities in terms of design properties. These models accurately simulate broadband device and parasitic behavior for many embedding configurations. In general, since the models are based on a physically meaningful equivalent

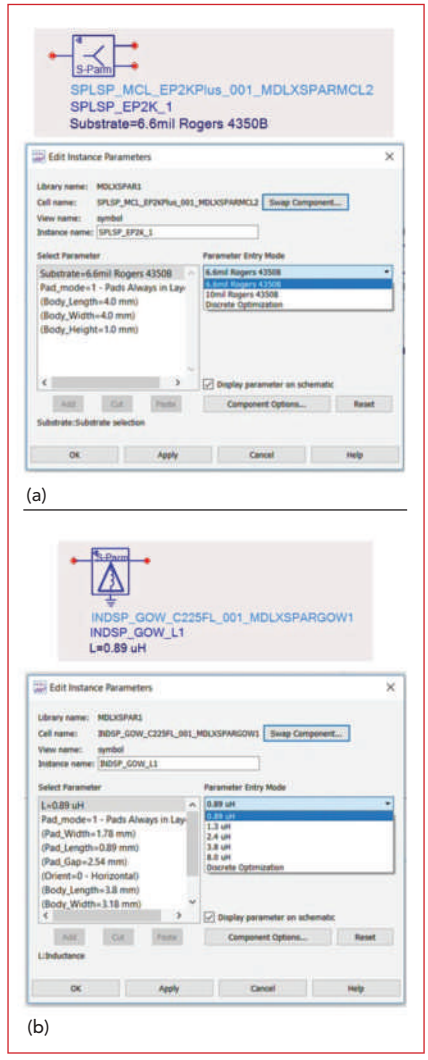

Fig. 2 S-parameter models with dropdown menus to select the substrate (a) or part value (b).

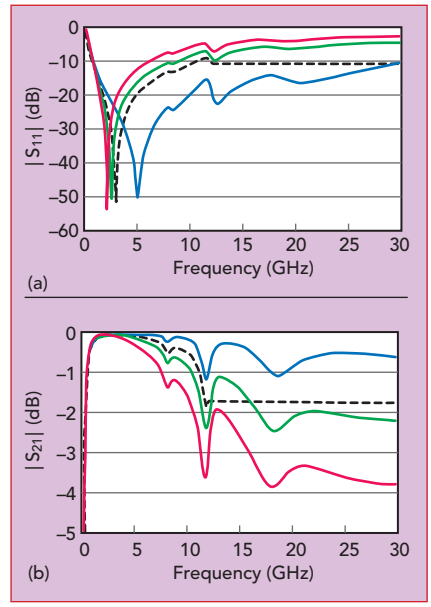

Fig. 3 $|S_{11}|$ (a) and $|S_{21}|$ (b) from a scalable equivalent circuit model for an AVX 0402xU 5.6 pF capacitor on three different substrates vs. AVX S2P data. Blue: 10 mil Rogers 4350B; Green: 30 mil Rogers 4350B; Red: 60 mil Rogers 4003C; Dashed: AVX data, measured on 20 mil Rogers 4350B.

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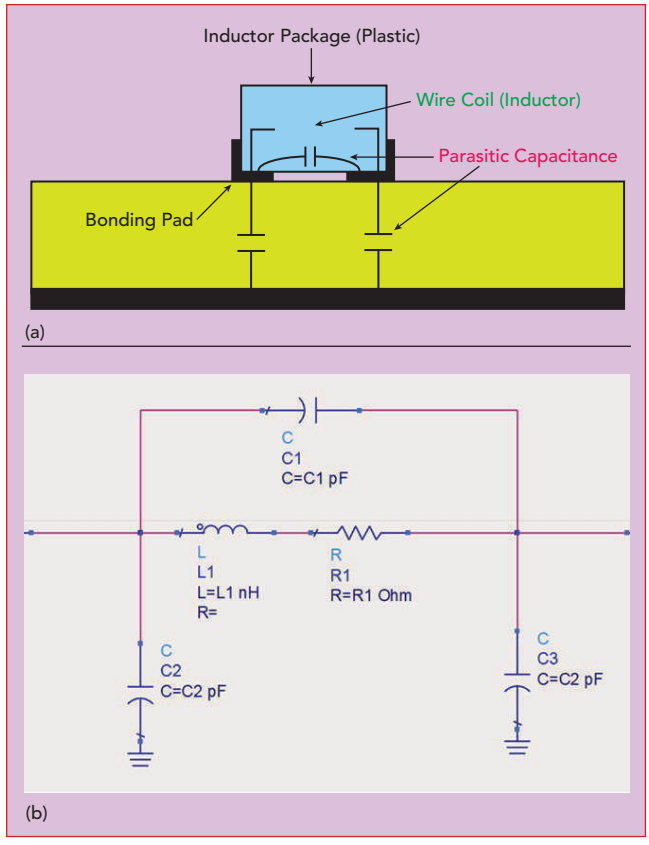
circuit topology, they remain physically valid when extrapolating and interpolating parameters. That is, equivalent circuit models will exhibit physically meaningful and reasonably correct behavior even beyond the measurement frequency range. ***Figure 3*** corresponds to Figure 1, but with the frequency sweep extended to 30 GHz. The simulated S-parameters from the scalable equivalent circuit model reveal a continuation of physical behavior on each substrate for the full frequency sweep (and beyond). The S-parameter file, which has a maximum frequency of 10 GHz, extrapolates as a straight line and is not valid above 10 GHz.



▲ Fig. 4 **Surface-mount inductor parasitics (a) and first-order, physically motivated equivalent circuit model (b).**

To illustrate the concept of a physically motivated equivalent circuit model, ***Figure 4*** depicts a surface-mount inductor mounted on a microstrip substrate. Also shown is a simple equivalent circuit that can be fit to the measured S-parameters of the part up to and including the first self-resonance. Scalable Microwave Global models can be likened to multi-faceted extensions of this approach in which additional elements are added to the circuit to represent higher-frequency and higher-order-resonant behavior. Complex equation sets are incorporated to add the scalability features discussed. In addition, the resistive loss is typically fit to effective-series-resistance measurements made with separate equipment, such as an impedance analyzer or resonant line.

Compatibility with statistical analysis evaluations is another advantage associated with scalable equivalent circuit models. Component tolerance values can be set, making it possible to perform a full design yield analysis.[4] If the yield is unacceptable, one can simply test different part tolerances until the most efficient and acceptable design is achieved. With suitably arranged scalable models, this design "testing" is executed quickly at the simulation stage, thereby saving time and cost incurred with extra board runs and redesigns.

3D EM MODELS

Typically, for lower-frequency designs in which surface-mount passive components and discrete or MMIC active devices are not packed into a compact layout, it is sufficient to employ circuit simulation for equivalent circuit models combined with planar EM simulation of the layout. Further facilitating these types of simulations is the availability of useful simulation features in the equivalent circuit models, such as advanced pad treatment that allows for the de-embedding of solder pads. Thanks to such features, the result is greater ease of use and accuracy when executing EM co-simulations.

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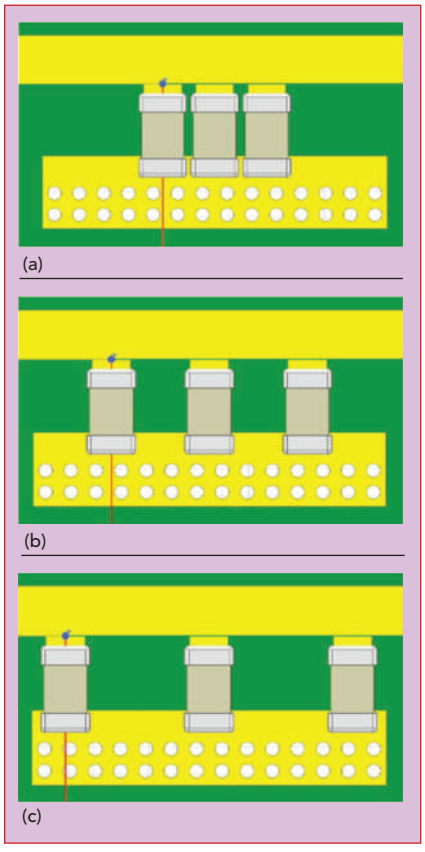
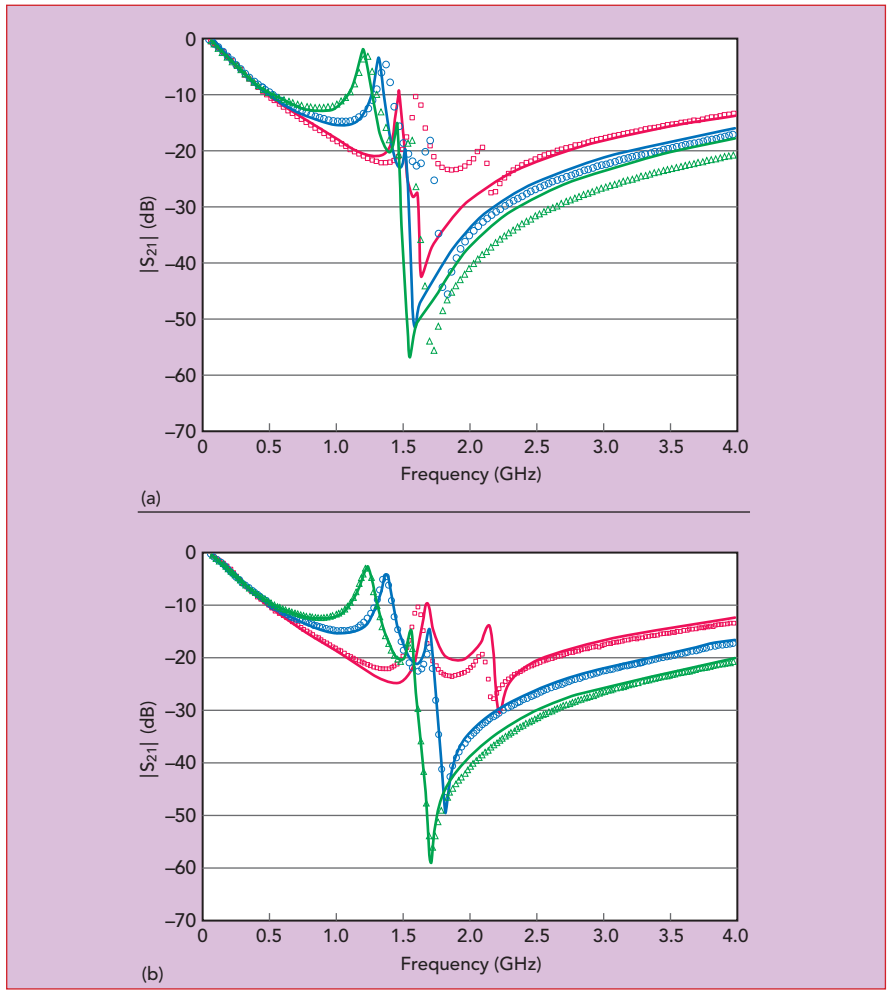
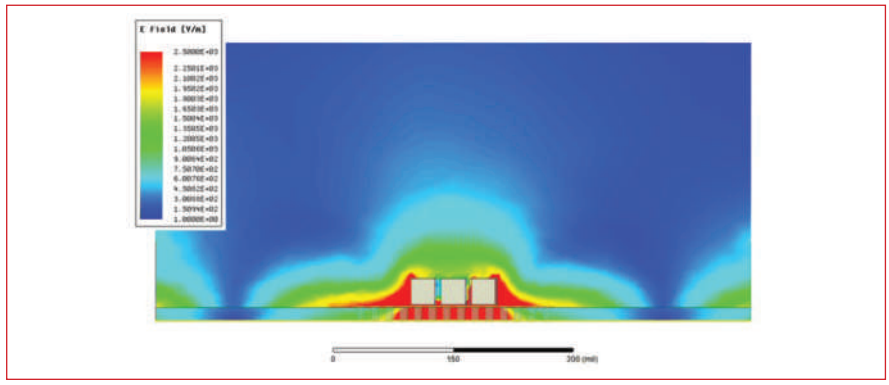


▲ Fig. 5 **Three capacitors in a shunt configuration on a 50 Ω line: 10 mil spacing (a), 42 mil spacing (b) and 74 mil spacing (c) between them.**



▲ Fig. 6 **Circuit (a) and 3D EM (b) simulations vs. measured data for the capacitor arrays of Figure 5. Red: 10 mils; Blue: 42 mils; Green: 74 mils.**



▲ Fig. 7 **E-field visualization of the closest spacing shunt capacitors showing component-to-component coupling.**

However, once components are placed in close proximity to each other and design frequencies are extended higher, this approach no longer captures all of the interactions present after the design is fabricated. This necessitates the use of 3D EM simulation to capture the coupling between components and their environment. Compounding this, the source of this coupling can be difficult to pinpoint without using 3D EM tools to visualize fields, whether it is component-to-component coupling or components coupling to adjacent lines or shielding. Fortunately, full-wave 3D EM analysis is a proven method with years of development leading to excellent prediction of measurement results, as illustrated in ***Figures 5, 6*** and ***7***. In Figure 5, three capacitors are shown placed in a shunt configuration on a 50-ohm line. The capacitor model is a 12-pF Johanson R14S in an 0603 case size (CAP-JOH-0603-101). The substrate is 16-mil Rogers 4003C. Three configurations are illustrated with 10, 42 and 74 mil spacings between capacitors.

3D SIMULATION: COMMON ISSUES

Obtaining Device Information

One of the main problems associated with using 3D EM simulations in a design flow lies in obtaining the necessary physical and material properties to enable analysis of the complete circuit. This information is typically proprietary manufacturer intellectual property. Even with all the physical parameters and material properties available to the designer, initial 3D model results may not be good when compared to measured data. Therefore, tuning of the model is often required. Model-to-measurement discrepancies are likely due to fabrication tolerances in the component or layout or un-

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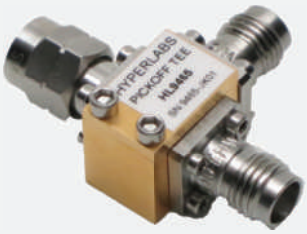

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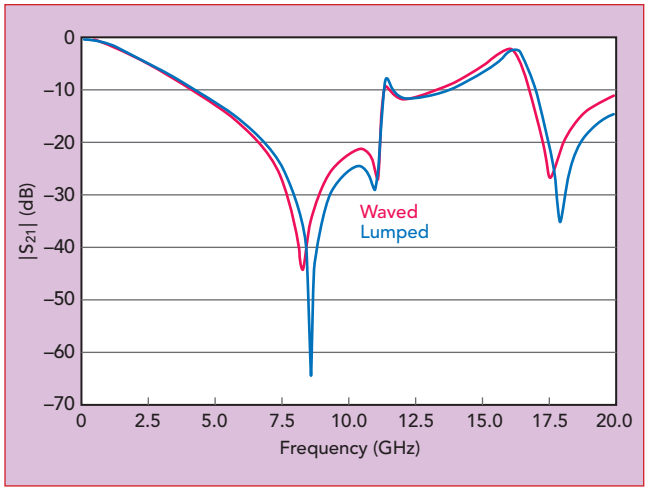

Fig. 8 3D simulation of a 10 nH Coilcraft IND-CLC-0603-101 inductor mounted on 10 mil Rogers 5880, comparing lumped and wave ports.

certainty in material properties. For this reason, measurement validation of EM models and EM simulation expertise is crucial for the designer. Using a library of validated 3D component models, such as Modelithics' COMPLETE+3D Library, is one way to mitigate some of the issues mentioned. These sorts of libraries are currently limited in terms of total model count but are continuing to grow.

Port Selection and Setup

Assuming the 3D component models are accurate, designers still need to integrate their layouts into the 3D environment and find the most appropriate way to excite the circuit with ports. While many port types exist in HFSS, lumped or wave ports generally provide similar results and are most appropriate for exciting a PCB-based 3D structure (see ***Figure 8***). Different port setups have their own advantages, depending on the layout itself and whether the ability to shift reference planes is needed. If the reference planes of the simulation are internal to the model and do not need to be shifted, lumped ports are simple and quick to set up. If the ports are external to the model or if the reference planes need to shift, wave ports may be a more appropriate choice (see ***Figure 9***).

Solution Setup

HFSS offers guidance in their help documentation on selecting an appropriate solution frequency. For example, in a resonant structure, the solution frequency should be set to the design frequency for that structure. The reason to choose the resonant frequency as the solution frequency is that the adaptive meshing process used by HFSS analyzes the mesh for large field differences between adjacent mesh elements. If the fields or transmission

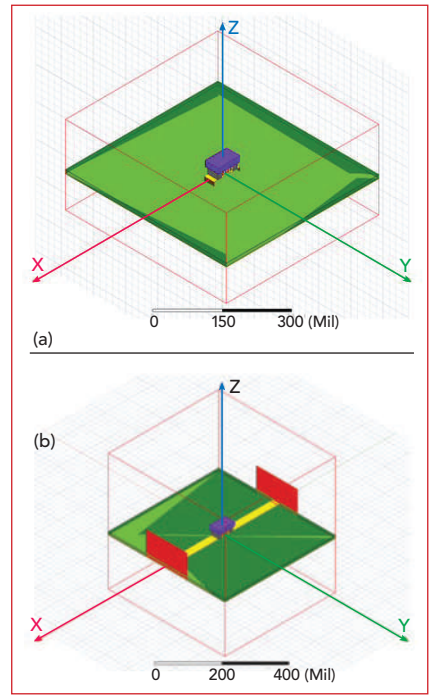

Fig. 9 Simulation geometries of the 10 nH Coilcraft IND-CLC-0603-101 inductor mounted on 10 mil Rogers 5880 using lumped (a) and wave (b) ports.

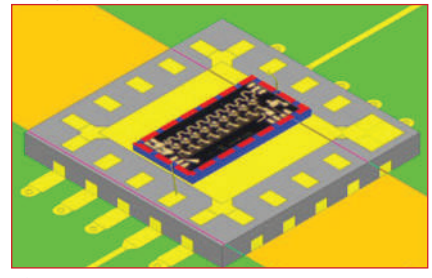

Fig. 10 MMIC amplifier mounted in a 4 mm QFN package used to illustrate 3D co-simulation.

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for a structure are very low at the chosen solution frequency, there may not be much difference between adjacent elements and the mesh may converge prematurely. At a resonant frequency, the fields are strongest, so the adaptive mesh process is likely to converge on an accurate mesh for that structure.

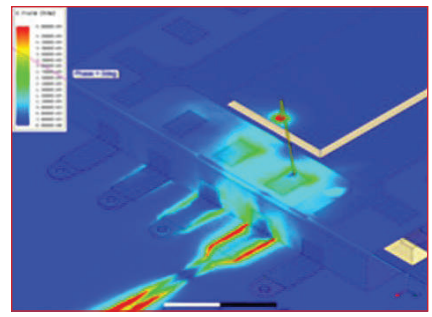
For broadband structures or structures in which the resonant frequencies are unknown, selecting the solution frequency is less straightforward. The user could hypothetically choose any frequency in the band of interest. The approximate frequency of first resonance could be a good initial selection if this value is known. The user should investigate the effect of selecting different solution frequencies on the results, as well as the maximum number of passes and maximum delta, to converge on an appropriate mesh and ensure a good result.

Imported Geometry Issues

If the designer is bringing the layout or a specific component model into the HFSS 3D environment from another tool, initial difficulties can arise when integrating these elements due to geometry issues. For example, non-manifold geometry errors that manifest once meshing is attempted are commonly encountered with imported computer-aided design (CAD) files. Other examples of commonly encountered errors are non-manifold vertices and edges. While the "Heal" function in HFSS may be able to resolve some of these issues, re-drawing the geometry within HFSS may still be required.

Tolerances in Model Geometry and Material Properties

Manufacturing tolerances on physical dimensions or material properties can cause discrepancies in simulation results, especially when comparing against measurement data. If a fabricated version of the structure is available, a detailed inspection of the actual dimensions can be useful to help identify possible causes for the differences between simulation and measurement. Unfortunately, material property variation can be harder to isolate and nearly impossible to identify by physical inspection. In such a case, the 3D model can be used to study the effect of material property variation. Tolerances can be added to the 3D model and a parametric analysis (or analytical derivatives) can be executed to study changes in performance.



▲ Fig. 11 **E-field visualization of the package and bond wire on an alumina motherboard, showing coupling between the bond wire and the adjacent package pin.**

An example of combining 3D EM analysis with S-parameter file data for completing a simulation is illustrated in ***Figures 10*** and ***11***. Shown is a MMIC amplifier mounted in a 4-mm QFN package. Package, bond wires and alumina motherboard were simulated in HFSS with ports added to enable co-simulation. Measured S-parameters of MMIC amplifier were connected to the ports in EM simulation. 3D co-simulation of the structure was performed using both S-parameter data and 3D EM simulation data yielding good agreement with measurement, as shown in ***Figure 12***. Also shown for reference is non-packaged MMIC performance available from a measured S2P file.

CONCLUSION

When moving beyond traditional S-parameter file representations for passive components, designers are provided with many advantages and conveniences. A next step involves well-documented S-parameter file-based models. Such models feature part value pull-down menus, for example. A physically motivated and scalable equivalent circuit model can provide for validity under extrapolation, as well as interpolation

Sourcing RF Passives That Meet Modern Performance Requirements

It is no surprise in the RF industry that there are many emerging applications that have sophisticated performance requirements for devices and components in the microwave and millimeter-wave frequencies. Moreover, the expectations of customers for these applications is also raising the bar for passives. To meet customer-driven device requirements, system suppliers are forced to meet modern specifications for passives that reach higher power levels, exhibit lower insertion loss, eliminate accessory components, and come it much more compact packages.

These challenges are the reason Exceed Microwave exists. As a business, Exceed employs some of the most skilled and experienced microwave passive designers who are dedicated to producing the highest quality custom components using innovative design techniques.

RF Passive Design Excellence with Exceed

Exceed is able to offer bleeding-edge passive performance by employing designers that are known to be among the best in the industry and with decades of full-wave EM simulation and design software experience and hundreds of full design/production cycles under their belts. This peerless expertise enables Exceed's design team to provide rapid turn-around designs, as the team requires less iterative manufacturing and minimal tuning of the finished products.

Exceed designers use their extensive simulation expertise, and even physical verification prototypes, to ensure that the proposed designs meet customer expectations and offer optimal performance. Exceed engineers are also skilled at selecting the ideal manufacturing services to produce the exact features and finishes needed for a given microwave passive design. In this way, Exceeds engineers aren't locked-in to high capital cost machine tools that would otherwise limit the material and techniques they could use to achieve an optimal design.

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Exceed's design expertise has manifested as several product series that benefit from innovative, and often proprietary, technologies and extreme engineering finesse. Exceed's product series' provide an insight into the capabilities of Exceed's designers. These products include waveguide passives, coaxial passives, microstrip filters, group delay/phase equalizers, combiners, adapters, and a wide range of other components, many of which are in stock.

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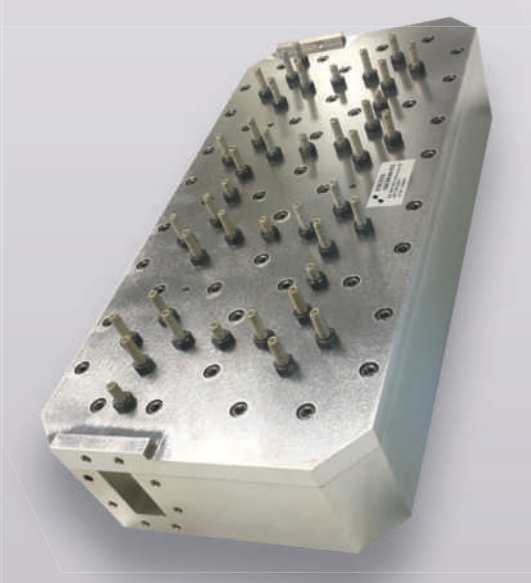
Comparison	Exceed WZ-Series	Traditional H-plane filter
Insertion Loss @V-band	0.5 dB	1.2 dB
Power Handling	>2X improvement (typ)	-
Bandwidth	Very Narrow <2%	Narrow <10%

WC Series Waveguide Filters can be as short as half the length of typical waveguide filters, and thus much lower weight. The WC-series are able to achieve very wide passband bandwidth with no frequency dispersion, enabling high rejection on both sides of the passband. These benefits result in a perfectly-tuned and compact filter that doesn't require additional filters to enhance out-of-band rejection.

Comparison	Exceed WC-Series	Traditional H-plane Filter
Bandwidth	Wide ~30%	Narrow <10%
Length	≤ 1/2 of traditional (typ)	-
High frequency rejection	Up to 2X Fc	Poor > cutoff frequency



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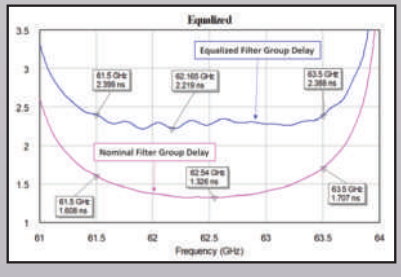

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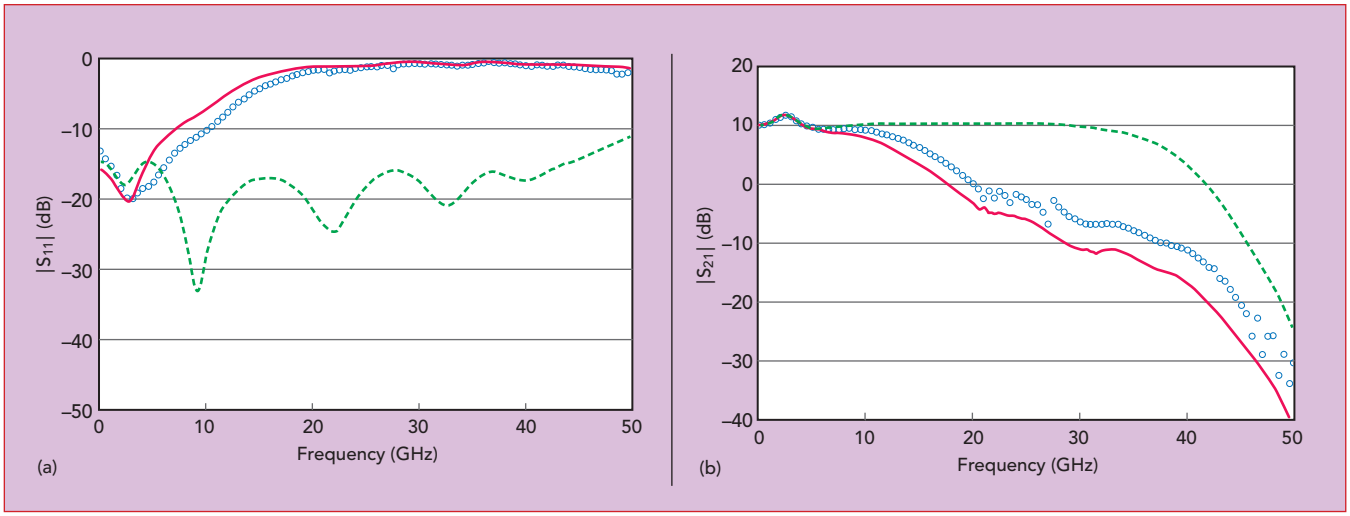

▲ Fig. 12 **3D co-simulation vs. measured performance of the MMIC amplifier mounted in an RJR 4 mm QFN package on an alumina motherboard and connected with bond wires: $|S_{11}|$ (a) and $|S_{21}|$ (b). Red: co-simulation; Blue: measurement; Green: measurement of the MMIC mounted on a carrier with no package or bond wire effects.**

between measured part values or test conditions. Such models can also enable a more accurate representation of loss and can enable tuning, optimization and tolerance analyses. 3D EM component models address coupling and interactions and can be used in the final stages of the design process to verify that EM interactions will not cause a failure when fabrication is complete. A well-balanced design flow takes advantage of the different strengths of circuit simulation scalable equivalent circuit models and EM analysis, provided the necessary circuit and 3D EM models are available and use S-parameter file-based models and S2P files when that is the best available representation.■

ACKNOWLEDGMENTS

We would like to thank Laura Levesque for her contributions. In addition, the very helpful technical collaborations with our electronic design automation (EDA) software partners in supporting Modelithics advancement and distribution of a wide range of passive model types is gratefully acknowledged. For this work, we thank Keysight Technologies and ANSYS Corporation for providing software and technical support.

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Innovation in Specialty Silicon Technology for 5G Front-End Modules

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The wireless data bandwidth needed to fulfill the promise of 5G imposes new performance requirements on the underlying specialty silicon technologies such as RF SOI and SiGe BiCMOS used in the front-ends of user equipment (UE), small cells and base stations. In this article, we review recent advancements in these platforms that support key 5G components like massive MIMO (mMIMO), the increased use of carrier aggregation, lower latency, beamforming and higher receive (Rx) sensitivity, all applicable to both the sub-6 GHz and mmWave spectrum.

Recently, Huawei's chairman compared the fifth generation (5G) wireless technology to "the new electricity" when combined with other emergent technologies such as artificial intelligence. This is a remarkably bold prediction, yet not without merit. 5G is expected to connect the world truly as never before, with massive machine-to-machine, ultra-low latency and Gbps mobile broadband. With a smart mix of macro cells, small cells and localized user-premises systems, 5G will provide high speed, ultra-low latency and reliable connectivity. Entirely new industries and business models will develop, ones we can only imagine today, such as augmented and virtual reality, autonomous driving and remote medical care, including surgery.

To monetize these opportunities, the race for 5G infrastructure deployment is well underway. China's largest mobile service providers are aggressively rolling out 5G to 40 large cities using carrier frequencies in the sub-6 GHz regime. In South Korea, KT and other operators have enabled 5G in the country's most populated areas. Verizon, AT&T and others are providing 5G service using a combination of traditional cellular and "mmWave" (really cm) wavelengths in selected U.S. cities. Deloitte estimated that 25 operators would launch 5G service in 2019, doubling to over 50 in 2020. Similarly, 20 handset vendors were expected to launch 5G ready handsets in 2019 and grow rapidly this year. The Global mobile Suppliers Association reported 78 suppliers had announced or released 208 5G devices

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through the end of January, including 62 phones. About 15 to 20 million handsets are expected to be 5G ready in 2020, increasing rapidly to 100 million in 2021. With a concurrent increase in RF content in 5G phones, the opportunity for the RF community is enormous, putting greater emphasis on system differentiation through IC design and semiconductor process innovation.

As a pure-play foundry focused on "more than Moore" technologies, such as specialty RF processes, Tower Semiconductor is enabling higher levels of performance for IC designers at top-tier front-end module (FEM) suppliers to support key 5G building blocks, such as mMIMO and carrier aggregation. In this article we provide an overview of recent advances in RF process technologies and design tools that underpin 5G base stations, small cells and UE.

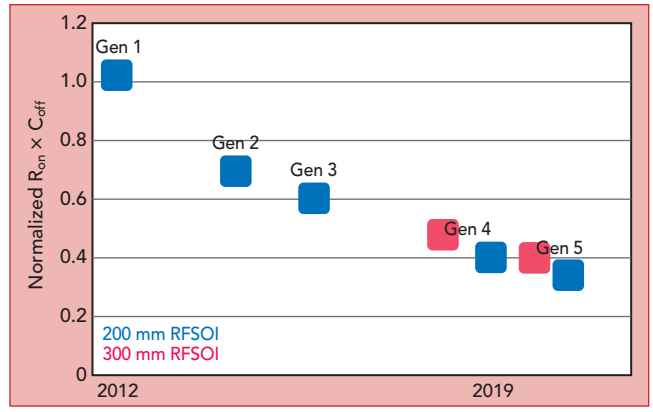

Fig. 1 RF SOI small-signal figure of merit, R_{on} x C_{off}, vs. process generation.

INNOVATION FOR 5G SUB-6 GHz RADIOS

Using the additional spectrum becoming available at S- and C-Bands is one way service providers are increasing capacity. In the U.S., initial commercial deployment has been approved in the 3.5 GHz band. While the sub-6 GHz spectrum is familiar territory for UE FEMs, the increased data rates defined by 5G create opportunities and challenges for silicon RF technology.

RF SOI continues to be a workhorse for sub-6 GHz RF switching, as the key small-signal switching figure of merit R_{on} x C_{off}—the product of device on-state resistance and off-state capacitance, independent of device width—has dropped by more than 2x from first-generation SOI technology (see ***Figure 1***). This improvement in small-signal performance translates directly to reduced power loss and better isolation, particularly for high throw-count switches, making it easier for FEM module suppliers to meet more stringent system requirements. It can also be leveraged to shrink the switch branches that typically dominate die area, reducing cost and saving FEM board space. 5G switch products that support mid-band frequencies are especially sensitive to C_{off}.

The increasing number of carrier aggregation combinations enabled by the latest 3GPP standards provides another challenge for FEM architectures. Intermodulation products generated by RF SOI switches during transmit (Tx) can cause desense problems on nearby Rx paths. Newer generations of SOI technology customized for RF switching show improved linearity (see ***Figure 2***), which helps mitigate this issue. For digital integration, standard cells in thin film SOI require special consideration, owing to the lack of a shared body contact. The more advanced generations of RF SOI typically support higher digital

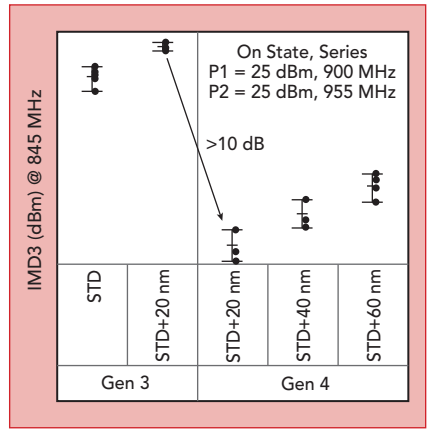

Fig. 2 >10 dB reduction in RF switch IMD3 achieved from Gen 3 to Gen 4 of the 200 mm RF SOI process vs. gate length.

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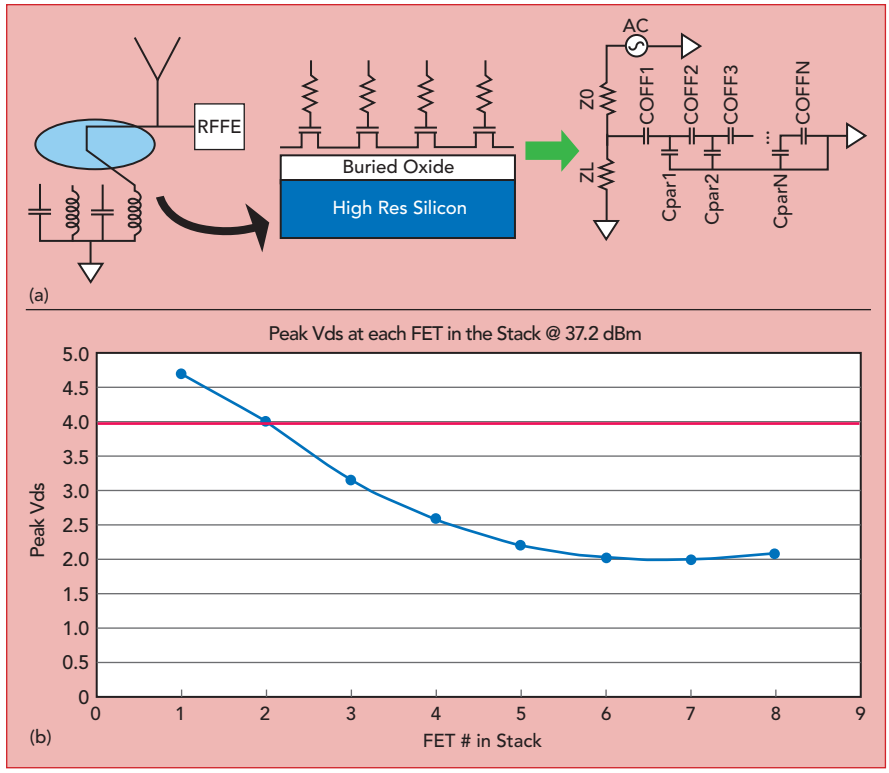

Fig. 3 Stack of SOI FETs used for a high voltage antenna tuner is represented as a capacitive network (a) with a non-uniform voltage distribution across the FETs (b).

densities that allow integration of mobile interface logic (MIPI) with reduced area and power consumption. The low latency requirements of 5G pushes switching times from the typical 5 µS to ~1 µS, which is challenging yet achievable in RF SOI with careful design.

5G mMIMO is increasing the demand for antenna tuners based on aperture or impedance tuning. RF SOI is the incumbent technology for solutions that involve switching impedance elements or modifying the antenna effective electrical length. For this application, series stacks of I/O FETs are typically used to handle high VSWR near the UE antenna. ***Figure 3*** shows a simplified schematic of the FET stack and the unequal voltage distribution resulting from substrate parasitics and other effects. These make it challenging to realize efficient FET stacks to handle >80 V in some tuner architectures. Specialized high power handling FETs with good small-signal figures of merit ($R_{on} \times C_{off}$) facilitate antenna tuner designs (see ***Figure 4***), since they make it easier to reach the voltage handling required of the stack. Process design kits (PDK) that enable these parasitic effects to be simulated with sufficient speed and accuracy enable the design of more sophisticated branches with lower insertion loss. Different assembly options (wire bonding versus flip-chip) can be simulated, as the packaging scheme significantly impacts the voltage distribution within the RF core. Where very high accuracy is needed, the designer can use electromagnetic (EM) simulation of the substrate and package and integrate the results with the PDK device SPICE models for circuit simulation.

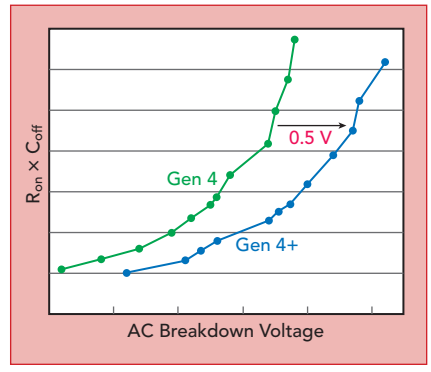

Fig. 4 Generational improvement in R_{on} x C_{off} and peak RF breakdown voltage; each point represents a different FET gate length.

RF MEMS, such as offered by Cavendish Kinetics (recently ac-

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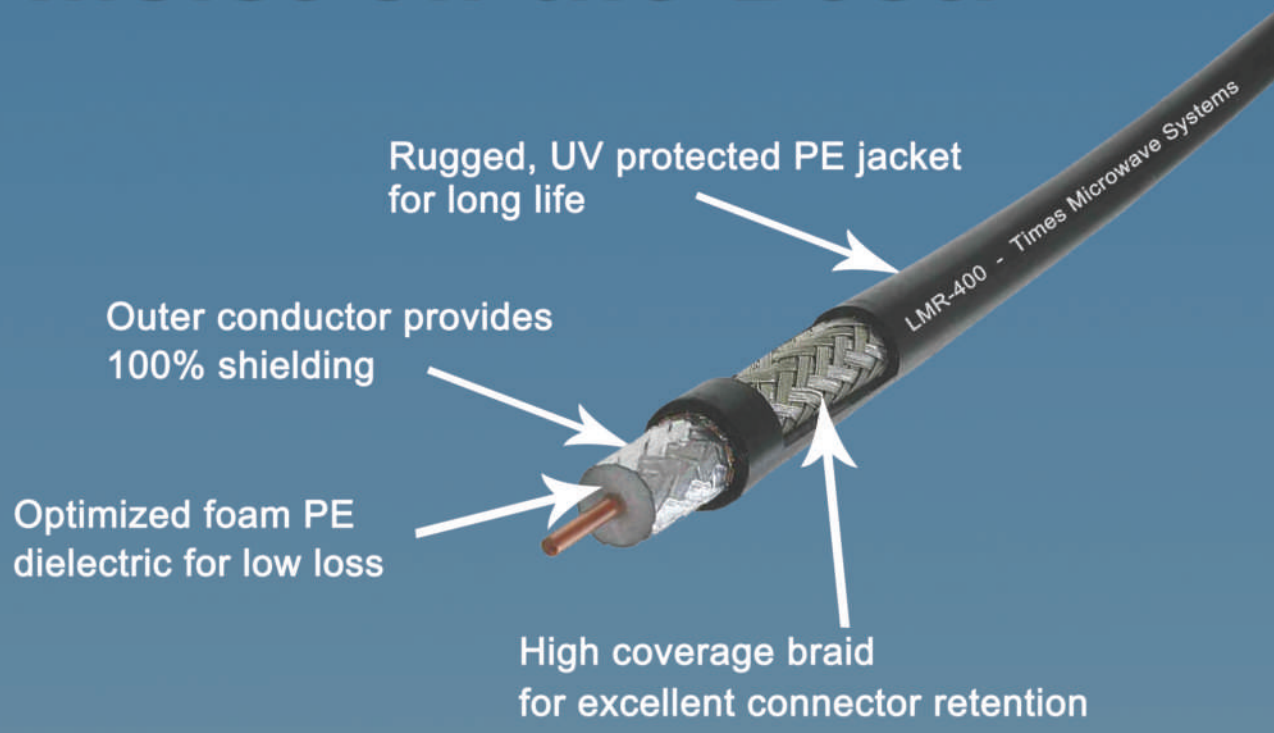

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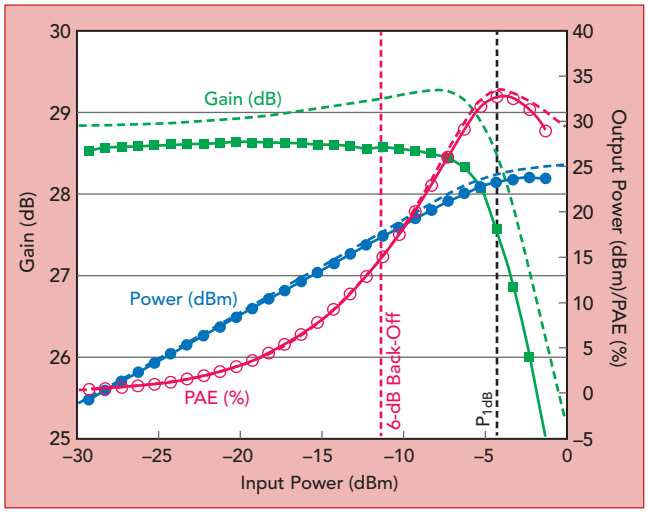
TABLE 1

RF SOI LNA DEVICE IMPROVEMENT VS. STANDARD FET

Parameter	RF SOI LNA Device
Self Gain (2.5 GHz)	+28%
Gain (2.5 GHz)	+0.84 dB
Minimum Noise Figure (5 GHz)	−0.07 dB
Input IP3 (2.5 GHz)	+4.25 dBm



▲ Fig. 5 28 GHz PA gain, Pout and PAE.[1]

quired by Qorvo), is a competing technology that offers superior small-signal performance, high voltage handling, wider tuning range and better linearity than SOI-based tuners. These characteristics will be more highly valued for 5G; however, time will tell if concerns about mechanical stability and reliability limit broad adoption of RF MEMS technology.

To improve the signal-to-noise ratio, another FEM trend is to move the main or diversity low-noise amplifier (LNA) closer to the UE antenna, where it can be combined with RF switching. On-chip impedance matching elements for the LNA can leverage the high resistivity SOI substrate for high Q-factors with this integration. Specialized LNA devices can now provide better self-gain and linearity than traditional NMOS (see ***Table 1***). On the other hand, high performance SiGe HBT devices developed for much higher operating frequencies—f_t and f_{max} >250 GHz—can offer better noise performance at lower supply current than MOSFETs. Tower Semiconductor offers low mask-count versions of high performance SiGe BiCMOS processes specifically tailored for stand-alone LNA applications. A slightly more complex process supports the addition of a customized RF switch with small-signal performance that rivals first-generation RF SOI. GaAs LNAs offer better dynamic range than SOI and SiGe but require higher supply voltages and draw currents that make them less suitable for battery sensitive mobile devices. The process technology choice for LNAs comes down to the application, architecture (i.e., LNA only or an LNA and switch), carrier frequency, power consumption and other FEM specifications.

Power amplifiers (PA) using GaAs HBTs have remained dominant in the UE for cellular Tx for 4G and are expected to remain so for 5G sub-6 GHz frequencies. Envelope tracking techniques should be more beneficial for 5G waveforms, given their higher peak-to-average power ratio. The more complex 5G modulation schemes motivate improvements in silicon platforms used for PA controllers: lower R_{dson} and higher digital density.

INNOVATION FOR 5G MMWAVE

A more integrated approach is generally required for the medium power Tx/Rx building blocks in the 28 to 40 GHz frequencies allocated in North America, Europe and Asia for 5G. Here, phased array architectures are needed to overcome the much higher path losses compared to the sub-6 GHz bands. For Tx, the choice is between using a fewer numbers of elements, each with higher output power provided by GaN or GaAs

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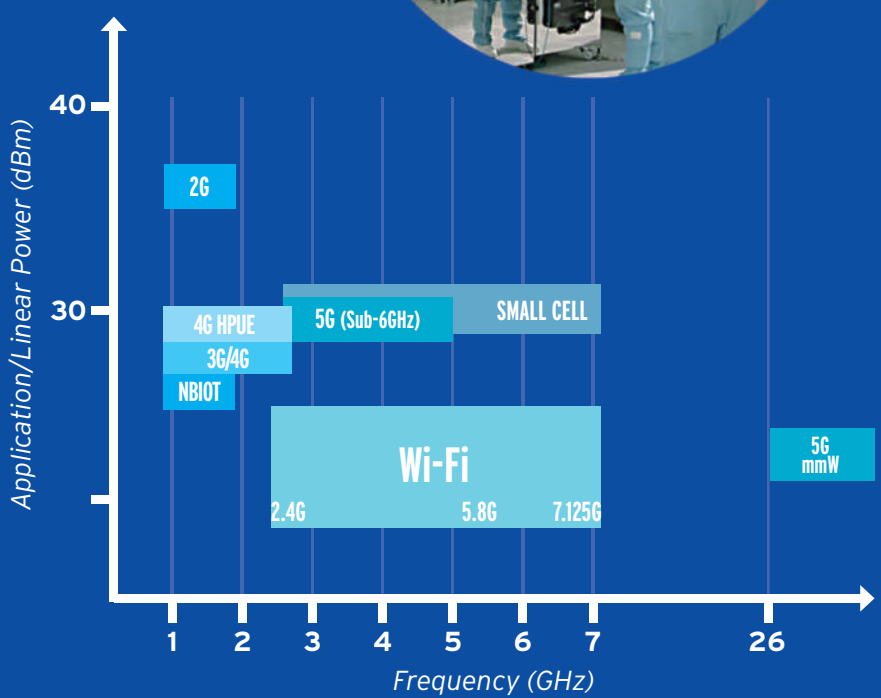
4G HPUE	HG2 HP1
5G (Sub-6GHz)	HG2 HP1
Wi-Fi	HG3 P25ED3 BiHEMT
4G/5G Small Cell	HV HP1 BiHEMT
5G (mmW)	0.15 pHEMT 0.10 pHEMT

100mm InP Process	
Air Standard	InP Process
5G (mmW)	1.0 DHBT



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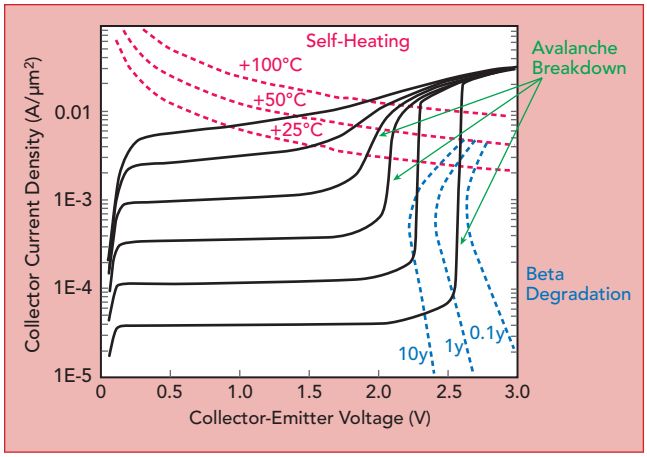

Fig. 6 SiGe HBT I-V characteristics, showing the safe operating area for a PA design.

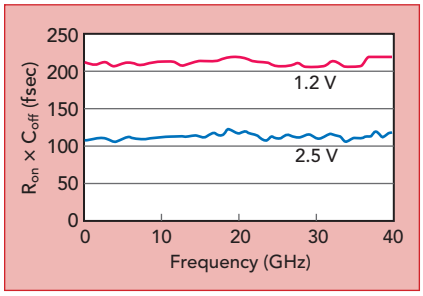

Fig. 7 300 mm RFSOI R_{on} x C_{off} is flat from 1 to 40 GHz, shown for V_{ds} = 1.2 and 2.5 V.

HEMT PAs, or using a larger array of lower power elements using RF SOI or CMOS PAs. Small (2 × 2 or 4 × 4) arrays of Tx/Rx chains can be arrayed to address a range of EIRP requirements. The technology of choice will depend on the required overall power levels. For small cells with up to 1 W per element, SiGe BiCMOS is in the sweet spot of power consumption and system cost.

For the PA at mmWave frequencies, SiGe HBTs offer better efficiency at high output power than FETs (see ***Figure 5***). The figure shows the measured performance of a 28 GHz PA fabricated in SiGe BiCMOS, which delivers 21 dBm output power with 33 percent power-added efficiency (PAE) and 28 dB gain.[1] SiGe BiCMOS phased arrays are already serving the Ku- and Ka-Band satellite communications market with high performance beamformers. Numerous publications from the University of California San Diego and other organizations have demonstrated the capability of this technology for phased arrays from 4- to 256-elements.[2] With his architecture, uniform feed lengths and advanced SiGe BiCMOS processing ensure uniform performance across the elements, reducing or eliminating the need for costly calibration. For switching, one can use high speed HBT devices biased in reverse saturation.[3]

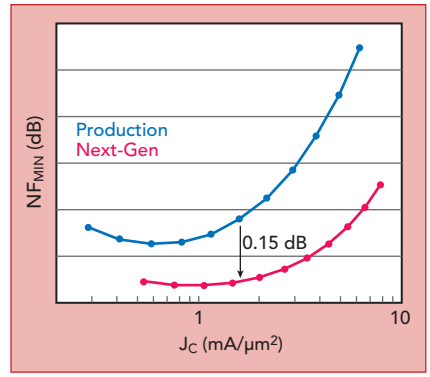

Fig. 8 Noise figure at 5 GHz showing 0.15 dB reduction with next-generation process.

For successful PA design, the SPICE models should include self-heating effects and the device's safe operating area (SOA), warning the designer of operating conditions outside the SOA during SPICE simulations (see ***Figure 6***).

For the mmWave UE, lower power PAs in advanced CMOS or RF SOI become more practical, and SOI is still the best technology for integrating the Tx/Rx switches. The power handling requirements are relaxed compared to what is currently done at sub-6 GHz. Also, the R_{on} × C_{off} degrades little over the mmWave frequency range (see ***Figure 7***). Since passive element area scales inversely with frequency, it becomes practical to consider including on-chip inductors to resonate out the capacitive loss from the off-state RF paths. Here again,

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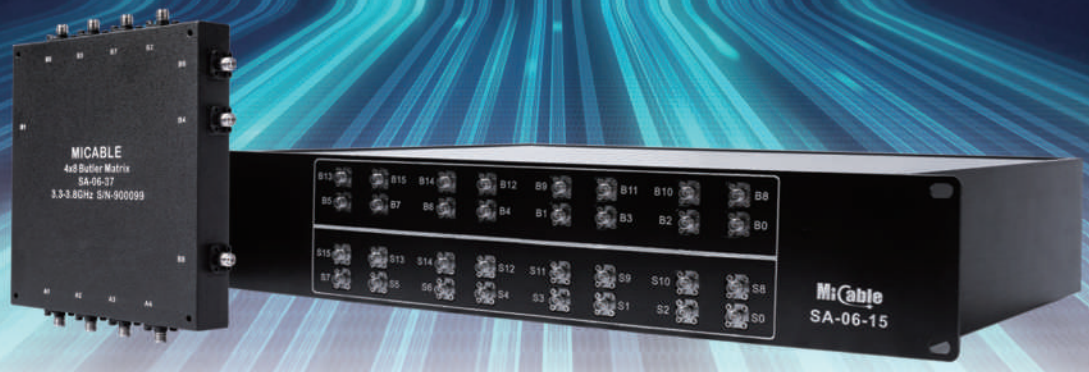

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• 3.3-3.8 • 4.4-5 • 5.2-6 • 24-52

Typical Performance

Frequency (GHz)	Structure	Phase Accuracy (Max.)	Insertion Loss (Max.)
1.7-2.2	16x16	±4°	15 dB
2-8	4x4	±6°	7.8 dB
2-8	8x8	±12°	12.5 dB
2.496-2.696	32x16	±4°	19 dB

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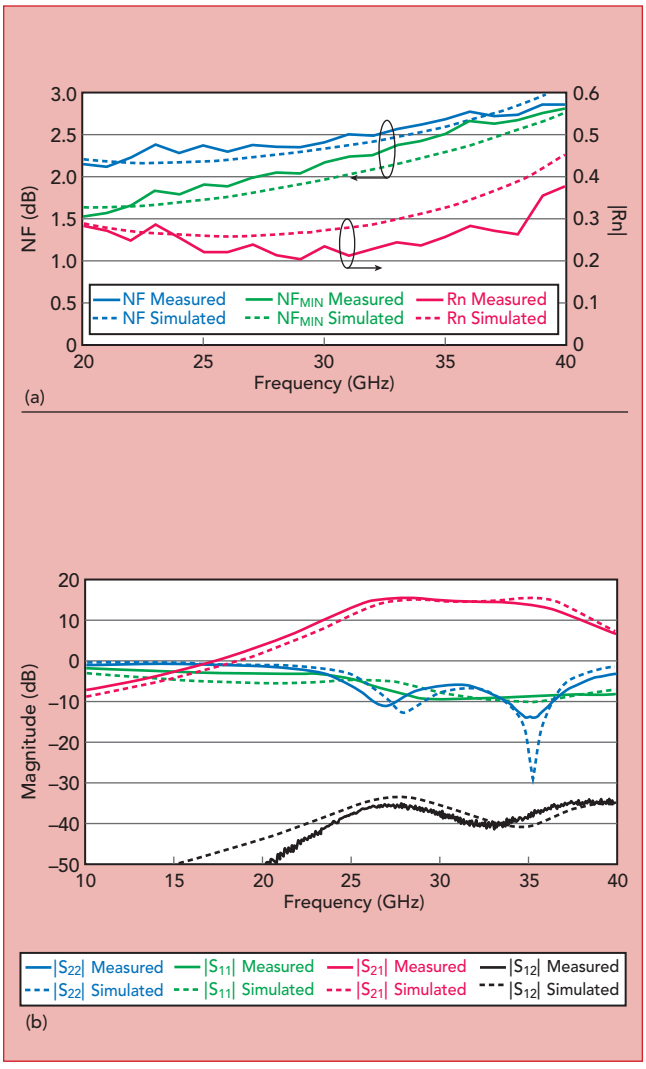

▲ **Fig. 9 Measured vs. simulated noise figure, Rn (a) and S-parameters for a 26 to 35 GHz LNA fabricated with fifth-generation SiGe BiCMOS.**

the improved passive performance is an advantage afforded by RF SOI's high resistivity substrate. Because available devices in advanced CMOS and SOI technologies lack the dynamic range of SiGe HBTs, the PA design is inherently more challenging. Self-heating in SOI PAs poses another technical challenge that must be mitigated through careful layout. GaAs HBT technology could be used as the final PA stage for better efficiency, albeit at higher cost. It will be interesting to see whether specialty RF technology such as SiGe or RF SOI can provide enough performance advantages for the mmWave Tx and Rx chain to win space in future FEM handsets, or whether this functionality will be integrated with the transceiver.

For the Rx path, the design can capitalize on the advantage of high speed SiGe HBT technology, which has evolved through many generations and is now providing >300 GHz f_t and f_{max} NPNs in volume manufacturing with good yields. Designers can leverage the improved performance to run at lower power for 28 to 40 GHz applications. Lateral device scaling has reduced extrinsic base resistance in the more advanced processes, resulting in lower RF noise (see ***Figure 8***). SOI is an alternative with good LNA performance and the ability to integrate passives and very good RF switches, as previously described. Foundry IP blocks and mmWave-friendly PDKs can significantly increase the probability of first-pass design success. ***Figure 9*** plots the performance of a 26 to 38 GHz reference LNA fabricated with the Tower Semiconductor 180 nm SiGe BiCMOS process, showing good agreement between measured and simulated performance. Such designs are facilitated by accurate RF models in the mmWave regime, inductor and transmission line toolboxes and validated EM stack-up files. ***Figure 10*** shows a 28 GHz LNA with on-chip matching and its measured and simulated small-signal performance. This design was fabricated with a 300 mm SOI platform with sub-100 nm gate lengths to achieve excellent noise figure. At these frequencies, the inductor Q is roughly 2x greater over the

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PMC-3G3D5G-6D8-SFF

PMC-33D7-6D8-SFF

PMI Model No.	Frequency Range (GHz)	Gain (dB)	Noise Temperature	Phase Balance	Amplitude Balance (dB)	Size (Inches) Connectors
MPC-20R2G21R2G-CD-LNF https://www.pmi-rf.com/product-details/mpc-20r2g21r2g-cd-lnf	20.2 - 21.2	0 to +10	100 K	±3°	±0.3	6.25" x Ø4.8" x 2.0" SMA (F)

PMI Model No.	Frequency Range (GHz)	Insertion Loss (dB)	Isolation (dB)	Phase Balance	Amplitude Balance (dB)	Size (Inches) Connectors
PMC-24-7D5-SFF https://www.pmi-rf.com/product-details/pmc-24-7d5-sff	2 - 4	0.8 - 7.5	18	±10°	±1.0	3.23" x 3.23" x 0.43" SMA (F)
PMC-3G3D5G-6D8-SFF https://www.pmi-rf.com/product-details/pmc-3g3d5g-6d8-sff	3 - 3.5	0.8 - 6.8	23	±5°	±0.4	3.23" x 3.23" x 0.43" SMA (F)
PMC-33D7-6D8-SFF https://www.pmi-rf.com/product-details/pmc-33d7-6d8-sff	3 - 3.7	0.8 - 6.8	24	±7°	±0.5	3.23" x 3.23" x 0.43" SMA (F)
PMC-9G10G-7D9-SFF https://www.pmi-rf.com/product-details/pmc-9g10g-7d9-sff	9 - 10	1.9 - 7.9	18	±6°	±0.6	3.48" x 3.48" x 0.43" SMA (F)
PD-CD-001-1 https://www.pmi-rf.com/product-details/pd-cd-001-1	9.3 - 9.9	8.0	30	±7°	±0.5	2.35" x 1.7" x 0.5" SMA (F)
PMC-9D5G10D1G-7D6-SFF https://www.pmi-rf.com/product-details/pmc-9d5g10d1g-7d6-sff	9.5 - 10.1	7.6	20	±5°	±0.5°	3.48" x 3.48" x 0.43" SMA (F)

PMC-9G10G-7D9-SFF

PD-CD-001-1

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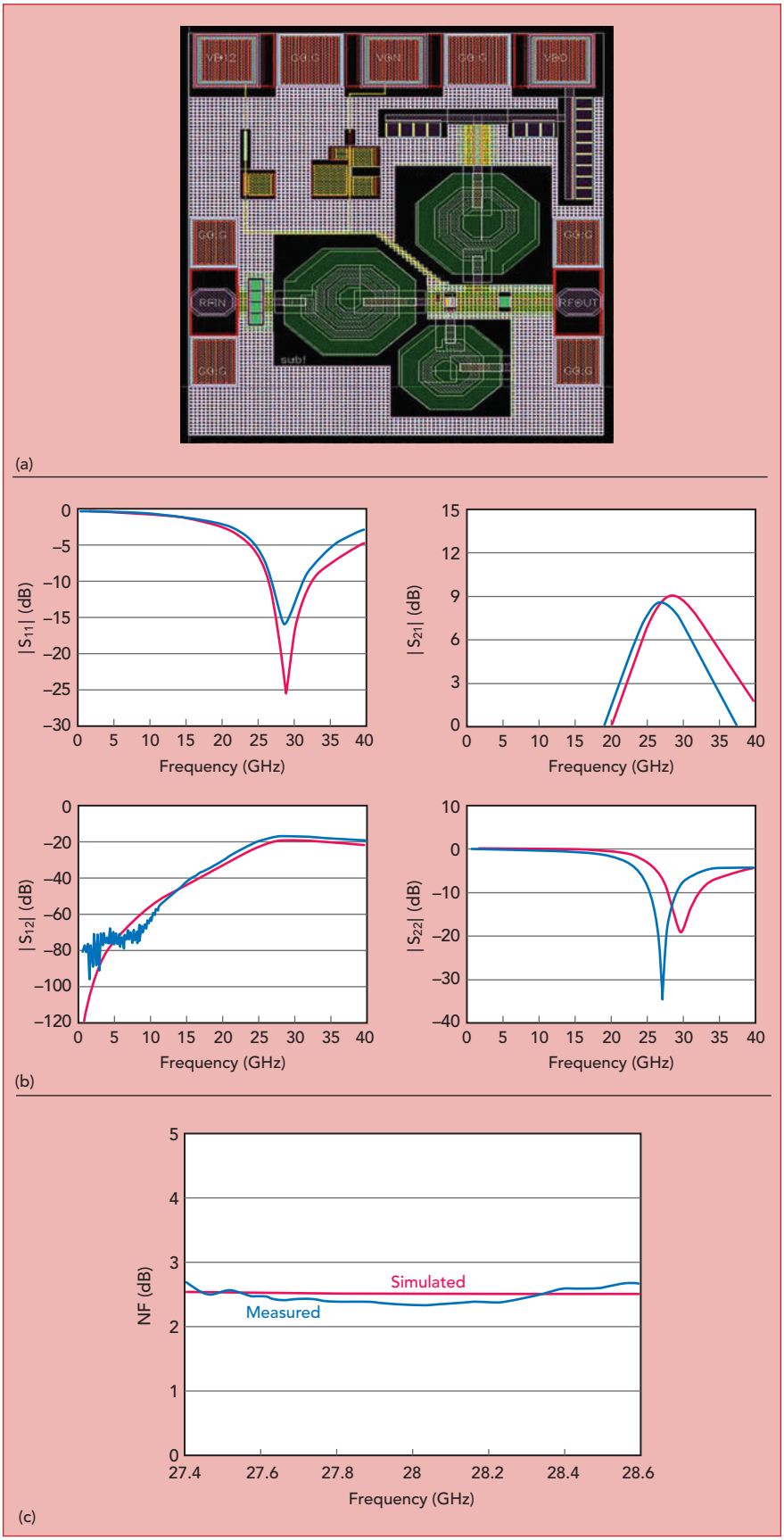

▲ Fig. 10 300 mm RFSOI LNA demonstrators (a) showing single-stage simulated (red) and measured (blue) S-parameters (b) and dual-stage design with 20 dB gain and 2.8 dB noise figure (c).

high resistivity SOI wafer than with a standard low resistivity Si substrate.

CONCLUSION

The 5G era is upon us, providing enormous market growth opportunities for the entire semiconductor ecosystem. The superior system performance required for Gbps speed, ultra-low latency and reliable 5G connectivity demands more stringent requirements on sub-6 GHz and mmWave radios. Specialty silicon process technology, such as SiGe BiCMOS and RF SOI, have evolved rapidly in the last few years to deliver the required performance for switching, LNA and PA applications in the price-sensitive, high volume consumer market. New capabilities have been added to the design environments of these platforms to minimize design cycles. Solutions for mmWave beamformers are manifold, and it is likely we will see different solutions adopted at different power levels, offering a range of cost versus performance choices.■

ACKNOWLEDGMENTS

The authors thank the FEM R&D and manufacturing teams in Newport Beach, California; Migdal HaEmek, Israel; and Uozu, Japan.

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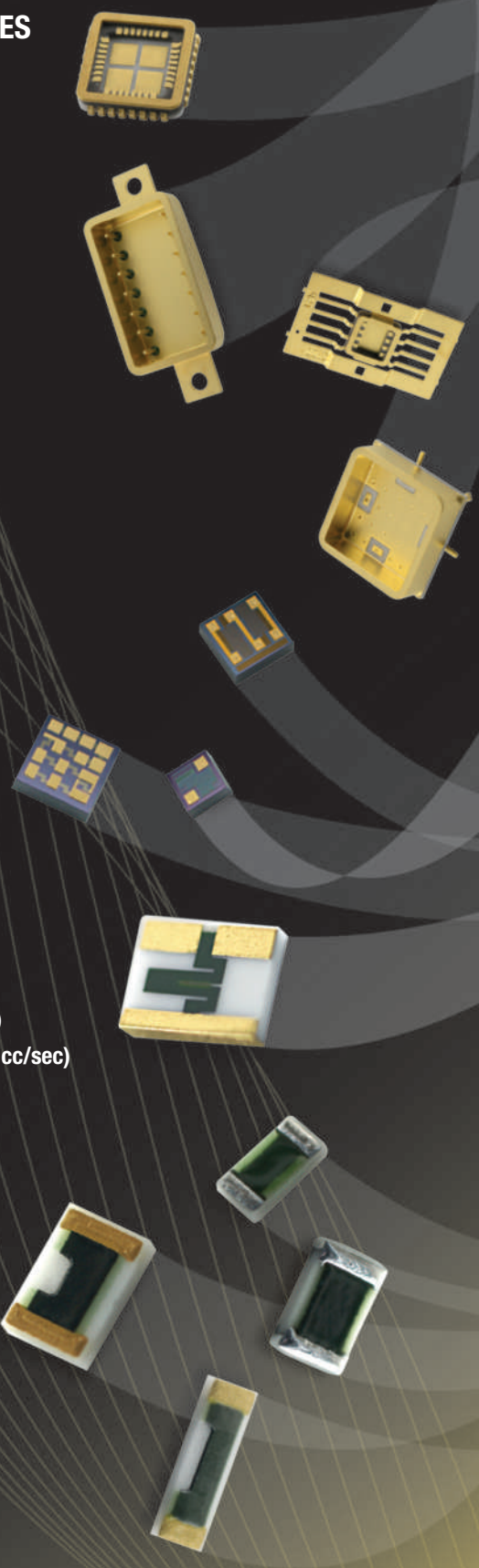

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Bent Balun Combined and AMC Backed Dipole Array Less Vulnerable to Nearby Metal Planes

Changhyeong Lee, Heejun Park and Sungtek Kahng
Incheon National University, Incheon, South Korea

A new array antenna of printed dipoles for beamforming mitigates the negative influence of nearby metal planes. This is made possible by placing a thin artificial magnetic conductor (AMC) beneath each of the printed dipole elements. Each dipole is fed by a compact bent balun suitable for connection to a Butler matrix feed network. Radiation measurements of the AMC backed dipole array demonstrate low vulnerability to a harsh environment.

Mobile communication equipment typically employs wire antennas such as monopoles or inverted L-shapes. To fit a wire antenna into a confined volume of space in an RF platform, it is a common practice to bend the radiating element close and parallel to a metallic ground, wet surface or skin (for a wearable device). In these situations, antenna input impedance matching is compromised, resulting in degraded return loss and poor radiation characteristics. This is because electromagnetic fields generated by the wire radiator in the vicinity of a perfect electrical conductor (PEC) become guided waves rather than emanating waves.[1] To make the best out of the wire antenna in a handset, this drawback is circumvented with the planar inverted-F antenna (PIFA);[2] however, changing the boundary condition of the metallic platform is another alternative.

The electromagnetic bandgap (EBG) structure has been adopted to mitigate the problems of a dipole near PEC or human tissue.[3-8] F. Yang et al.[3] placed a dipole off the edge of a pair of 4-by-3 periodic mushrooms. The PEC-backed mushroom EBG at 8 GHz reduced S_{11} and generated omnidirectional coverage. Abkenar and Rezaei[4,5] used 7-by-7 PEC-backed mushrooms over a large footprint to generate a surface wave stopband from 11 to 14 GHz. They obtain a wide-band EBG, but with no clear benefit to antenna characteristics. According to Kim et al.,[6] the radiating element can be placed on the same plane as the EBG components for 7 or 8 cells of a meandered shorted-line and an interdigital gap. Shahvarpour et al.[7] calculated the height of the PEC-backed multilayered media for an AMC effect and showed 40 percent improvement in radiation efficiency for 24 GHz operation. The patches of

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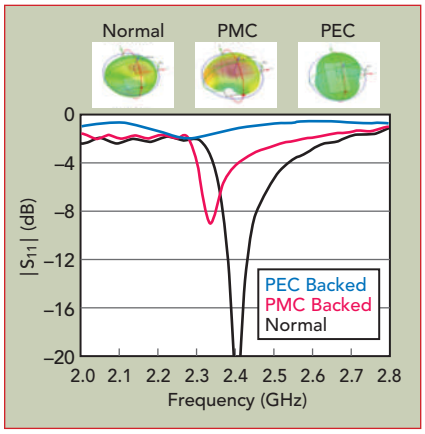

Fig. 1 **Effect of normal, PEC and PMC boundaries on the dipole $|S_{11}|$.**

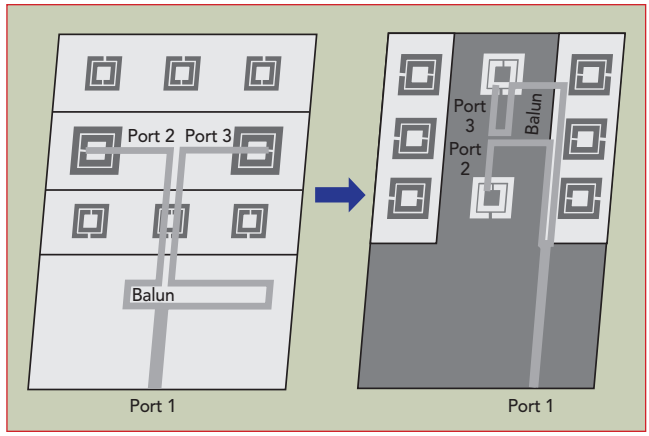

Fig. 2 **AMC-backed dipole comparing the conventional layout (a) with a bent balun feed (b).**

Ayad et al.[8] were modified to those of Soh et al.[9] to create notches. Instead of straight dipoles, slotted patches or bent lines can be used to excite thick and wide AMCs.[10-11] For these and other results reported to date, however, AMC-included antennas do not have beamforming and steering features.

In this work, we describe a thin AMC-combined array of printed dipoles connected to a Butler matrix for beamforming that is suitable for operation in harsh environments such as a close proximity to metal planes or lossy soft surfaces. To apply this method to wearable beamforming devices, 2.4 GHz is set as the operating frequency. The profile of the total structure is low, in contrast to other AMC-added antennas. It has four beams that remain nearly unchanged even in the proximity of a PEC surface. The method is verified by full-wave simulation, and by the measurement of S_{11} and far-field patterns.

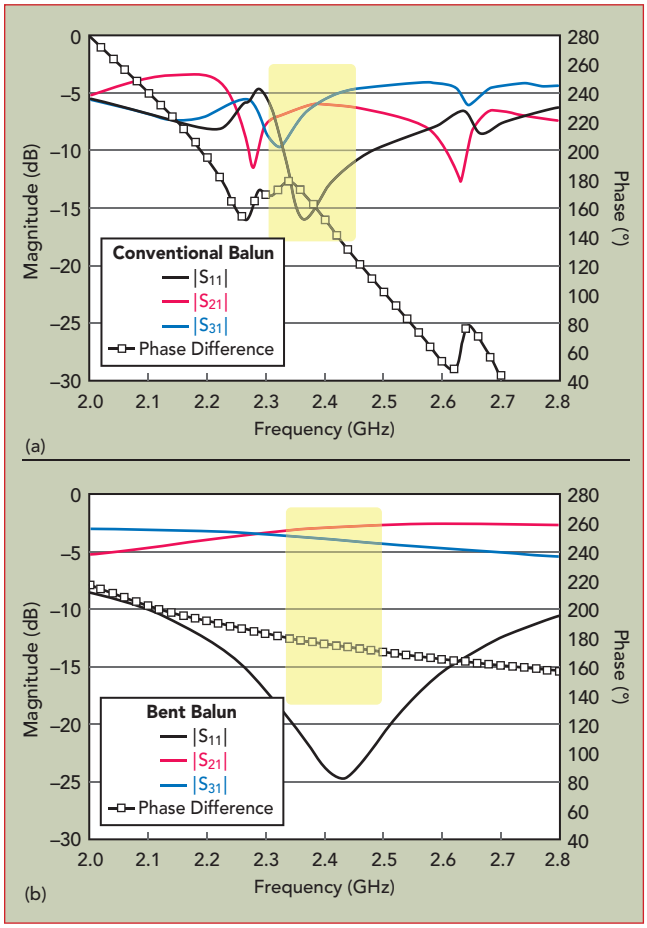

Fig. 3 **S-parameters vs. frequency of the conventional balun (a) and bent balun (b) structures.**

ELEMENT AND ARRAY OF AMC BACKED DIPOLES

To demonstrate the advantages of an AMC, we conduct experiments with three different boundary conditions for a dipole antenna fabricated on FR4-substrate with a thickness of 1 mm, relative permittivity of 4.3 and tangential loss of 0.02. In ***Figure 1***, the condition denoted as 'normal' (unbacked substrate) shows a sharp resonance at 2.4 GHz with an omni-directional radiation pattern. When backed by a PEC, S_{11} is significantly degraded as is the far-field radiation pattern. By substituting a perfect magnetic conductor (PMC) for the bottom boundary of the dipole antenna, the S_{11}-curve and radiation pattern of the antenna are improved when in the vicinity of the PEC. To realize the PMC as an AMC, we must make an AMC that operates over the frequency band of interest.

A thin AMC-combined dipole was suggested by Khattak, and S. Kahng[12] that achieves a good impedance match, adequate antenna gain and low specific absorption rate even when very close to human skin.[12] This is adopted as our array antenna building block, but the geometry is improper for the planar array application, since it is fed by a coaxial cable. For the line to feed a dipole, a transmission-line balun is needed. The balun which consists of an in-phase path and an out-of-phase (180 degree) path must be carefully configured so as not to interfere with the intended characteristics of the AMC printed below the antenna.

The shape of the right-angle bent balun is compared to a conventional design in ***Figure 2***. If the elements of the array are aligned in the lateral direction, the printed dipole should be perpendicular to the axis of the array, which makes the conventional layout inappropriate (see Figure 2a). The design is determined through optimization in an electromagnetic (EM) simulator. As shown in ***Figure 3***, the structure divides the input RF energy equally to both the paths at the target frequency with a phase difference of 180 degrees. In contrast with the conventional balun, the bent architecture feeds the antenna elements with minimal influence on the AMC.

A more detailed view of the structure is shown in ***Figure 4***. The printed dipole is fed by the 90 de-

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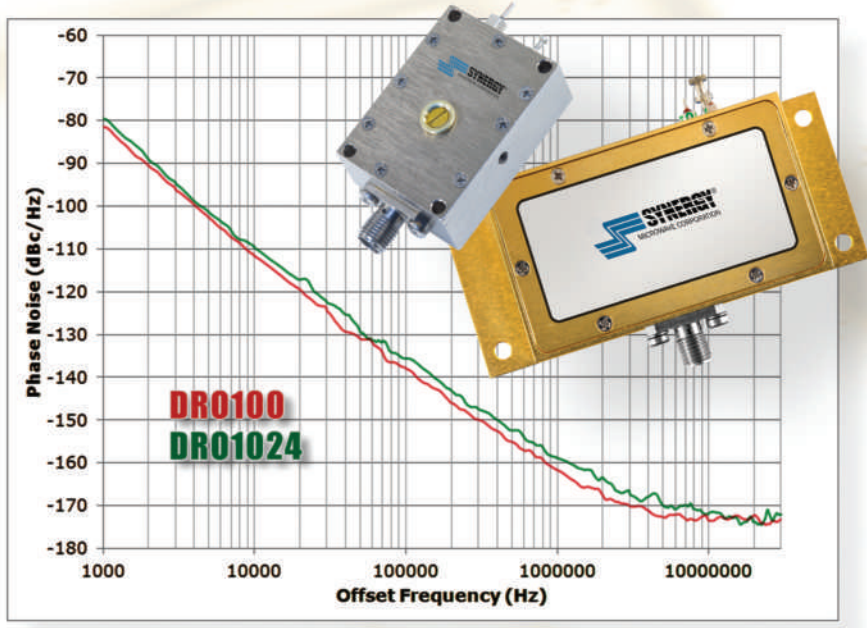

Model	Frequency (GHz)	Tuning Voltage (VDC)	DC Bias (VDC)	Typical Phase Noise @ 10 kHz (dBc/Hz)
Surface Mount Models				
SDRO800-8	8.000	1 - 10	+8.0 @ 25 mA	-114
SDRO900-8	9.000	1 - 10	+8.0 @ 25 mA	-114
SDRO1000-8	10.000	1 - 15	+8.0 @ 25 mA	-107
SDRO1024-8	10.240	1 - 15	+8.0 @ 25 mA	-105
SDRO1118-7	11.180	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1121-7	11.217	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1130-7	11.303	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1134-7	11.340	1 - 12	+5.5 - +7.5 @ 25 mA	-104
SDRO1250-8	12.500	1 - 15	+8.0 @ 25 mA	-105
Connectorized Models				
DRO80	8.000	1 - 15	+7.0 - +10 @ 70 mA	-114
DRO8R95	8.950	1 - 10	+7.0 - +10 @ 38 mA	-109
DRO100	10.000	1 - 15	+7.0 - +10 @ 70 mA	-111
DRO1024	10.240	1 - 15	+7.0 - +10 @ 70 mA	-109
DRO1024H	10.240	1 - 15	+7.0 - +10 @ 70 mA	-115
KDRO145-15-411M	14.500	*	+7.5 @ 60 mA	-100

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gree bent balun above the metal strip extended ground plane. The balun runs beside, without passing over, the complementary split ring resonators on the 1 mm thick FR4 substrate, leaving them undisturbed. The design is more complicated than the conventional balun because the 90 degree-bend in the main and coupled paths makes impedance matching difficult, while the small gap between the two feed lines to avoid crossing over the spirals influences the impedance matching as well. The geometrical

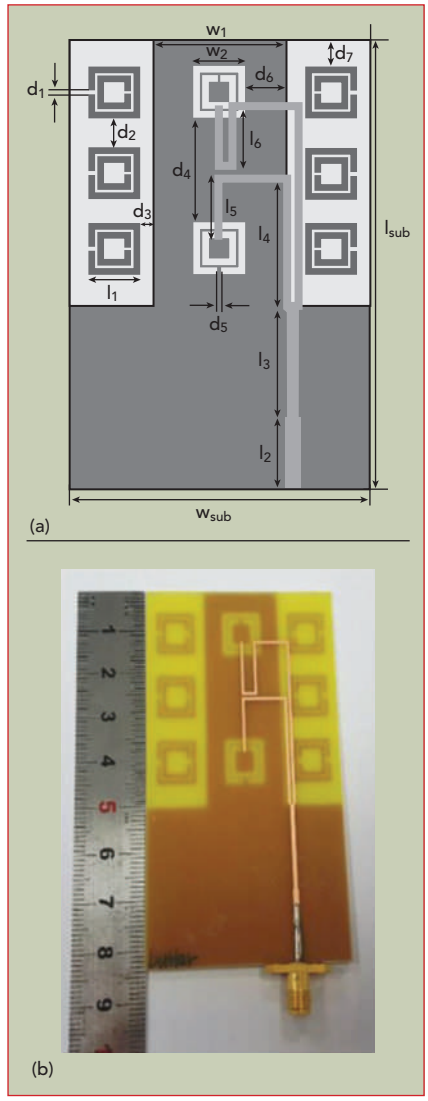

Fig. 4 AMC-backed balun dipole layout (a) and fabricated antenna (b).

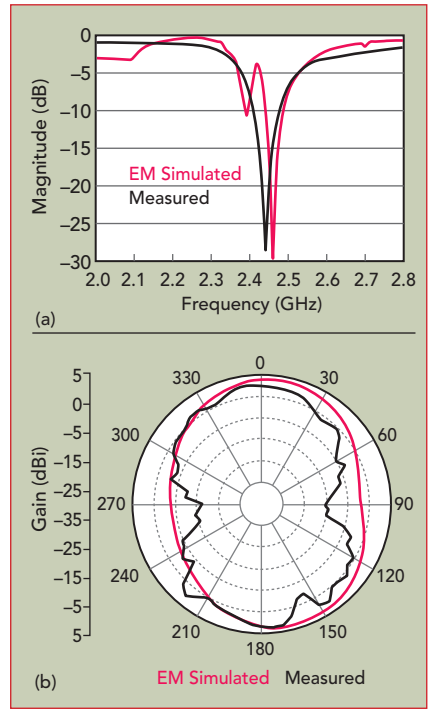

Fig. 5 Element antenna $|S_{11}|$ (a) and E-plane far-field pattern (b).

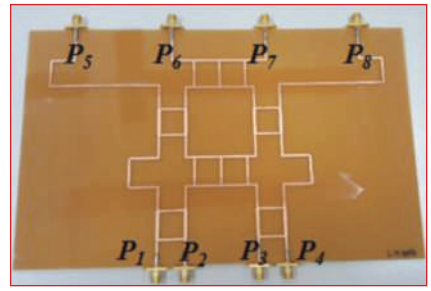

Fig. 6 Fabricated Butler matrix for beamforming.

TABLE 1

BUTLER MATRIX MEASURED MAGNITUDE AND PHASE

Relationship		Port 5	Port 6	Port 7	Port 8
Port 1	Mag (dB)	–8.39	–9.32	–8.15	–9.47
	Phase (°)	42.6	104	145	–166
Port 2	Mag (dB)	–8.19	–8.29	–9.33	–8.9
	Phase (°)	–32	–170	40.8	–73.1
Port 3	Mag (dB)	–8.75	–9.15	–8.32	–8.29
	Phase (°)	–74.7	40.7	–166	–30.7
Port 4	Mag (dB)	–9.02	–8.12	–9.88	–8.37
	Phase (°)	–163	150	111	43.5

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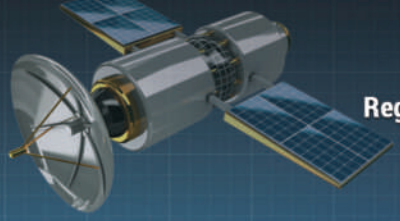

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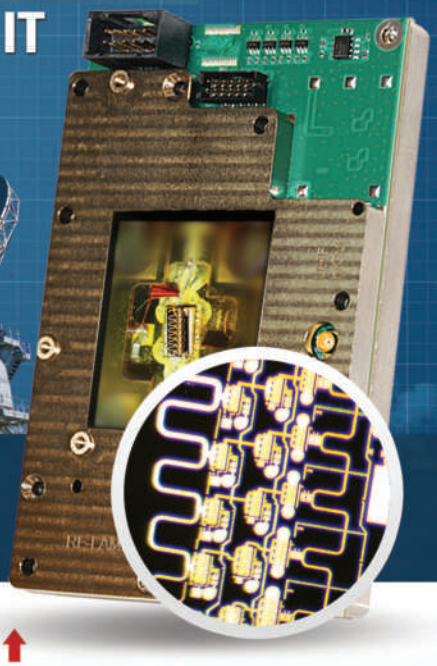

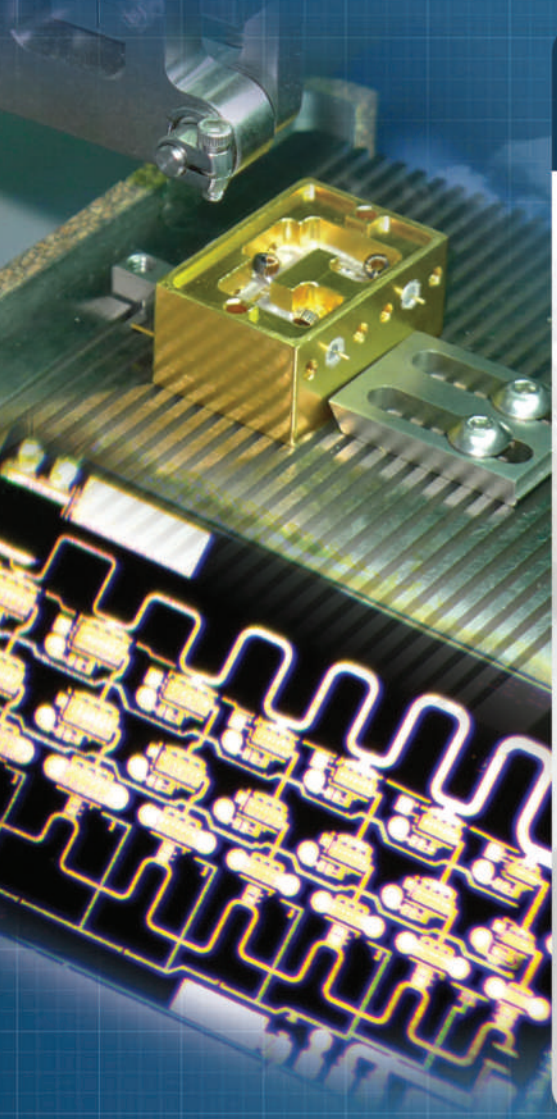

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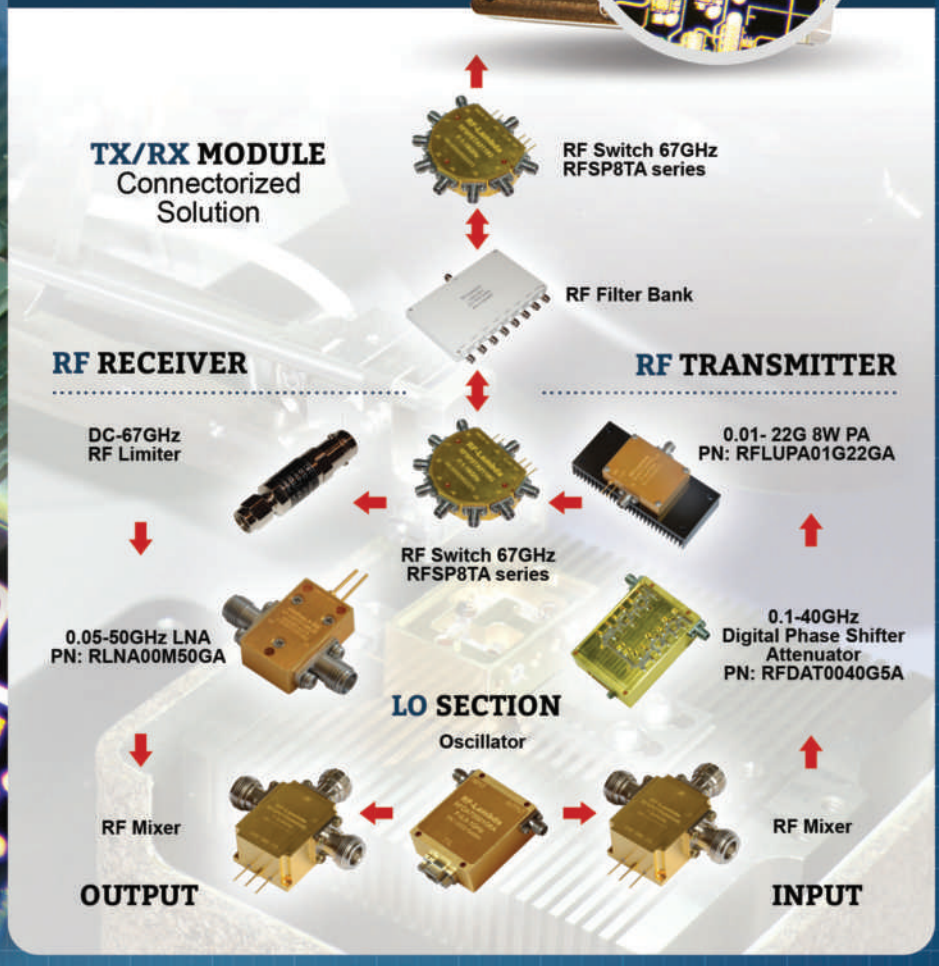

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Despite the discontinuities in the balun, the impedance is matched at the targeted resonant frequency of 2.4 GHz. EM simulation and the measured results closely agree. Antenna gain is nearly 2.5 dBi with a broad beam suitable for array synthesis, although there is a slight difference between the pattern measurement results and simulation.

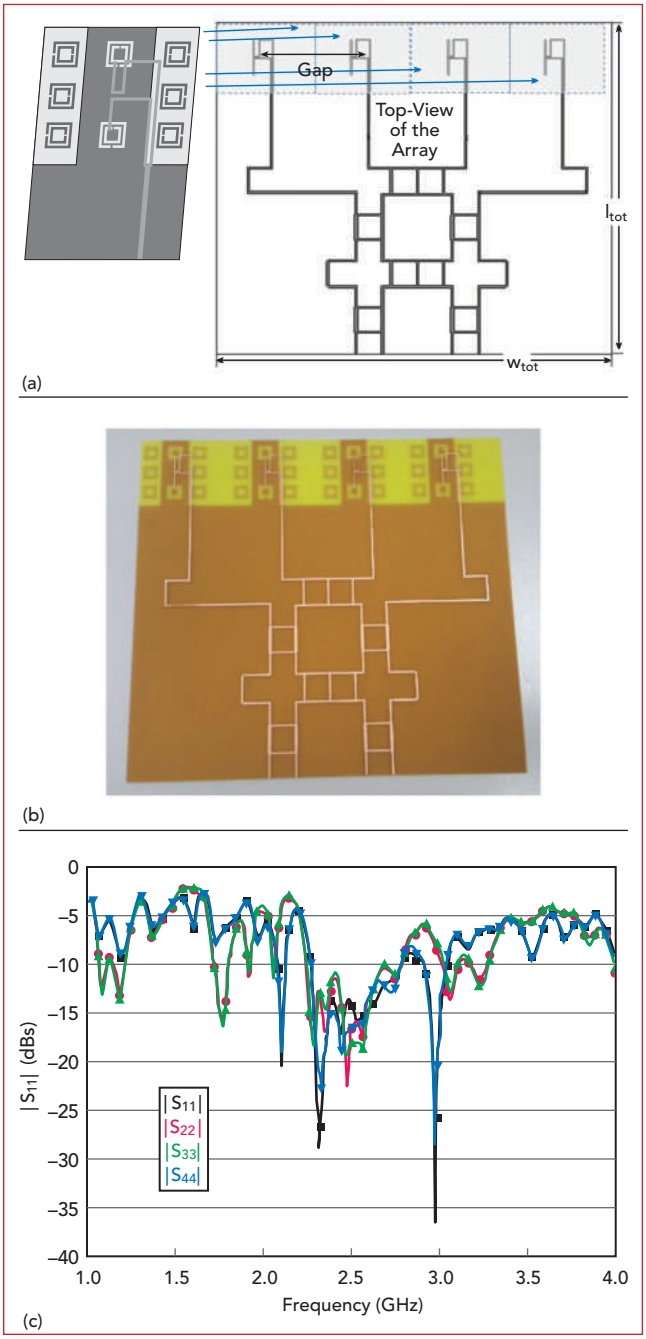

Fig. 7 AMC-backed dipole array antenna and Butler matrix layout (a), fabricated board (b) and measured return loss (c).

BUTLER MATRIX AND ANTENNA ARRAY DESIGN

The Butler matrix is a beamforming network that is often used in beamforming antennas.[13] It enables beamforming through hybrid branch line couplers, crossover networks and phase-shifters (see ***Figure 6***). ***Table 1*** shows the measured power distribution and phase relationships for each input port. Due to dissipation in the FR-4 substrate, losses are higher than ideal; however, the loss characteristics are uniform in each path and the phase relationships are similar to those of an ideal Butler matrix.[14] The single antenna element is repeated in the lateral direction to form an array with a measured return loss less than 10 dB in the target frequency band (see ***Figure 7***).

MEASUREMENTS

Figure 8 shows the integrated antenna array far-field radiation patterns along with simulated and measured array patterns in a benign (normal) environment. There is good agreement in the number and shapes of the beams. Differences stem from losses and irregularities in the FR-4 substrate.

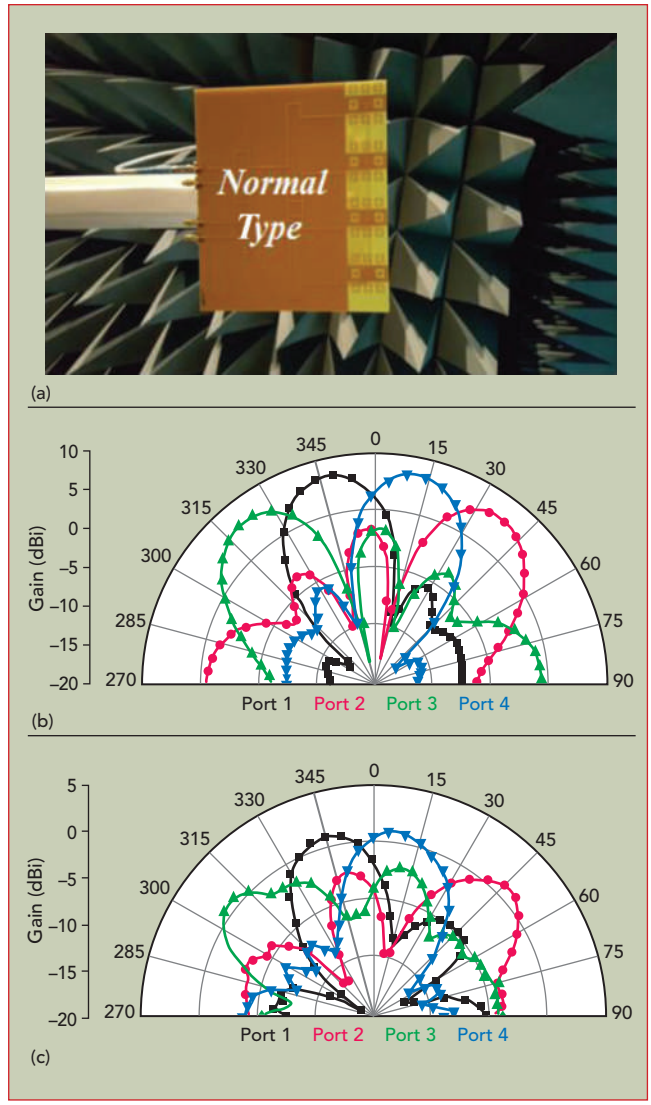

Fig. 8 AMC-backed dipole array antenna measurement set-up (a) and simulated (b) and measured (c) far-field patterns.

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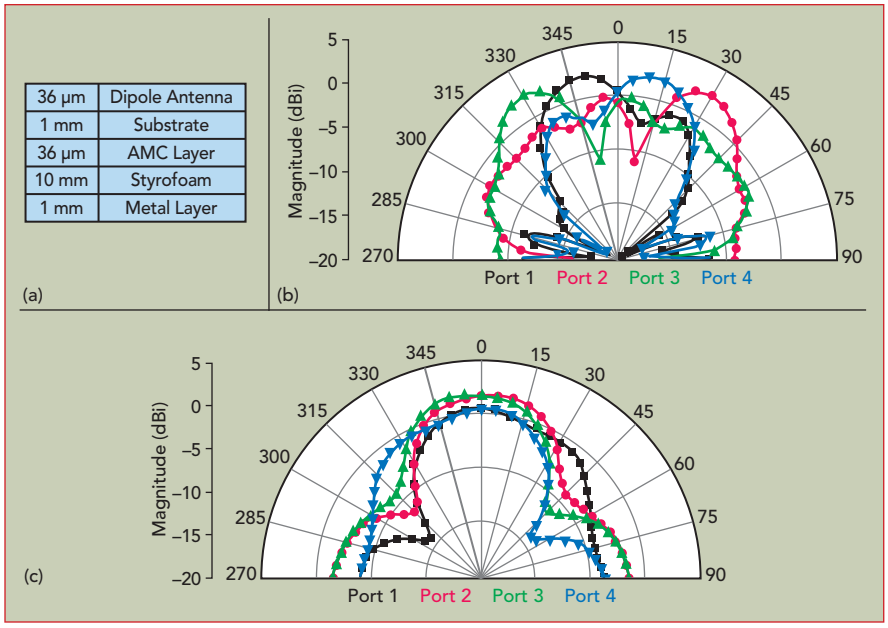

▲ Fig. 9 **Configuration for determining array sensitivity to a nearby metal plane (a) and patterns with four distinct beams (b) and an array without AMC (c).**

As shown in ***Figure 9a***, a metal plane is placed in close proximity to the AMC backed dipole antenna array. ***Figure 9b*** shows four distinct beams similar to those in Figure 8c, which were measured in a benign environment. Measurements of a dipole array without the AMC (see ***Figure 9c***), however, show a strong impact, compromising beam directionality. This pattern degradation is accompanied by an impedance mismatch ($|S_{11}| > -4$ dB) over a broad bandwidth.

CONCLUSION

A new flat beamforming antenna element, employing a thin AMC-backing dipole and a new balun, has low susceptibility to harsh boundary conditions. Four of these elements are arrayed with a Butler matrix to produce four directional beams with little effect from the introduction of a closely located metal plane.■

ACKNOWLEDGMENT

This work was supported by Incheon National University Research Grant 2015. Prof. Qun Wu's collaborative advice on the work with equivalence to co-authorship is appreciated.

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20 GHz Synthesizer Delivers Ultra-Low Phase Noise and Fast Switching

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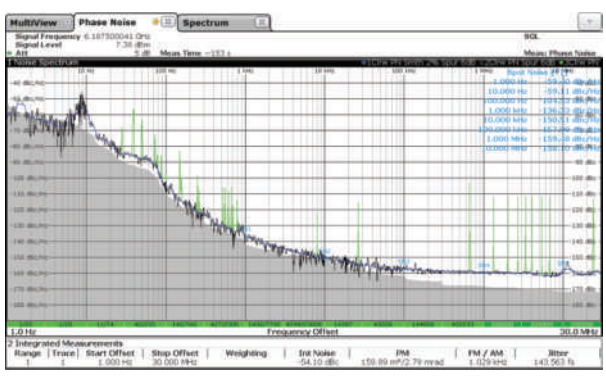
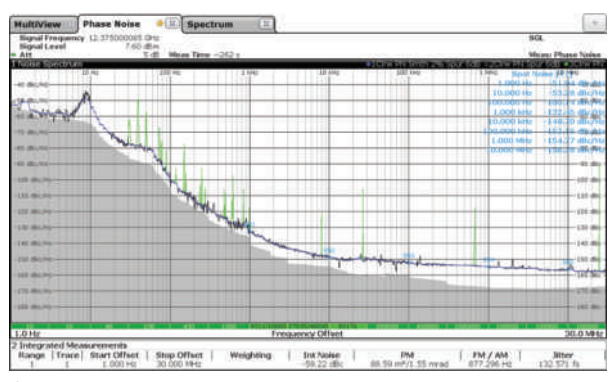
Rapidly evolving microwave and mmWave technology is imposing more difficult requirements on the generation of microwave signals. The systems of tomorrow—from high speed analog-to-digital and digital-to-analog converters (ADC and DAC), to radar and fundamental research applications—all need signals with better frequency stability and spectral purity, as well as sub-microsecond frequency switching. The design of such systems can be simplified using a bench-top microwave frequency synthesizer capable of pushing conventional performance specifications close to theoretical limits. The new 100 kHz to 20 GHz frequency synthesizer developed by Trisynt Technology addresses this challenge, providing a unique combina-



(a)



(b)

▲ Fig. 1 **Measured phase-noise at the ends of the main frequency band: 6.1875 GHz (a) and 12.375 GHz (b).**

tion of ultra-low phase noise, excellent spectral purity and ultimate frequency agility not previously available in a commercial instrument.

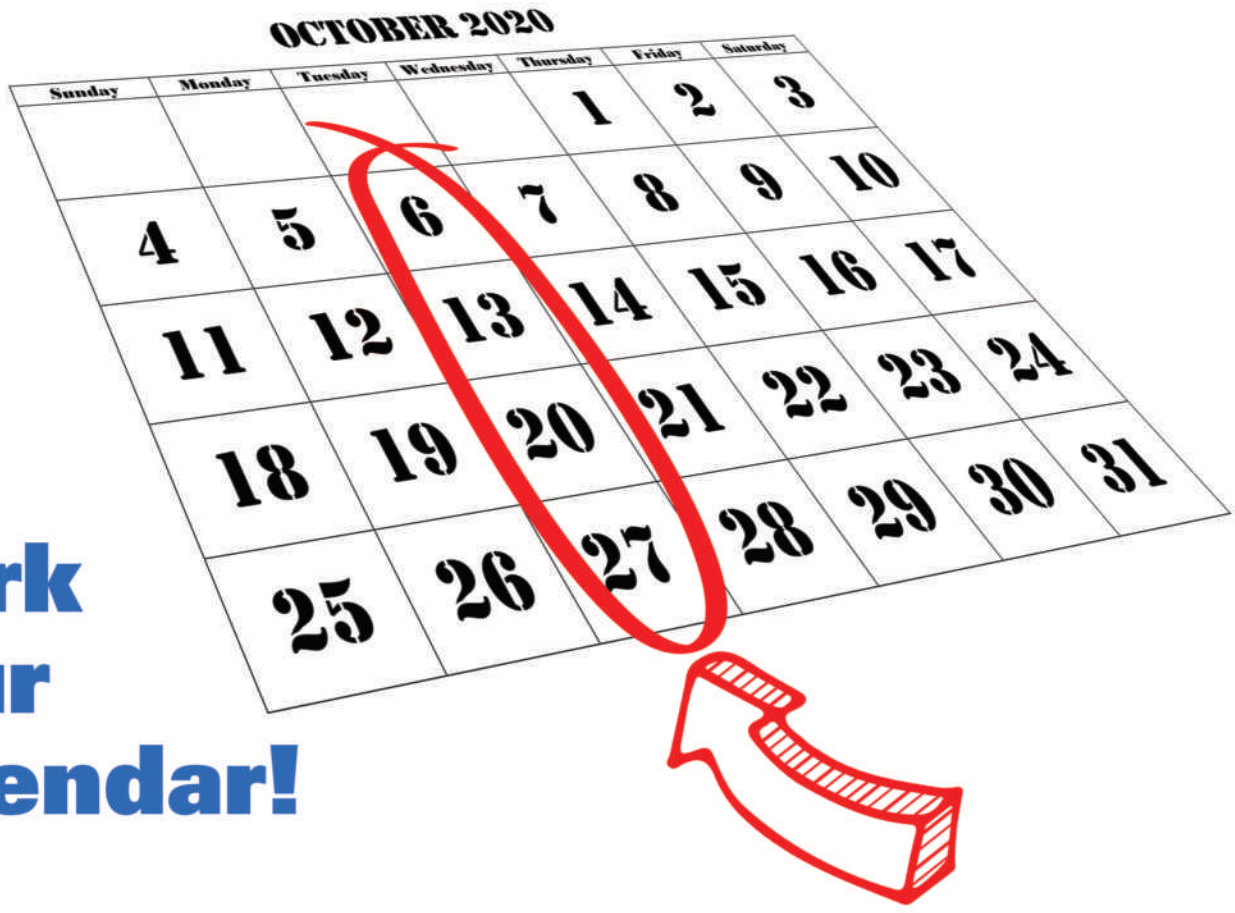
While the best available commercial synthesizers target -130 dBc/Hz at a 10 kHz offset from a 10 GHz carrier, Trisynt's SAPSYNT-200 provides 20 dB improvement compared to the industry standard, achieving an ultra-low -150 dBc/Hz at 10 kHz offset at 10 GHz. This dramatic advance in phase noise is possible using an X-Band frequency reference with a high Q sapphire resonator locked to a high stability 10 MHz OCXO, yielding a frequency stability better than $\pm 1 \times 10^{-11}$ over an operating temperature range from 0°C to 50°C. While the low noise characteristics of sapphire-based oscillators have been known for years, there were only a few systems which provided the frequency stabilization of sapphire oscillators with a low start-up time and without using cryogenic methods. The SAPSYNT-200 uses a novel approach where the sapphire oscillator frequency and phase are constantly measured by a high-resolution ADC and a dedicated FPGA, forming a corresponding linear FM signal to digitally phase-lock the sapphire to a 10 MHz reference. The system settles within just a couple of minutes after the instrument is switched on.

Engineers familiar with low noise frequency synthesis are aware that a low noise reference is not enough to build a synthesizer; a synthesis core broadband enough to be extended to a frequency octave is required. Transferring the reference characteristics without significant noise degradation to other frequencies is not trivial. Nevertheless, the SAPSYNT-200 accomplishes this, where all the frequencies in the main frequency band, from 6.1875 to 12.375 GHz, have consistently superb phase noise performance (see ***Figure 1***).

In addition to the frequency range available at the standard synthesizer output, the SAPSYNT-200 provides signal outputs derived from the combined 9.9 GHz reference: f/2 or 4.95 GHz, f/4 or 2.475 GHz, f/8 or 1.2375 GHz and f/16 or 618.75 MHz. These frequencies have enhanced phase noise comparable to "golden" phase noise standards and can be used for applications such as clocking an ADC or DAC.

ENHANCED SPUR PERFORMANCE

The SAPSYNT-200 carefully tackles unwanted synthesis spurs in the spectrum. A specialized DDS built as a combination of FPGA and high speed DAC has been developed to suppress non-harmonic spurs using both hardware and software, achieving levels well below -90 dBc. The SAPSYNT is a fully direct synthesizer with no VCOs, YTOs or PLLs—only direct frequency mixing, multiplication and division. All spur products from unwanted mixing, multiplication and division go through a multichannel switched filter bank, where they are rejected to very low levels. This is achieved using ninth-order



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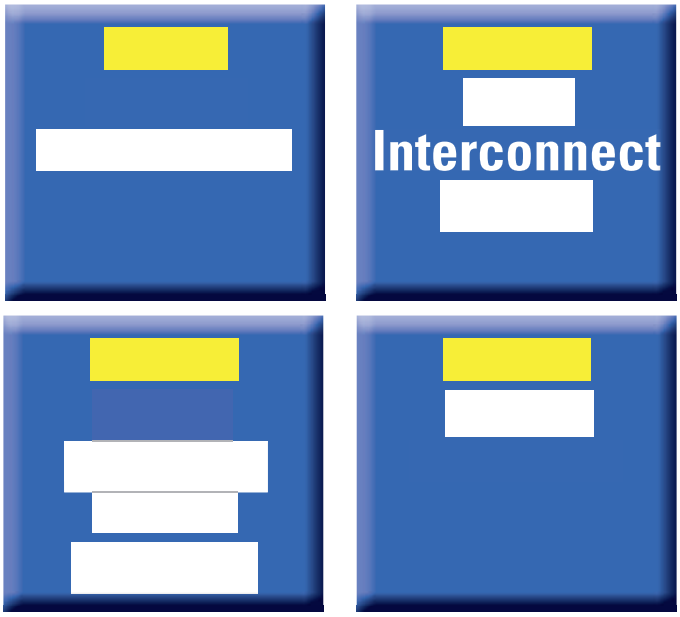

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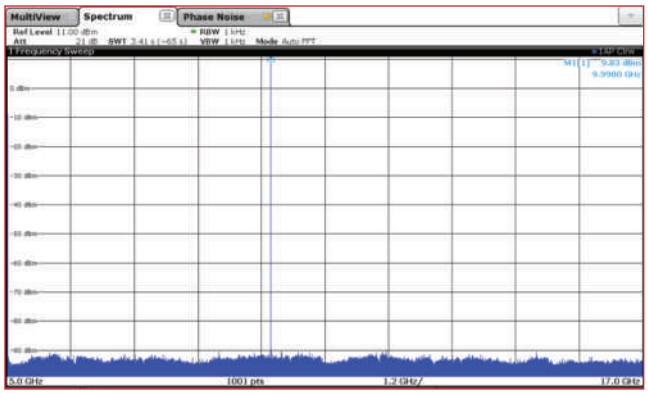

Fig. 2
Broadband spectrum around a 10 GHz synthesized signal, showing spurs below –90 dBm from 5 to 17 GHz.

hardware filters with very sharp skirts and by routing the signal through multiple switch isolations. Conceptually, low spurs within a 500 MHz band around the signal are achieved by DDS and outside this bandwidth by the switched filter bank. ***Figure 2*** shows the broadband spectrum around a 10 GHz CW at the output of the synthesizer.

FAST SWITCHING SPEED

The direct synthesis architecture of SAPSYNT-200 enables very low dwell time when switching between frequencies. The switching speed is only limited by the broadband switches and the data upload rates of the internal interfaces. The hardware filters are typically 500 MHz wide and contribute negligibly to the switching speed of the instrument. Within the main frequency octave, i.e., from 6.1875 to 12.375 GHz, the switching speed is within 200 ns for any two frequency points in the list mode, remaining in the sub-microsecond region across the specified frequency range from 100 kHz to 20 GHz. The synthesizer has a minimum frequency step of 1×10^{-6} Hz.

OPTIONS AND EVOLUTION

The architecture of the SAPSYNT-200 supports extension of the frequency range and adding functionality, as well as performance upgrades as microwave technology evolves. For example, the synthesizer can be modified to work from a photonic time-base of 9 to 10 GHz extracted from an optical frequency comb produced by mode-locked lasers. In this case, all the internal core frequencies including the DDS clock will be regenerated from a virtually noiseless reference, only limiting the synthesizer characteristics by the thermal noise of its active components.

The SAPSYNT-200 direct frequency synthesizer offers a new standard for phase noise and frequency agility, a safe investment since it will remain one of the lowest noise and fastest synthesizers for years to come.

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The ACM2506 covers 20 kHz to 6.5 GHz and is fully automatic, controlled and powered via USB. CMT VNAs have a built-in function enabling one-touch, automatic calibration using the ACM. The module switches to each of the required impedance states, one by one, and calculates the calibration coefficients using the measured S-parameters at each state, which are stored in memory.

The ACM includes a 20 dB in-line attenuator characterized at the factory and used to simulate a device under test (DUT). After calibration, the ACM loads the DUT factory data into memory and compares it with the measured S-parameters of the attenuator to verify the calibration. The memory can also store up to three user characterizations, enabling the setup to include adapters and fixtures. The two ports of the 50 Ω ACM2506 can be fitted with either Type N or 3.5 mm connectors.

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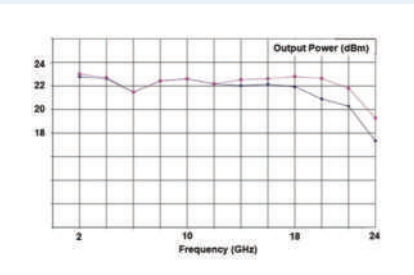

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This distributed amplifier MMIC has input return loss better than 10 dB, as expected, and is packaged in an RoHS compliant, 4 mm QFN package; it is also available in die form. The operating temperature range is -40°C to +85°C; at +85°C, the maximum junction temperature is 110°C.

Founded in 2001, Eclipse MDI develops high performance RF, microwave and mmWave semiconductor devices for commercial and industrial applications. The company has strategic alliances with foundries to access the leading process technologies and manufacturing facilities for high volume production of MMICs. In addition to MMICs, Eclipse offers a portfolio of passive components, including directional couplers, power dividers, detectors, limiters, equalizers and tunnel diodes. Eclipse MDI's goal is to supply cost-effective, high-quality products for complex systems operating to 40 GHz, and its products are found in applications from communications to military and automotive.

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Ensuring Component Supply for Long-Lived Programs

Long-lived defense programs face the challenge of components no longer available, reflecting the consolidation of sources, obsolete technologies or suppliers discontinuing products because of low demand or poor profit margins. It's serious enough that the Department of Defense has created a program to address it, called Diminishing Manufacturing Sources and Material Shortages (DMSMS).

As a long-term supplier to the defense industry, MECA Electronics has formalized its own DMSMS policy and program to support all products it manufactures, whether standard or custom. MECA's policy is to maintain availability of its own products, pricing them economically at industry supply standards.

For similar products discontinued by other manufacturers, MECA will review the available documentation to assess electrical performance and mechanical packaging, determining whether it can provide a product meeting the form, fit and function requirements. In the best case, MECA will offer an off-the-shelf design; otherwise, it will provide a quotation to develop a custom product meeting the requirement.

Privately held, MECA Electronics designs and manufactures an extensive line of RF/microwave components, including fixed attenuators, directional couplers, hybrid couplers, isolators and circulators, power divider and combiners, RF loads, DC blocks, bias tees, cables and adapters. Since 1961, MECA has served the RF/microwave industry with passive components and equipment operating to 50 GHz, used in high performance applications such as satellite communications, mobile radio, radar, telemetry, aviation, air traffic communications, space and defense. ISO 9001:2015 certified, MECA manufactures its products in the U.S.

The company's 15,000 square foot design and manufacturing facility supports low volume production; medium to high volumes are produced with the support of domestic contract manufacturers. This capable supply chain is key to MECA's ability to deliver quality, cost-effective solutions.

VENDORVIEW

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An internal, digitally-adjustable, voltage-controlled, temperature-compensated crystal oscillator ensures frequency errors are minimized over temperature. Alternatively, an external 10 MHz input may be used to achieve 0 ppm frequency error. Stability over temperature is ±0.28 ppm, and typical aging is less than 1 ppm/year. A trigger output is available to synchronize the VSG60A with other test equipment.

Signal Hound provides a custom API to continuously stream I/Q data to the VSG60A at an arbitrary sample rate up to 51.2 MSPS. The software can also load a CSV format binary short integer or binary floating point I/Q file. Corrections are applied automatically as the data is streamed to the instrument.

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https://radhardsolutions.com

Amplifier Search Engine & Applications Newsletters

Guerrilla RF® is committed to supplying the high performance RF solutions you need to meet your challenging device requirements. Guerrilla Search™ provides easy identification of the optimum amplifier for your application, using measured performance data over power supply and frequency. Guerrilla RF provides practical applications guidance with performance data to support design engineers via their informative monthly newsletters. Please visit their website to subscribe or reference archived issues at www.guerrilla-rf.com.

Guerrilla RF

www.guerrilla-rf.com

Phase Constant Over Temperature Video

VENDORVIEW

HUBER+SUHNER Constant over Temperature (CT) cable assemblies for phase critical applications create a stable and reliable interconnect solution to satisfy a huge range of applications where phase stability is key, e.g. aerospace and defense, test & measurement and industrial environments. Watch the video and find out how CT cables increase system accuracy and experience the unique range of cable constructions to fulfill any demands.

HUBER+SUHNER

www.youtube.com/watch?v=kIlrk8jKLwQ

Updated Website

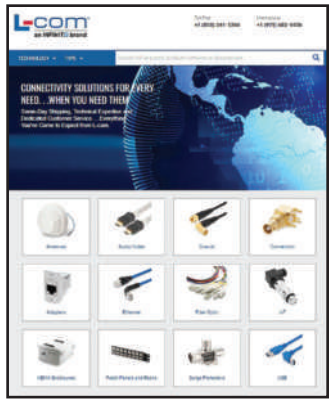
K&L Microwave's website provides information and tools, such as the Filter Wizard® web application, to speed the identification of custom design solutions from a full range of company products. The latest web update features a new look, mobile device support and social media links. Research capabilities, access data sheets, submit quote requests, read the latest news and download K&L's product catalog and space brochure.

K&L Microwave

www.klmicrowave.com

L-Com Launches Website

VENDORVIEW



L-com has recently launched a new and improved ecommerce website that includes an improved look and feel (UI & UX), new and improved site navigation and search capabilities to help customers find the right products faster and mobile optimization to make finding and buying products easy on any device. Other enhancements including a quick one page checkout, custom cable configurators and a library of helpful technical resources. L-com's new website features thousands of wired and wireless connectivity products that are in-stock and available for same-day shipping.

L-com

www.l-com.com

E-Commerce Website

As Marki Microwave innovation continues to bring performance-shattering products to the market, the company kicks off the new year with the launch of their new e-commerce website for your shopping convenience. Now you can shop and place orders online, securely and seamlessly; access your account 24/7: product orders, shipment history; and manage your Favorites and Product Watch List. Thank you for being a valued member of the Marki Microwave customer community.

Marki Microwave

https://shop.markimicrowave.com

Web&VideoUpdate

Research & Educational Kits

VENDORVIEW

The first of the Univeristy Project kits, UVNA-63, includes all the elements students need to build a fully functioning vector network analyzer, develop S-parameter algorithms and perform real-time measurements of 2-port RF devices. The kit comprises Vayyar's high performance transceiver chip with a variety of RF components from Mini-Circuits, along with control software and a development environment for Python and MATLAB®. Mini-Circuits has expanded its collaboration with Vayyar to offer its second kit, VTRIG-74, a ready-to-use, 4D mmWave imaging and sensing application development platform.

Mini-Circuits

www.minicircuits.com/products/researcheducation.html

New In-Building Wireless Solutions Web Pages

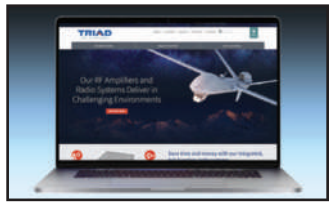
VENDORVIEW

With more than 1,000 installations worldwide, SPINNER is one of the leading suppliers of in-building wireless solutions. Passive systems can rival and easily beat the performance of active solutions. They have two big selling points in their favor: low CAPEX and zero OPEX. And with SPINNER, you get the added benefits of bandwidth efficiency and future-proofing. Read more on SPINNER's new in-building wireless solutions web pages.

SPINNER Group

www.spinner-group.com/in-building

Amplifier and Integrated Radio System Design and Manufacturing



Triad RF Systems has announced the launch of a new brand identity and website. Founded in 2013 by three partners with decades of accumulated knowledge of RF/microwave amplifier and integrated radio system design and manufacturing experience, Triad is making a strategic move to continue its dominance within high-performance radio system applications. Visitors to their website will discover Triad's track record of creating RF/microwave amplifier products that push the limits of size, features, efficiency, and linearity.

Triad RF Systems

www.triadrf.com

NEW PRODUCTS

FOR MORE NEW PRODUCTS, VISIT WWW.MWJOURNAL.COM/BUYERSGUIDE
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COMPONENTS

High Voltage Molded Power Inductors

Coilcraft has expanded its market-proven XEL Family of high-performance, molded power inductors to include three new higher-voltage series: the XEL401xV, XEL4020V and XEL4030V. All three offer operating voltage ratings of 120 V, 50% higher than the standard versions. They also offer exceptionally low DC resistance and ultra-low AC losses for greater power converter efficiency at high frequencies (2 to 5+ MHz) and high ripple current. XEL40xxV Family inductors measure just 4 × 4 mm with a maximum height of 3.2 mm.
Coilcraft
www.coilcraft.com

Edge-Coupled Bandpass Filter Design Library

VENDORVIEW

If you need designs for edge-coupled bandpass filters on alumina substrate, Exceed Microwave has a long list of filters you can choose from. Exceed will provide you with .dxf or .step file in which you can use to fabricate your filters. Simulation plots are generated using HFSS and if you don't see what you need, the company can design it for you. Some 4 section filter designs are available for free so you can evaluate its designs.
Exceed Microwave
www.exceedmicrowave.com

High Frequency 90° SMD Couplers

Innovative Power Products announces two high frequency 90 degree SMD coupler models, IPP-7112 and IPP-7114. These surface mount couplers are conservatively rated at 50 W CW, and operate from 8 to 12 GHz and 6 to 12 GHz, respectively. The IPP-7112 and IPP-7114 pages on the Innovative Power Products website list the complete product specs, and provide links to pdf files of the detailed outline drawings and the typical test data results for several parameters.
Innovative Power Products
www.innovativepp.com

SPDT Manual Toggle Coaxial Switches

These switches offer high reliability for your RF/microwave requirements. The SOC12EMT performs from DC to 18 GHz with a VSWR of 1.5:1 max., insertion loss of 0.5 dB max. and isolation of 60 dB min. The SOC12EKT performs from DC to 40 GHz with a VSWR of 2.0:1 max., insertion loss of 0.9 dB max. and isolation of 50 dB min.
Logus Microwave
www.logus.com

26 to 34 GHz mmWave 2-Way Power Divider

VENDORVIEW

MECA expanded offering of 5G mmWave products. Featuring 2-way power dividers covering 26 to 34 GHz with 2.92 mm interfaces. Typical specifications of 1.3:1 VSWR, 22 dB isolation, 1.5 dB insertion loss and 0.4 dB amplitude balance. Also available are attenuators, terminations, bias tee's, DC blocks and adapters. Additionally octave & multi-octave models covering up to 50 GHz built by J-Standard certified Assemblers & Technicians. Made in USA and 36-month warranty.
MECA Electronics Inc.
www.e-MECA.com

Tiny High-Rejection LTCC Low Pass Filter

VENDORVIEW

Mini-Circuits' LFCG-530+ is an LTCC low-pass filter with a passband from DC to 530 MHz. This model provides 1 dB typical passband insertion loss and stopband rejection of 30 dB typ. The filter is capable of handling up to 4 W RF input power and provides a wide operating temperature range from -40° to 85°C. Housed in a tiny 0805 ceramic form factor with wraparound terminations, the LFCG-530+ is ideal for dense PCB layouts with minimal performance variation due to parasitics.
Mini-Circuits
www.minicircuits.com

18 to 40 GHz Ultra-Wideband High Accuracy Programmable Phase & Amplitude Controller

MAP1840-50E is a high accuracy programmable phase & amplitude controller, covers 18 to 40 GHz frequency, can change phase and amplitude of signal at minimum step 1° and 0.1 dB with dynamic range 360° and 50 dB. The absolute accuracy is 2° and 0.2 dB max. from ideal setup at any frequency. The size is 227×114×50 mm with 100 to 240 VAC. It is controlled through USB and Ethernet with user-friendly GUI. The unit provides DLL for users to program.
Mitron
www.mitron.cn

Capacitor Application Program

Passive Plus Inc.'s brand new Capacitor Application Program (C.A.P.) helps engineers and designers select capacitors according to parameters such as cap value and frequency. C.A.P. will provide options (Case Size, Terminations, Mounting), and parameters (ESR, Q, Impedance) along with Datasheets. C.A.P. allows engineers to insert capacitors requirements (Cap value, Frequency), producing Scattering Matrices (S2P) Charts. Once engineers have determined their capacitor requirements, C.A.P. also includes online RFQs and/or sample requests.
Passive Plus Inc.
www.passiveplus.com

High Frequency Waveguide Straights, Bends and Twists

VENDORVIEW

Pasternack has launched a new series of waveguide straight sections, bends and twists that are commonly used in

satellite communication, radar and airport security system applications. Pasternack's new waveguide transmission components feature high frequency ranges from 90 to 220 GHz in 3 waveguide bands, with waveguide sizes including WR-8, WR-6 and WR-5 and UG-387/U mod round cover style flanges. Additionally, all new high frequency waveguide components feature low VSWR performance of 1.15:1 typical.
Pasternack
www.pasternack.com

Coarse Microwave Discriminator

VENDORVIEW

PMI Model No. CMDA-4D1G6D1G-3TTL-SFF-DP is a 4.1 to 6.1 GHz, coarse microwave discriminator centered at 5.1 GHz. Using state of the art MMIC and MIC technology, the coarse microwave discriminator assembly consists of a four-way in-phase power divider where three of the outputs connect to bandpass filters with center frequencies of 4.7 GHz ± 270 MHz (1 dB bandwidth & 11 poles), 5.1 GHz ± 400 MHz (1 dB bandwidth and 16 poles) and 5.5 GHz, ± 270 MHz (1 dB bandwidth & 11 poles) respectively.

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

5 to 3000 MHz SPST High Isolation Absorptive Switch

The QPC4270 is a high isolation Silicon on Insulator (SOI) single pole single throw (SPST) 75Ω absorptive switch designed for use in CATV, satellite set top and other high performance communications systems, provided in a low cost small 6-pin DFN package.
Qorvo
www.qorvo.com

X-Band Filter

VENDORVIEW

RFMW announces availability of a portfolio of broadband SMD filters from Knowles (DLI). The portfolio is comprised of ceramic substrate filters using patented materials which exhibit excellent temperature stability and high K factors. Combined, these characteristics enable small size with high performance. Supporting general purpose and T&M applications, popular bandwidths include 2 to 4 GHz, 4 to 8 GHz, 8 to 12 GHz and 12 to 18 GHz. Catalog devices come complete with integrated shielding and the surface mount versions are designed for use on most RF PWB materials.
RFMW
www.rfmw.com

Pickoff Tees

RLC Electronics manufactures pickoff tees which offer excellent through-line insertion loss and pickoff stability rise times of < 10 Pico-seconds (at 40 GHz). Units are offered in standard frequency ranges from DC to 18 GHz, DC to 26 GHz and DC to 40 GHz, with the option to customize the Pickoff insertion loss value to meet customer specific requirements. The units provide extremely broadband signal monitoring in a very small package (0.54" × 0.39" × 0.32"). RLC offers both catalog options and customized options, and can provide form factor drop-in replacement/obsolescence assistance as needed.
RLC Electronics
www.rlcelectronics.com

Wideband Directional Coupler

The KBK-703S is a wideband directional coupler operating from 1 to 500 MHz. Product features include 11.25 dB coupling with excellent coupling flatness of ± 0.6 dB across the band. The mainline loss is 0.8 dB (Typ.) / 1.0 dB (Max.) and directivity of 25 dB (Typ.) / 20 dB (Max.). This 1.25" square SMA connectorized package can handle up to 1 W of input power and operates over the temperature range of -55° to +85°C. Other connector options are available.
Synergy Microwave Corp.
www.synergymwave.com

New**Products**

CABLES & CONNECTORS

Coax Adapters
VENDORVIEW

Fairview Microwave Inc. has introduced a new series of waveguide to coax adapters that are ideal for use in 5G, telecommunications, satellite communications, point-to-point radio, automotive radar and terrestrial communications applications. Fairview's new line of waveguide to coax adapters consists of 50 models with aluminum construction for reduced weight and compatibility with existing aluminum systems.
Fairview Microwave Inc.
www.fairviewmicrowave.com

Ruggedized Cable Line

HASCO's new ruggedized cable line includes high quality, low-loss, phase-stable cable assemblies constructed with robust connectors, internally ruggedized with multi-layer copper spiral and braided armor; offering excellent phase and amplitude stability with flexure. The ruggedized series of armored cables are RoHS Compliant and available in Male-to-Male and Male-to-Female configurations, with a range of connector and frequencies: SMA, 2.92mm, 2.4mm and 1.85 mm from 26.5 GHz up to 67 GHz.
HASCO
www.hasco-inc.com

Edge Launch Connector with 1.15:1 VSWR

Signal Microwave's new line of higher-performance edge launch connectors is designed for the thinner substrates used today. 1.15:1 max connector VSWR through 40 GHz (23 dB return loss). The data shown is for 2 connectors on a 1 inch 8 mil RO4003 substrate with an FR-4 backer. The new design of the connector is intended for substrate thicknesses between 5 to 10 mils (0.005" to 0.010"), (0.127mm to 0.254mm).
Signal Microwave
www.signalmicrowave.com

AMPLIFIERS

X-Band Solid State Power Amplifier

COMTECH PST introduced a new GaN amplifier for applications in the X-Band radar market. The AB linear design operates over the 9.2 to 10 GHz frequency range intended for use in radar applications.

The amplifier design features include options for control of phase and amplitude to allow for integration into high power systems utilizing conventional binary or phased array combining approaches for power levels of up to 10 kW.
COMTECH PST
www.comtechpst.com

Solid State Power Amplifier System
VENDORVIEW

Exodus Advanced Communications introduces its compact high power 5.4 to 5.9 GHz, 2.5 KW Pulse amplifier. Exodus AMP4039P-3 provides 2500 W with a minimum power gain of 64 dB. The unit has excellent gain flatness, fast Rise/Fall times and excellent pulse characteristics. Optional features for monitoring parameters are Forward/Reflected power, as well as voltage, current & temperature sensing for optimum reliability & ruggedness for all applications. Weight is <30 Kg, and dimensions of 19"W × 22"L × 8.75"H.
Exodus Advanced Communications
www.exoduscomm.com

SGA/SGN Series SSPA's

KRATOS General Microwave's SGA/SGN Series SSPA's offer GaAs/GaN technology reliability that can be customized to meet specific pulse or CW output powers. The product line supports both X-Band and Ku-Band applications with bandwidths up to 10% and offers peak power outputs up

New**Products**

to 400 watts. Designed for demanding defense, aerospace and satellite communication applications. General Microwave SSPA's have excellent power efficiency with demonstrated field proven performance and reliability. General Microwave's vertical integration process affords flexible layouts and architectures to meet individual specifications for electrical, mechanical and environmental parameters.
KRATOS General Microwave
www.kratosmed.com

Modelithics GaN HEMT Model for Qorvo QPD1006 Package

VENDORVIEW

Modelithics has introduced a new nonlinear model for the Qorvo QPD1006. The QPD1006 is a 450 W (P3 dB), internally matched discrete GaN on SiC HEMT that covers a frequency range of 1.2 to 1.4 GHz and operates from a 50 V supply rail. The GaN IMFET device is fully matched to 50 ohms. It comes in an industry standard air cavity package and is ideally suited for military and civilian radar. The device can support pulsed and CW operations.
Modelithics
www.Modelithics.com/MVP/Qorvo

SEMICONDUCTORS

RF Circuit Collection

Richardson RFPD Inc., an Arrow Electronics company, announced the availability and full design support capabilities for a comprehensive library of RF circuits from NXP

Semiconductors. This collection of RF circuits addresses a wide range of fast-growing markets, from 5G communication infrastructure to smart industrial applications. The collection, which enables browsing multiple design ideas at once to facilitate RF power amplifier development, includes discrete RF transistor evaluation boards and RF power amplifier IC evaluation boards.
Richardson RFPD Inc.
www.richardsonrfpd.com

SOURCES

40 GHz CW Signal Source

The SC5520A and SC5521A are part of its ultra-high frequency synthesizer series (UHFS) of signal sources. They boast a frequency tuning range of 160 MHz to 40 GHz stepping at 1 Hz resolution, and an amplitude range of -10 dBm to +15 dBm typ. with phase noise among the lowest in the market. These compact modules are ideal for system integration and appropriate for applications in communication transceivers, automotive radar and optics, and as clocks in modern day digital data converters.
SignalCore
www.signalcore.com

TEST & MEASUREMENT

High Output Power E-Band X3 Frequency Extender

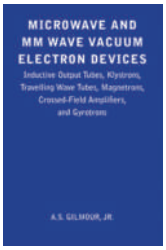
Eravant's model STE-KF312-13-S1 is a high output power E-Band X3 frequency extender that uses an input frequency range of 20 to 30 GHz at 0 dBm along with harmonic generation and filtering to produce a 60 to 90 GHz RF signal at +13 dBm. The extender is designed and manufactured as a bench top unit to extend the low frequency synthesizer or sweeper without losing all of the functionalities and features.
Eravant (formerly SAGE Millimeter)
www.eravant.com

Test Solutions for Wireless and High Speed Digital Interfaces

VENDORVIEW

In the wireless sector, the R&S CMW platform of testers simplify testing of Bluetooth®Low Energy (LE) devices and wearables. Rohde & Schwarz has developed a variety of Bluetooth®LE test solutions that perform RF tests over the air interface without a control cable. These unique solutions enable quick preconformance tests over the air and in shielded chambers. They support the test mode for Bluetooth Classic and direct test mode (DTM) up to Rel. 5.1 for Bluetooth LE.
Rohde & Schwarz
www.rohde-schwarz.com

MICRO-ADS



Microwave and MM Wave Vacuum Electron Devices: Inductive Output Tubes, Klystrons, Traveling Wave Tubes, Magnetrons, Crossed-Field Amplifiers, and Gyrotrons

A.S. Gilmour Jr.

Written by an internationally recognized as an expert on the subject of microwave (MW) tubes, this book presents and describes the many types of microwave tubes, and despite competition from solid-state devices (those using GaN, SiC, et cetera), which continue to be used widely and find new applications in defense, communications, medical and industrial drying. Helix traveling wave tubes (TWT), as well as coupled cavity TWTs are covered. Klystrons, and how they work, are described, along with the physics behind it and examples of devices and their uses. Vacuum electron devices are explained in detail and examines the harsh environment that must exist in tubes if they are to operate properly. The secondary emission process and its role in the operation of crossed-field devices is also discussed.

The design of collectors for linear-beam tubes, including power dissipation and power recovery, are explored. Discussions of important noise sources and techniques that can be used to minimize their effects are also included. Presented in full color, this book contains a balance of practical and theoretical material so that those new to microwave tubes as well as experienced microwave tube technicians, engineers and managers can benefit from its use.

To order this book, contact

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Thomas J. Fagan, Sr. Project Engineer, The Aerospace Corp.

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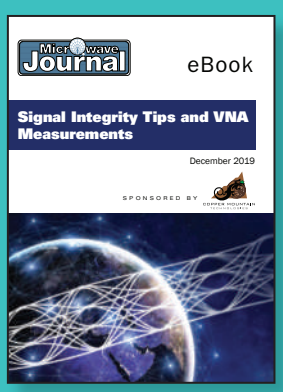

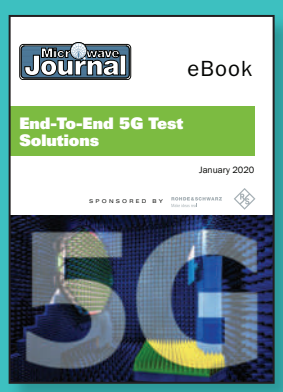

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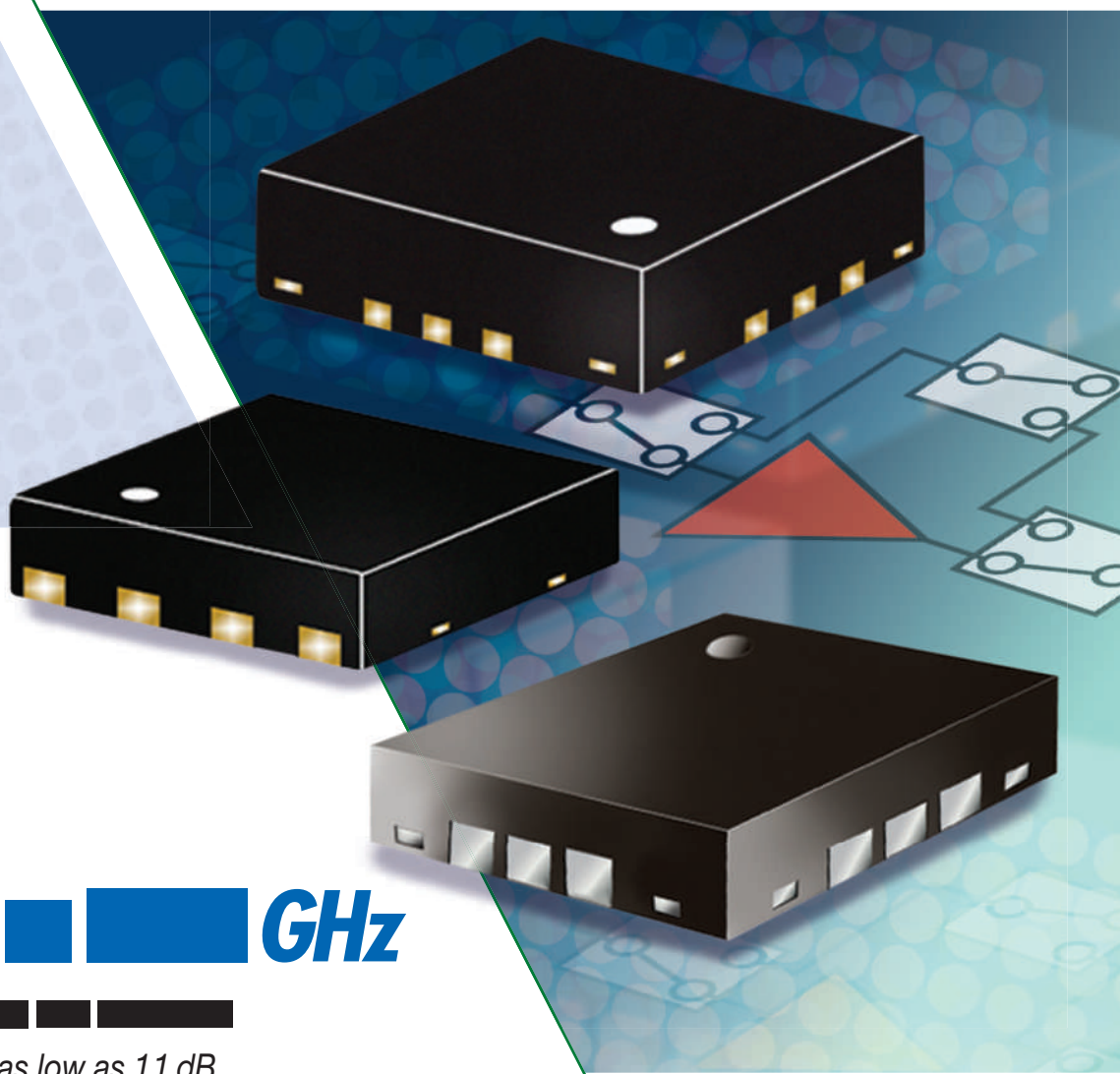

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584 Rev B_P

AnaPico Provides Swiss Precision and Quality at Affordable Prices

When microwave engineers Jakub Kucera and Urs Lott formed AnaPico in 2005, their goal was to build a company based in Switzerland, one focused on their common interest in microwave measurement. Their first product was an integrated 40 GHz sampling head IC for a large-signal network analyzer. That did not satisfy their ambitions, so they decided to develop test equipment, tapping the high quality standards Switzerland is known for with a twist: attractive prices.

Building on that vision, AnaPico now offers RF/microwave signal generators, frequency synthesizers and signal source analyzers. Their signal sources comprise single channel analog and vector signal generators and multichannel systems with frequency coverage to 40 GHz. The frequency synthesizers are available in single and multichannel units operating to 43.5 GHz. The signal source analyzer has a portfolio of measurement functions to characterize sources — amplitude and phase noise of CW and pulsed signals, Allan deviation and time stability and cross-spectrum FFT — and is available with frequency options from 1 MHz to 7, 26 or 40 GHz.

AnaPico's differentiation and success are based on the strong technical infrastructure in Zurich. It begins with the universities, a source of technical talent and collaboration to develop innovative products. All product development is done by the company, including the electronic hardware, mechanical design, firmware and the test and calibration software and instrument drivers. To achieve the goal of affordability, without compromising performance or quality, AnaPico creates innovative architectures and uses affordable components in the designs.

All AnaPico products are manufactured and tested in Switzerland, leveraging the country's strong manufacturing capabilities. Specialized local subcontractors manufacture the modules used in AnaPico's instruments, and the final assembly, calibration and testing are performed in-house. This local supply chain with optimized logistics enables AnaPico to achieve short lead times on product orders, even for custom designs. Consistent with its commitment to quality, AnaPico is ISO9001:2015 certified.

The founders believe a strong and healthy company culture leads to great customer service, which creates a positive reputation in the market. AnaPico's culture builds on Switzerland's reputation for strong engineering and quality. The founders' own emphasis on innovation and quality is translated to AnaPico's business strategy, and they work to maintain a team environment where each person supports the company's goals, with a commitment to maintain its reputation for engineering excellence.

Since its formation, AnaPico has served customers worldwide, developing unique strategies for each market region: Europe, the U.S. and Asia Pacific. To support its large customer base, AnaPico has established distribution networks in more than 30 countries, including a tight partnership with Berkeley Nucleonics in the U.S.

Jakub Kucera, AnaPico CEO, says the firm has always been attentive to customers' special needs, being open to customization requests. This responsiveness begins with designs that enable cost-effective customization. "We do what the customer wants, and we do it quickly." This philosophy and its strategy have proven successful. AnaPico is growing rapidly and has been profitable for ten consecutive years.

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Model	Type	Frequency (MHz)	Power (W CW)	Coupling (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
C8740	Dual	20-512	200	40	0.3	Tabs	1.5 x 0.95 x 0.55
C9655	Dual	20-1000	100	30	0.7	Tabs	1.5 x 0.95 x 0.55
C8631	Dual	20-1000	150	40	0.35	Tabs	1.5 x 0.95 x 0.55
C10561	Dual	20-1000	250	50	0.1	SMT	1.35 x 1.0 x 0.15
C8025	Bi	500-3500	125	30	0.3	Drop-In	1.3 x 1.0 x 0.07
C8098	Bi	800-2000	200	30	0.25	Drop-In	1.3 x 1.0 x 0.07

0° (In-Phase) Combiners/Dividers

Model	Type	Frequency (MHz)	Power (W CW)	Isolation (dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
D9888	2-Way	1000-3000	500	15	0.35	SMT	2.8 x 2.2 x 0.27
D9922	2-Way	2000-6000	200	15	0.35	SMT	1.4 x 1.1 x 0.14

90° & 180° Hybrids

Model	Type	Frequency (MHz)	Power (W CW)	Amp. Bal. (±dB)	Insertion Loss (dB)	Mounting Style	Size (inches)
QH9056	90°	30-520	400	1.2	0.80	Drop-In	4.0 x 1.7 x 0.29
QH9304	90°	60-1000	150	1.0	1.0	Drop-In	2.0 x 1.0 x 0.16
QH8849	90°	80-1000	250	1.0	0.65	Drop-In	2.9 x 2.1 x 0.31
QH11489	90°	80-1000	600	0.8	0.6	Drop-In	3.33 x 2.25 x 0.31
QH8100	90°	100-512	250	0.5	0.45	Drop-In	3.3 x 1.52 x 0.28
QH8922	90°	150-2000	100	1.0	0.75	SMT	1.47 x 1.13 x 0.16
QH11643	90°	200-1000	200	0.55	0.4	SMT	2.8 x 0.75 x 0.16
QH10900	90°	380-2500	150	0.6	0.55	Drop-In	1.3 x 1.3 x 0.15
QH7900	90°	450-2800	125	0.45	0.55	SMT	1.5 x 1.1 x 0.095
QH7622	90°	500-3000	150	0.6	0.55	Drop-In	1.65 x 1.1 x 0.09
QH11687	**90°**	**500-6000**	**150**	**0.7**	**0.75**	**SMT**	**1.28 x 1.08 x 0.13**
QH11113	90°	600-4000	150	0.7	0.5	SMT	1.29 x 0.99 x 0.12
QH10756	90°	700-6000	100	0.6	0.55	SMT	0.75 x 0.45 x 0.09
QH10541	90°	700-6000	150	0.6	0.5	SMT	0.86 x 0.66 x 0.09
QH10089	90°	800-2800	200	0.4	0.35	SMT	1.25 x 0.55 x 0.08
QH11805	90°	800-3200	200	0.5	0.4	Drop-In	2.2 x 0.8 x 0.174
QH8105	90°	800-4200	150	0.5	0.55	Drop-In	1.5 x 1.08 x 0.09
H10125	180°	1000-3000	350	0.3	0.5	SMT	2.31 x 1.21 x 0.25
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	0.9	SMT	0.65 x 0.5 x 0.07
QH10148	90°	2000-6000	100	0.5	0.3	SMT	0.75 x 0.45 x 0.08
H10126	180°	2000-6000	100	0.4	0.8	SMT	1.15 x 0.6 x 0.14

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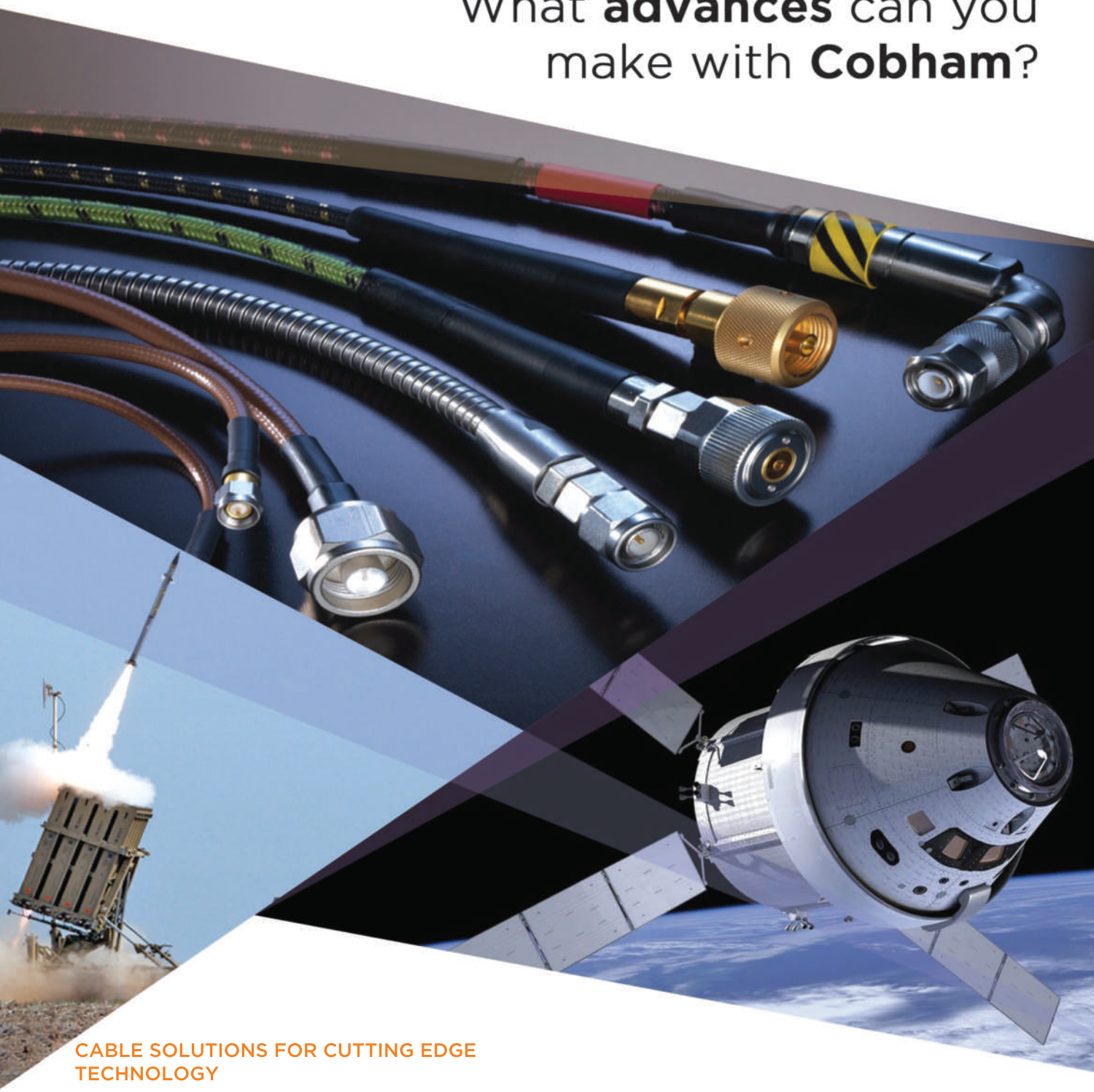

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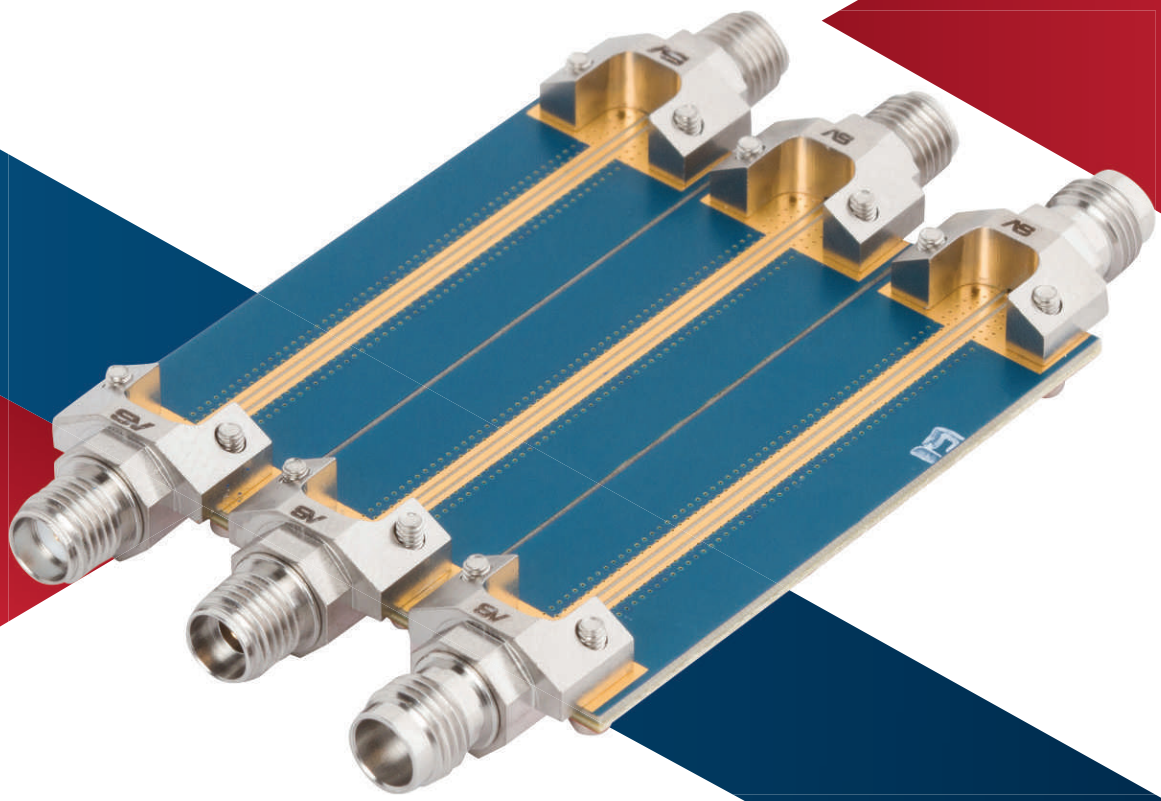

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INVITED PAPER

Designing Coaxial Cable Assemblies for High Performance and Reliability

Pasternack
Irvine, Calif.

Outside the traditional parameters such as insertion loss, return loss and VSWR found on datasheets, additional design and construction methods can enhance a coaxial cable for more accurate and consistent performance or a longer operational lifetime. Many applications call for precise construction to ensure repeatable and reliable performance. This article dives into some of these requirements, the detrimental effects of poor cable construction and fabrication methods to enhance a coaxial cable's performance.

INSERTION LOSS

Dielectric Choice

Air is a perfect dielectric, allowing signals to pass at nearly the speed of light, relatively unimpeded. This, however, is not practical in commercial coax construction, as air provides no structural support to uniformly separate the inner and outer conductors, so another dielectric is used (see ***Figure 1***).

The main intrinsic sources of loss within a coax are:

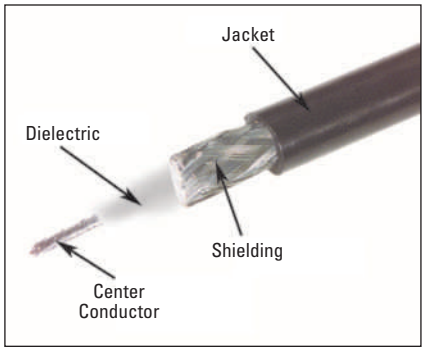
- Resistive losses in the inner and outer conductors.
- Loss tangent and conduction current in the dielectric.

While the first source is hard to avoid, addressing the latter has more options. The relative permittivity or dielectric constant of the insulating material contributes to the overall attenuation of the coax, given by the equation

$$L_d = \frac{\pi f}{c} * \tan\delta\sqrt{\varepsilon_r} \qquad (1)$$

where L_d is the loss due to the dielectric, f the frequency, tanδ the loss tangent, ε_r the dielectric constant and c the speed of light. The dielectric constant of high density polyethylene (HDPE) is 2.34, low density PE is 2.28 and foamed PE drops to 1.6. Introducing air into the dielectric nearly halves the dielectric constant and greatly reduces the loss tangent. Solid dielectrics exhibit the highest insertion loss, low density dielectrics have moderate loss and expanded or microporous dielectrics have the least loss.

Still, using a solid dielectric provides benefits of homogeneity and isotropy, while lower density materials typically have a less consistent dielectric constant along the length of the cable. For heterogeneous, anisotropic systems such as microporous structures, the dielectric constant is heavily dependent on the shape of the cells within the structure,[1] and the expanded dielectrics are also the least temperature sensitive, with stable loss and phase.



▲ Fig. 1 Typical RF/microwave cable assembly construction.

Wider Coax

Although a dimensionally smaller coax generally operates mode-free to higher frequencies, smaller diameter coax is often chosen because of its reduced mass and greater flexibility. The reason for this increased flexibility is shown by the bend stress equation:

$$\sigma = E\frac{y}{R} \qquad (2)$$

where σ is the bend stress, E the elastic modulus, y the distance from the neutral axis and R the radius of the bend. The bend stress increases linearly from the neutral axis, so a thicker coax experiences more strain at the farthest point from the neutral axis than does a thinner cable.

A thicker cable, however, has less resistive loss due to the greater amount of material in the metallic conductors—yielding less overall loss. Equation 3 shows the loss per unit length is inversely proportional to the diameter of the inner and outer conductors.

$$L_R = \sqrt{\frac{f}{\pi}}\left(\frac{1}{d}\sqrt{\frac{\mu_{in}}{\sigma_{in}}} + \frac{1}{D}\sqrt{\frac{\mu_{out}}{\sigma_{out}}}\right) \qquad (3)$$

where L_R is the resistive loss of the conductors, d and D the diameters of the inner and outer conductors, σ_{in} and σ_{out} the conductivity of the inner and outer conductors and μ_{in} and μ_{out} the permeability of the inner and outer conductors. Many low loss cables are generally thicker than their RG counterparts and can be used for large communications installations, such as cellular. For cellular installations, passive intermodulation distortion (PIM) is also a major consideration.

PIM IN HIGH POWER, MULTI-CARRIER SYSTEMS

Depending upon the operating frequency and application, the choice of connector head can be vital to achieve good performance. For cellular installations with two carrier frequencies and high signal levels, PIM can occur from the mixing of these two signals in the transmission line. PIM can also occur in the passive components used in multicarrier systems, including the circulators, duplexers, attenuators, waveguide and antennas. Although the nonlinear intermodulation distortion (IMD) products from PIM are generally at low signal levels, the resulting PIM can degrade the dynamic range of the system—unacceptably in highly sensitive radios, where PIM can interfere with the transmit and receive bands of a communications link.

There are two main sources of PIM:

- Electrothermally induced PIM (ET-PIM), occurring at a rough surface or a metal junction.
- Paramagnetic or ferromagnetic materials.

Other sources, such as tunneling and nonlinear conductivity, can exacerbate the problem of PIM but are not known as major contributors.

With ET-PIM, any metallic surface is a resistive element whose resistance is a function of its temperature and temperature coefficient of resistance (TCR), per the thermo-resistance equation. A thermal and electrical interdependence occurs from the dissipation of electrical power causing self-heating. This can be described by its thermal capacity, the ability of a material to store heat, and the rate at which the heat is radiated into the surrounding environment when the temperature increases. These self-heating effects behave dynamically with a periodically varying resistance, especially when two or more high frequency signals are applied and with a nonlinear metal contact, such as inadequate mating or surface roughness. The combination of thermal resistance and capacitance represents a lowpass filter in the thermal domain. If the beat frequency of the two carriers falls within this thermally created lowpass filter, the periodic heating and cooling of the resistive element functions as a passive electrothermal mixer, upconverting the envelope frequencies at baseband to RF frequencies and creating PIM.[2-3]

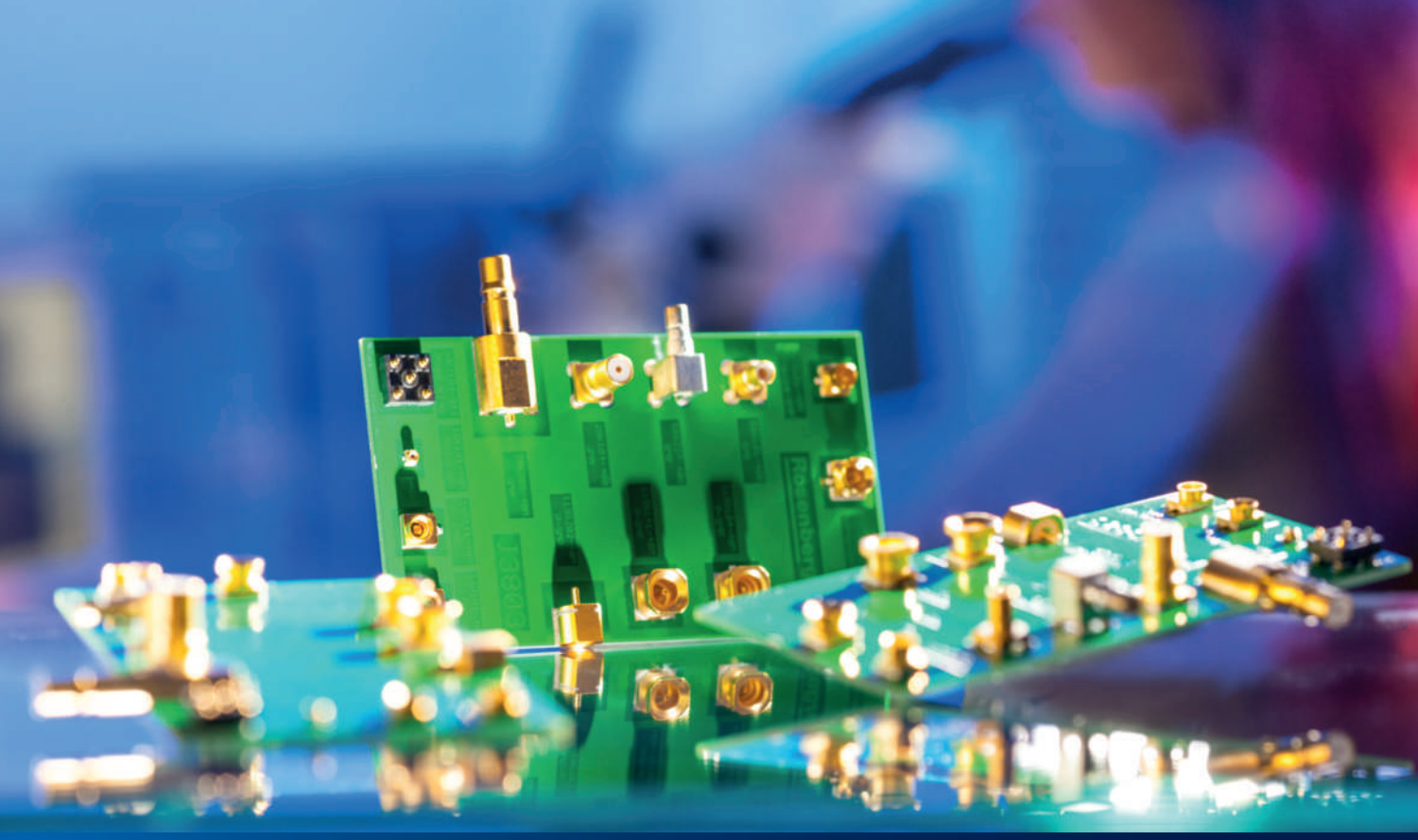
ET-PIM has a strong link to current density, the TCR and the electrical and thermal conductivities of the metals used in the connector heads (see ***Table 1***). A low TCR and high thermal conductivity material with moderate current densities will yield lower PIM. Current density increases at high frequency due to the skin effect; this is worse with dimensionally thinner coax, as the current density increases as the radial distance to the center conductor decreases. The uniformity of the current along the face of a metal also gets worse with increasing surface roughness. Microscopic inconsistencies on a metallic surface can limit the amount of current flowing through the junction, adding to poor PIM performance. A wider connector head would likely be better, with an adequate tightening of the joints.

Using magnetic materials is typically a secondary contributor to PIM in sensitive cellular systems. Here, PIM is caused by the magnetic hysteresis of ferromagnetic materials or the irreversible magnetization of the ferromagnetic material due to an externally applied alternative magnetic field. Nickel and chromium are common ferromagnetic materials used in coaxial connector heads. This source of PIM can be effectively eliminated by carefully selecting the base and plating materials in the connector head, such

TABLE 1

PARAMETERS OF COMMON METALS

Material	Thermal Conductivity, k (W/m-K)	Electrical Conductivity, σ (10^6 S/m)	Thermal Coefficient of Resistance, α (per °C)
Platinum	107	9.3	0.0037
Copper	385	58.7	0.004
Gold	317	44.2	0.0037
Silver	406	62.1	0.0038
Brass	109	15.9	0.0015
Nickel	91	14.3	0.0059
Stainless Steel	15	1.3	-
Nickel Chromium	11.3	~1	0.00005–0.0004
Beryllium Copper	109	~10	0.0010–0.0018



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as a plated brass body. In some cases, nickel-chromium components function better than platinum non-ferromagnetic components; this could reflect the improved TCR of nickel-chromium compared to platinum.[4]

TEMPERATURE EFFECTS

Amplitude Variation

Coaxial cables will physically expand with increasing temperature, and these variations cause measurable differences in the insertion loss and phase. The increase in loss is due to the decrease in conductivity of the metallic material with temperature: as the temperature increases, molecular vibrations increase the collisions of the electrons traveling through the medium. This phenomenon is commonly seen with highly conductive materials, since the thermal conductivity increases with average particle velocity, while electrical conductivity decreases due to the vibrations inhibiting the forward movement of charge, as described by the Wiedemann-Franz law. In general, the resistance of pure metals increases linearly with temperature.

The resulting increase in insertion loss with increasing temperature is generally unavoidable; however, phase instability can be optimized by carefully selecting materials.

Phase Stable Coax

Phase instabilities are a consequence of the change in the electrical length, i.e., the number of wavelengths for a length of cable. For most systems, this is not a concern; however, for systems relying on phase for constructive or destructive interference—beam steering, for example—repeatable and stable phase and amplitude over temperature and cable flexing is vitally important.

Phase stability is a measure of the ability of the insertion phase ($\angle S_{21}$) of a coaxial cable to remain constant with temperature change and mechanical stressors such as flexure, vibration or bending. The time delay and insertion phase are related by

$$\tau = -\frac{\angle S_{21}}{360f} \quad (4)$$

where f is the frequency; τ the time delay, usually measured in nanoseconds; and $\angle S_{21}$ the insertion phase, measured in degrees. The relationship between time delay and the length and relative permittivity of a coaxial cable is given by

$$\tau = \frac{l\sqrt{\varepsilon_r}}{c} \quad (5)$$

where l is the mechanical length of the coax. Both l and ε_r change with temperature. While the increase in length at high temperatures generally opposes the decrease in dielectric constant, they are not typically in proportion to yield stable time delay or phase.

As the coax will experience linear volumetric expansion at elevated temperatures and contraction at cooler temperatures, the linear coefficient of thermal expansion (CTE) is a useful parameter for understanding the incremental increase and decrease in the size of a solid material with respect to temperature—as it will be directly proportional to the increase or decrease in the cable. ***Table 2*** shows the CTE of some materials used in coaxial assemblies and the temperature coefficients of the dielectric constant, showing the insulating materials expand more rapidly than the metals. The cable length is fixed by the conductors, due to their inherent stiffness, while the elastic modulus of metals are typically in the hundreds of gigapascals (GPa) and insulators rarely go beyond 5 GPa. Therefore, the rapidly expanding insulating material becomes compressed between the inner and outer conductors. This compression is more pronounced at lower temperatures, where the contraction of the shielding causes a density increase in the dielectric that can ultimately change the dielectric constant, depending on the type of material used. The dielectric also affects the electrical length of the cable, from the change in the dielectric constant over temperature. As stated earlier, foamed dielectric materials tend to be more stable with temperature changes.

The applications for a phase stable cable often require more than one cable to distribute system signals. In such cases, the phase change among the coax cables in a set must be as close as possible. Skew-matched cable assemblies ensure a tight phase match between cables, in terms of length and ε_r, despite temperature changes or flexure. Phase tracking—close matching of phase—between coaxial assemblies is also important. Preconditioning through a controlled temperature cycling of the cables can be performed to provide temperature stress relief, so the cables will perform reliably in harsh climates. This process anneals the dielectric and metallic conductors, reducing the likelihood of surface cracks and internal stressors that could cause premature failure. In addition to temperature variation, phase instability often occurs from the flexure at the point of the bend.

MECHANICAL STRAIN

Vibrations, Bends and Flexure

Mechanical strain can have a significant impact on electrical performance. Cables may be subject to vibrations from wind shear or frequent flexure caused by the application. Both the connector heads and coax can undergo a combination of tensile, compressive, bending, shear and torsional forces. Of all these, coaxial strain from frequent bending or flexure is particularly troublesome, as it increases the strain on the connector-cable junction and the shielding. Referring to equation 2, the forces on the shielding material are far greater than those on the center conductor and dielectric, and the elastic modulus of the jacketing and dielectric polymers are several orders of magnitude lower than those of the metallic conductors in the shielding and center conductor, making them far less susceptible to bending stresses. Since the coax is orthotropic and symmetric, designed for impedance and continuity, the neutral axis would most likely be along the very center of the center conductor. Therefore, the center conductor will typically experience less mechanical strain due to bending than will the shielding. For this reason, flexible coaxial cables should have a combination of these qualities:

- Smaller inner and outer conductor diameters, for less overall bend strain.

TABLE 2

COAXIAL ASSEMBLY MATERIALS[5]

Material	CTE (ppm/°C)	Temperature Coefficient of Dielectric Constant (ppm/°C)
Copper	18	-
Aluminum	24	-
Solid PE	200	–350 (from 0 to 60°C)
Foamed PE	-	–110 (from 25° to 40°C)
PUR	57.6	-
PTFE	100	–400

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- Strain relief boots or overmolding.
- Armoring to prevent bends beyond the prespecified bend radius.

These attributes will mitigate the strain at the bend in a coax and yield better phase performance. Almost any bend in a coax will cause a bend at the joint between the connector head and cable, which can cause the relatively elastic cable to push against the stiff crimp joint, eventually kinking the cable or breaking through the jacketing material. Strain relief boots are nearly always necessary in assemblies that experience high flexure.

Impact, Crushing and Abrasion

Coaxial cables can experience shear forces due to crushing or torsion from installation or daily use. Typically, a cable can withstand forces from a human step; however, the strain from a rodent gnawing or from the weight of a vehicle could cause enough pressure to deform the cable and cause failure. Typically, basic abrasion and tear resistance are ensured by using a strong jacketing material such as polyurethane (PUR). Additional crush resistance is enabled through armoring; often an interlocked metallic hose can provide extraordinary immunity to crushing.

SUMMARY

The design of a coaxial cable requires careful consideration of its application, as the cable will likely not function properly without appropriate definition. Low loss, phase stable cables often require the use of relatively low dielectric constant materials and extensive thermal cycling. Cables that are expected to withstand bending and flexure will likely be smaller in diameter or have external features to prevent failure, such as armoring or strain relief boots. Low loss coaxial cables for cellular installations are typically thicker than their RG counterparts and have low PIM connector heads that do not use ferromagnetic metals. Every application calls for a slight adjustment in cable fabrication to achieve long operational lifetimes and optimized electrical performance.■

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INVITED PAPER

Wireless Infrastructure RF Connector Market to Thrive as 5G Deploys

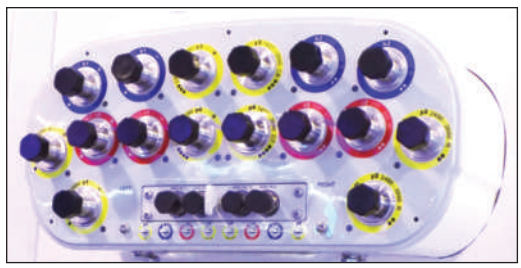
Earl Lum
EJL Wireless Research LLC, Half Moon Bay, Calif.

RF coaxial connectors are still alive and kicking, even with the promise of massive MIMO (mMIMO) antenna systems threatening to eliminate RF jumper cables and RF connectors on these cables, the remote radio units (RRU) and base station antennas.

Historically, the infrastructure market has transitioned from N-type to 7/16 DIN to 4.3/10 DIN (or 4.3-10) to NEX10 and 2.2/5 (or 2.2-5) coaxial connectors. The need for smaller RF coaxial connectors has been driven by the physical size limitations of the base station antenna faceplate (see ***Figure 1***). This photo shows a 16-port base station antenna using 4.3/10 DIN connectors. Current generation antennas may require up to 30 or more RF connector ports, which is possible but not feasible, using current 4.3/10 DIN connectors. The example with 16 ports is near the maximum RF connector port density that can be achieved with the standard width of a base station antenna.

IS SMALLER BETTER?

Beyond the current 2.2/5 and NEX10 shrink lies a new solution from Telegartner, the 1.5/3.5 (or 1.5-3.5) connector, which is 75 percent smaller than the current 4.3/10 DIN connectors (see ***Figure 2***). This is the newest connector in the Telegartner Cell IQ family. The footprint is based on the SMA form factor of a 12.7 mm square footprint for a flange mount. These connectors are targeted for small cell applications supporting up to $^1/_4$ in. corrugated coaxial cables. While smaller is better, outdoor small cells currently support up to four transmit and four receive (4T4R) configurations and are not space limited using 4.3/10 DIN connectors, although some equipment manufacturers migrating to NEX10 or 2.2/5 connectors.



▲ Fig. 1 Connectors for a Huawei Technologies 16-port antenna. *Source:* EJL Wireless Research LLC.

RF cable losses are still critical for outdoor applications, with jumper cables typically a minimum of $^3/_8$ in. diameter and $^1/_2$ in. diameter preferred. Indoor small cells typically have integrated antennas that use SMT antenna components rather than flange mount antenna ports. So it is somewhat perplexing which small cell applications would require a 1.5/3.5 connector. Additionally, creating a four-port cluster connector with the 1.5/3.5 for macrocell applications is not feasible, due to potential limitations using $^1/_4$ in. coaxial cables with their RF losses. Perhaps the market for the 1.5/3.5 is test and measurement equipment, where front panel space is limited, or for mMIMO switch matrices supporting the test equipment.

ONE FOR ALL AND FOUR (OR FIVE) FOR ONE

As previously noted, a standard width antenna face plate can typically support up to 16 single RF ports, maybe 18 or 20 if the area reserved for the AISG remote electrical tilt interface is reduced. Beyond this port density, a cluster connector solution is the only viable approach to support the growing number of ports for passive antennas.

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Fig. 2 1.5-3.5 DIN connector. *Source:* Telegärtner Karl Gärtner GmbH.

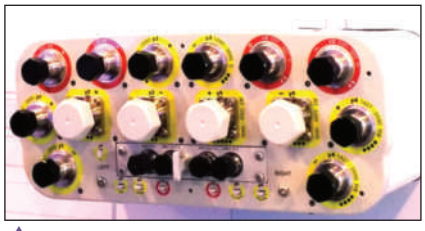

Fig. 3 Connectors for a Huawei 26-port FDD/TDD antenna. *Source:* EJL Wireless Research LLC.

Fig. 4 Huawei MQ4/MQ5 cluster connector. *Source:* Huawei Technologies.

Fig. 5 Rosenberger NEX10-4 cluster connector. *Source:* Rosenberger.

Fig. 6 CommScope MLOC-4 with NEX10 compatible cluster connector. *Source:* CommScope.

cy bands for the U.S. market (600, 700, 800, 1900 and 2100 MHz) and seven frequency bands for mobile networks in Europe and the rest of the world (700, 800, 900, 1500, 1800, 2100 and 2700 MHz), each having a separate RRU for each frequency band. The port count for the RRUs in each frequency band has been increasing as the MIMO order has increased, resulting in the current 4T4R RRU configuration for most mid-band (1800 to 2700 MHz) RRUs globally. A fully loaded, seven band, passive antenna array supporting 4×4 MIMO RRUs requires 28 antenna ports.

The advent of 5G is forcing mobile operators to consolidate all legacy 2G/3G/4G services onto a single antenna to make room for the new 5G NR antennas for each sector at a macro site. In many countries, TDD frequency bands are available in addition to FDD frequency bands for LTE services. Many mobile operators are choosing to deploy a multi-mode FDD/TDD service, which requires an FDD/TDD antenna supporting all of the operator's frequency bands. The typical TDD configuration supports 8T8R RRUs, which requires nine RF ports. This leads to cluster connectors in 4- and 5-port configurations, where two clusters can support all nine ports. The FDD/TDD antenna example shown in ***Figure 3*** has 10 single-port connectors along the perimeter of the antenna faceplate and four multiport clusters in the center. Each pair of the multiport cluster connectors is a 4-port + 5-port combination supporting a single 8T8R RRU, resulting in a total of 26 RF ports and two calibration ports for the TDD bands.

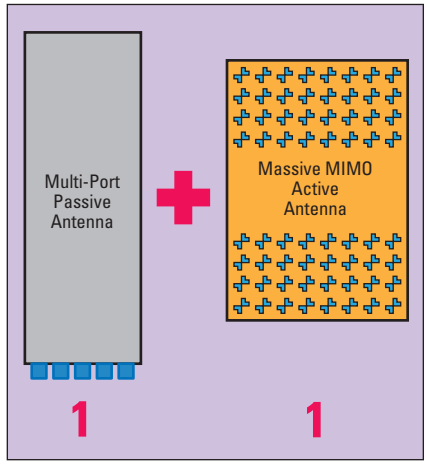

Fig. 7 5G 1P + 1MM-ARS antenna configuration, each sector.

While the NEX10 and 2.2-5 connectors are available in a single port, the better use of the connector is as a multiport cluster. The Next Generation Mobile Networks (NGMN) Alliance recently recommended the Huawei Technologies MQ4/MQ5 cluster connector to support TDD 8T8R 5G RRU and antenna configurations. This was one of four connector systems submitted to the NGMN Alliance:

- 2.2-5
- MLOC (CommScope)
- MQ4/MQ5
- NEX10

Following aggressive lobbying efforts by Huawei, the MQ4/MQ5 solution was chosen (see ***Figure 4***). The Rosenberger NEX10-4 cluster connector is shown in ***Figure 5***, and CommScope's MLOC-4 cluster connector, designed to be compatible with the NEX10, is shown in ***Figure 6***. Unlike the others, the CommScope MLOC cluster solution is agnostic to a specific connector design and can be used with the 2.2-5, NEX10 or MQ4/MQ5. The MLOC solution is unique because it eliminates the need to use a torque wrench in the field, preventing issues from hand tightening the RF connectors.

One unresolved issue with the current NGMN Alliance recommendation: it only covers the TDD mode, not FDD. 4-port multiport cluster connectors for FDD systems are quickly approaching, given the continued increase in the number of frequency bands, as well as 8 x 8 MIMO FDD.

5G NR DRIVES PASSIVE ANTENNA PORTS AND CONNECTORS

For 5G applications using a 1+1 antenna configuration for each sector, one position will be occupied by a high port count (>20) passive antenna supporting FDD and FDD + TDD modes, while the other position will be occupied by a mMIMO antenna radio system (MM-ARS), typically 32T32R or 64T64R (see ***Figure 7***).

5G MM-ARS equipment is not inexpensive and is extremely power hungry. Considering capital and operating ex-

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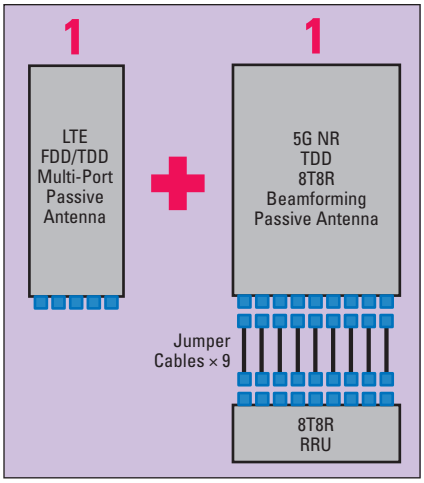
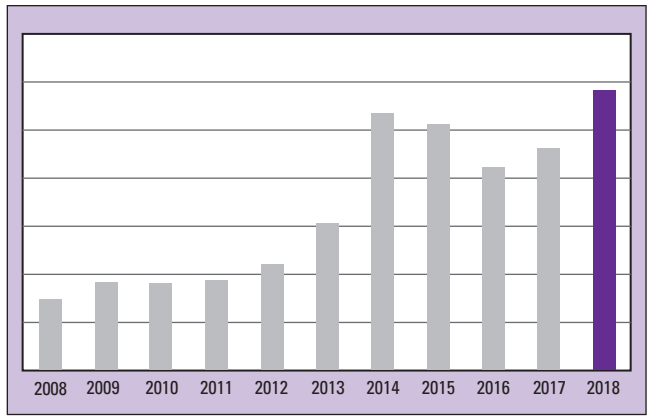
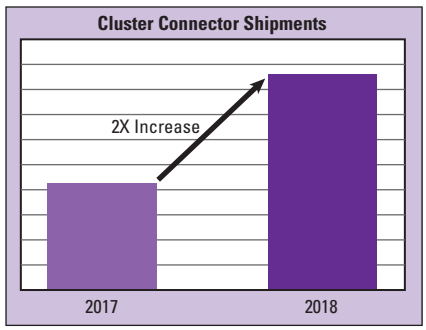


▲ Fig. 8 5G 1P + 1P antenna configuration, each sector.

penses, the least expensive way for a mobile operator to deploy 5G is to use a 1+1 configuration, replacing the MM-ARS with a traditional passive antenna (8T8R) and RRU (see ***Figure 8***). This second antenna will only support the 5G frequency bands (typically, Band 41 at 2.5 GHz and Band 42 at 3.5 GHz). Current deployments in Europe and Asia are using 5G passive antennas in both dense urban and rural areas where the mobile traffic does not require an MM-ARS solution. A single band 5G NR passive antenna typically uses single-port connectors, for a total of nine: eight RF ports and one calibration port. Nine jumper cables are also required for this configuration. Either N-type or, more likely, 4.3-10 DIN connectors will be used for the antenna connectors, the jumper cables and the RRUs, the latter depending on the equipment manufacturer. A 5G NR 8T8R passive antenna requires a total of 36 RF connectors per sector to support the RRU, antenna and jumper cables—in addition to the multitude of RF connectors for the legacy antenna configuration.



▲ Fig. 9 Base station antenna RF connector port shipment trends, 2008–2018.



▲ Fig. 10 Relative RF cluster connector shipments, 2017–2018.

MARKET TRENDS

EJL Wireless Research has been tracking base station antenna shipments and port counts since 2008. We believe we have the most extensive database of base station antenna shipments globally. From this, we extracted the total RF antenna port shipments each year to create a view of shipments over the past 10 years (see ***Figure 9***). The dip in 2015 and 2016 largely reflects the completion of the 4G network in China. The rebound in 2017 and 2018 shows the emergence of 4 × 4 MIMO FDD LTE and dual-mode FDD/TDD antennas.

While 4.3/10 DIN connector shipments nearly tripled in 2018, legacy 7/16 DIN also increased by 10 percent. While all new antenna designs are using 4.3/10 DIN connectors, legacy antennas still use 7/16 DIN connectors; antenna manufacturers did not redesign and upgrade their legacy antennas with the new 4.3/10 DIN connectors as an option. Nearly all new RRU designs are using 4.3/10 DIN connectors, with some equipment manufacturers opting for the smaller NEX10 or 2.2/5 connectors.

Cluster connector shipments for the base station market have more than doubled from 2017 to 2018 (see ***Figure 10***), and we expect continued growth from 2019 due to shipments of dual-mode FDD/TDD antenna solutions. The jumper cables to support RF cluster connectors are in a pigtail configuration, with one cluster connector at the antenna and single connectors at the RRU.

The following trends over the next five years will drive single-port and multiport cluster connectors in the base station infrastructure market:

- Migration from 2 × 2 MIMO (2T2R) RRUs to 4 × 4 MIMO (4T4R) RRUs supporting FDD LTE.
- Emergence and adoption of FDD 8 × 8 MIMO RRU technology for mid-band (1800 to 2700 MHz) frequencies.
- Adoption of high port count (>20) dual-mode, multi-band FDD/TDD antennas.
- Adoption of single- and dual-band TDD 5G NR 8 × 8 MIMO beamforming antennas.
- Use of the Citizens Broadband Radio Service (CBRS) spectrum in the United States, supporting 4 × 4 MIMO FDD.

The RF connector market, whether single connectors or multiport clusters will thrive. While the crossover point for unit shipments of the 4.3/10 DIN connector compared to the legacy 7/16 DIN connectors will eventually occur, we believe that 2020 or 2021 may be the time, as 2018 RF connector volumes heavily favored 7/16 DIN.■

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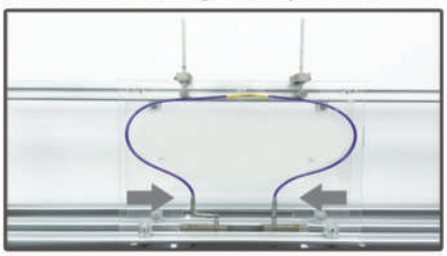
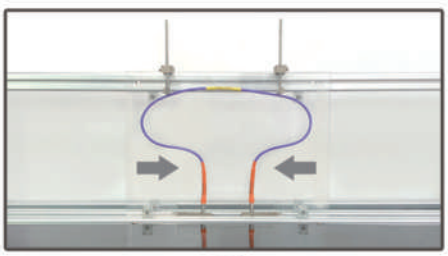


T26 Cable Assembly Test (Straight Connectors)



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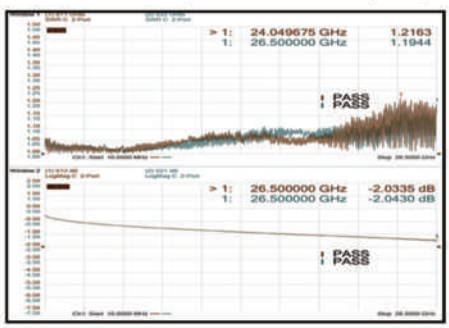
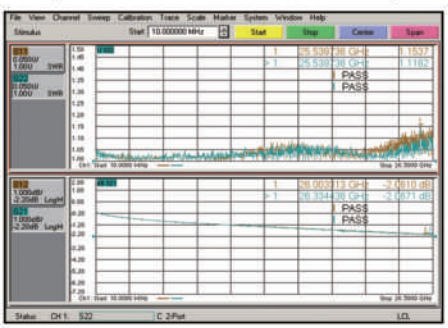


(3.5mm M - 3.5mm M, 1 Meter)



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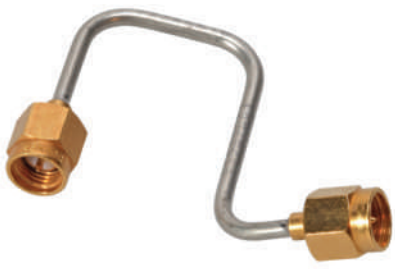

Microwave Cable Family Provides Phase Stability over Temperature

HUBER+SUHNER
Herisau, Switzerland

The challenge of phase stability in coaxial cable assemblies is a recurring topic, which an increasing number of equipment manufacturers are encountering when designing or verifying their systems. Any application where temperature plays a role is subject to phase changes.

For example, temperature fluctuations influence the signal transmission in differential pairs, which are used to eliminate noise and increase a system's digital data rate. If every channel uses at least a pair of cables to transmit or receive information, the effect of temperature will multiply and will tangibly affect phase stability, meaning different electrical lengths for the same application. Phased array antennas are another example of the relevance of phase sensitive components, since the accuracy of the system relies on the phase of each individual component in the signal chain. Satellites, such as used for synthetic aperture radar, are even more sensitive to the environment. Typically, a cable bus surrounds the satellite and is exposed unpredictably and simultaneously to sun and shadow. Unless phase invariant cables are installed, the effects of these temperature differences will need to be corrected, often using complex algorithms or additional subsystems. In test and measurement applications, a high degree of measurement accuracy is very important, such as network analyzers requiring phase invariant components.

As seen, phase stable interconnects are an essential part of the system and must be comprehended from the beginning of the design. Failure to do so can unnecessarily increase the cost—multiplying by several hundreds the cost of an individual cable assembly. It may also have severe consequences in the final application, whether radio systems, radar, direction finding or transport signaling.

The challenge to achieve phase stability over temperature in coaxial cables begins with one of the most common dielectric materials, PTFE. Since PTFE offers excellent dielectric properties at high frequencies, it should be no surprise that most microwave cables use this material. Unfortunately, its phase change characteristic with temperature is nonlinear, especially noticeable in the 15°C to 25°C range, an effect known as the "PTFE knee" (see ***Figure 1***). The figure compares the coefficient of temperature expansion (CTE) of PTFE with the fluoropolymer FEP, which has a smooth change over temperature.

To end the compromise between the optimal dielectric properties and excellent phase stability, HUBER+SUHNER has released a Constant over Temperature (CT) cable family. The family was

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developed for phase-critical applications requiring precision electrical length, and it offers three platforms providing stable and reliable interconnect solutions for a range of applications.

For static applications requiring a stationary connection with excellent VSWR, HUBER+SUHNER offers its semi-rigid CT product, with the added capability to fit in small, high density areas and save connection time. Lightweight, these semi-rigid cable assemblies reach 40 GHz and are available in 0.086 in. and 0.141 in. sizes. They are widely used in test and measurement and aerospace and defense subsystems.

For static applications needing a hand-formable cable without tooling, HUBER+SUHNER offers the Sucoform CT. Sucoform CT enables space saving routing and is especially suitable for delay lines in communication systems, where low passive intermodulation (PIM) is required. Sucoform CT is also available in 0.086 in. and 0.141 in. sizes, with frequency coverage to 40 GHz.

HUBER+SUHNER also provides a solution for "dynamic" applications needing a combination of high flexibility and high shielding effectiveness at high frequencies. Multiflex CT products are quick and easy to assemble, and they comply with the MIL-DTL-17 standard. In addition to excellent phase stability over temperature, Multiflex CT cable assemblies have low weight and insertion loss and are available in three sizes: 0.141 in., 0.210 in. and 0.318 in. ***Figure 2*** compares the insertion loss of the standard PTFE cables with the Multiflex CT family, and ***Figure 3*** similarly compares the phase stability over temperature. With the proper connectors, which are also available from HUBER+SUHNER, Multiflex CT cables can be used for thermal vacuum applications.

The full CT cable family provides excellent phase and insertion loss stability with temperature change, as well as outstanding return loss and shielding effectiveness. This cable assembly family ensures system performance is stable beyond a single temperature. More information about the CT cable family of products is available using the QR code.

VENDORVIEW

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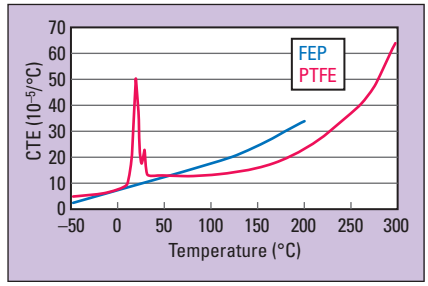

Fig. 1 Expansion of PTFE and FEP vs. temperature.

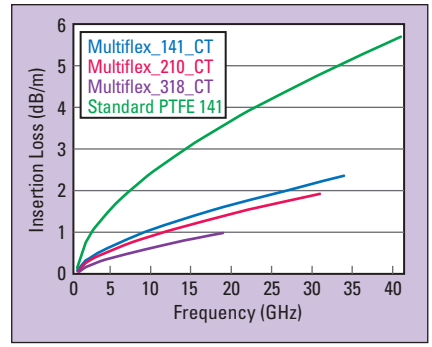

Fig. 2 Insertion loss vs. frequency of standard PTFE and Multiflex CT cables.

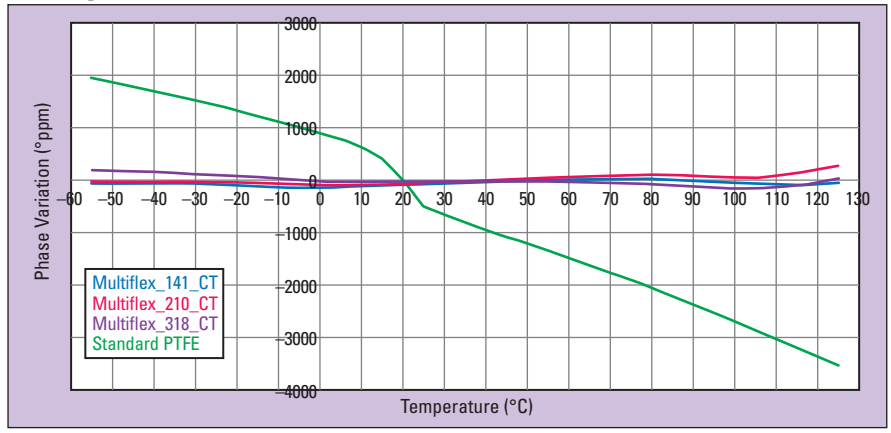

Fig. 3 Phase variation vs. temperature of standard PTFE and Multiflex CT cables.

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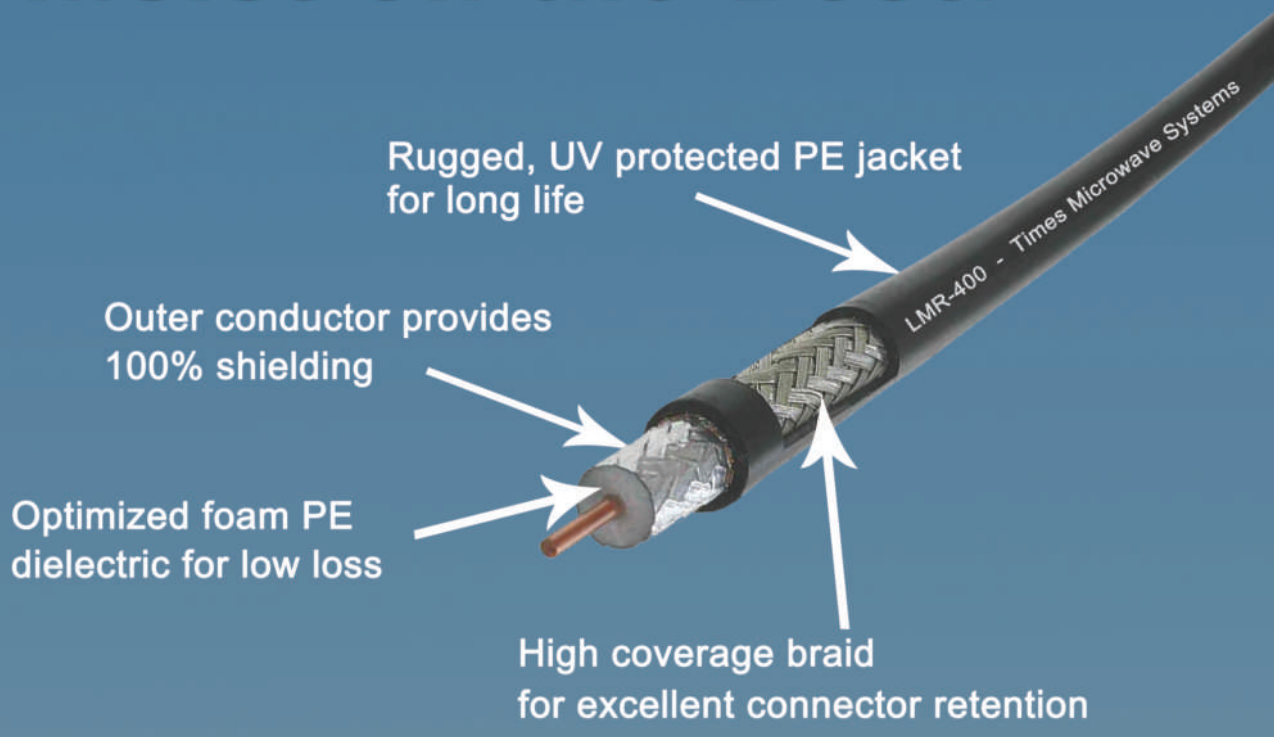

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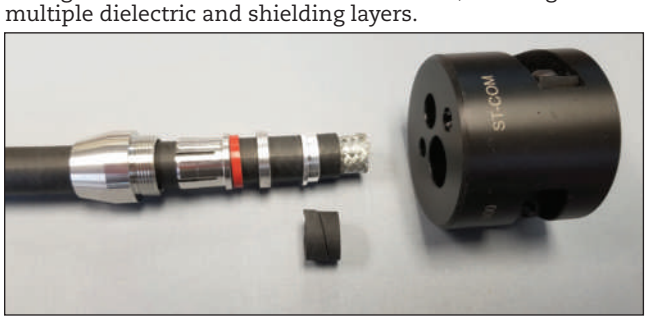
▲ Fig. 1 Cross section of two TCOM cables, showing the multiple dielectric and shielding layers.



▲ Fig. 2 Prepping the TCOM cable for the connector.

Times Microwave Systems developed the family of TCOM® cables to be the most versatile line of low loss coaxial cables on the market. They exhibit the qualities of the popular LMR® cable family—low loss, flexibility and ease of termination—and then take it up a couple of notches. The TCOM cables are extremely rugged, often making them the first choice for field applications in both military and commercial markets. TCOM is also a cable with low passive intermodulation (PIM), maintaining solid dynamic PIM performance of approximately –160 dBc (i.e., using two 20 W carriers) even after bending, coiling and continuous flexure. TCOM is an excellent cable choice for mobile communications platforms such as "cell on wheels" and "cell on light truck," as well as ground-based satellite communications up to and including Ku-Band.

The TCOM cables are built using the same dielectric cores as the LMR cables: a nitrogen-injected, closed cell polyethylene foam optimized for loss and ruggedness. The outer conductor construction is the greatest differentiator between the LMR and the TCOM cables. Where the LMR uses a single bonded metal-polyester shield under the round wire braid, the TCOM uses a multi-layer shield, which allows for direct, low resistance out-

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▲ Fig. 3 One of the tools used to replace a connector in the field.

er conductor contact, making this construction the most flexible, rugged, low loss, low PIM coaxial cable available (see ***Figure 1***).

The first layer is composed of a silver-plated copper flat braid, which is designed to flex with the movement of the cable rather than hardening—which would occur with corrugated, tubular or bonded taped outer conductor constructions. The second shield layer is a helically-wrapped, aluminum-mylar-aluminum tape, which contains and maintains the flat braids during flexure. Last, the helically-wrapped tape is covered by a heavy tinned copper flat braid. This triple shield is optimized for flexure and provides greater than −100 dB shielding. Just prior to jacketing, the outer braids of these cables are flooded with a material that basically makes the cable self-healing. If the jacket were ever breached, however unlikely that is, moisture will not enter the cable itself. The jacket is a very strong, pliable, UV-resistant polyurethane compound.

It is not often that high shielding and the ability to perform with continuous flexure are found in the same cable—not to mention excellent dynamic PIM performance, abrasion and chemical resistance and core sizes large enough to satisfy feeder cable lengths in most field applications. Times Microwave offers these rugged TCOM constructions with both a solid center conductor (PUR-DB) and a seven-strand center conductor (Flexstrand-DB), both available in 1/4, 3/8 and ½ in. The PUR-DB cable is flexible, and the Flexstrand-DB is very flexible. These cables have had rigorous flex testing in nearly every conceivable configuration: coiling and uncoiling, bend and reverse bending (Tic-Toc), Flex Trac and simulated continuous handling.

As rugged as these cables are, they would not realize their full potential without the TCP connector design. This unique construction, which uses materials, plating and tolerances optimized for low PIM, has a BeCu spring collet with rows of barbs on each finger, which grip the cable jacket roughly ¾ in. behind the electrical contact when the back nut is torqued (see ***Figure 2***). This unique construction isolates the bulk of any sideloading force on the cable from the electrical transition between the cable and the connector. TCP connector options comprise male Type N, 4.3/10.0 and 7/17 DIN, which are available for all cable diameters.

Understanding that many applications are demanding of coaxial assemblies, Times Microwave has designed the connectors to be field replaceable and supplies a set of five, easy-to-use tools for cutting, prep and pin crimping, assuring reliable, low PIM terminations in the field (see ***Figure 3***).

Times TCOM coaxial cables were developed for a wide range of applications: low PIM, high shielding and harsh environments, including where a cable sees handling and movement after the initial installation or where flexure or coiling is expected through its life. With its rugged construction, the TCOM cable is also a good choice for flexing applications where PIM is not a requirement.

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1251	70	2.14 / 7.02
0471	110	4.95 / 16.23

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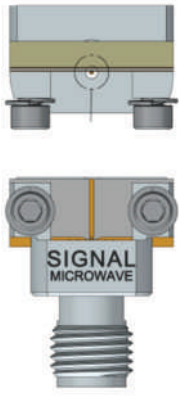

Signal Microwave's line of 2.92 mm, high performance, edge-launch connectors was designed for the thinner substrates being used today, typically between 5 and 10 mils thickness (0.127 to 0.254 mm) with dielectric constants from 3.0 to 3.5. Previously, high frequency board materials were around 30 mils thick, and the dielectric constants were lower, from 2.0 to 2.5.

The trend to thinner substrates and higher dielectric constants follows the development of mmWave systems. Impedance matching and 50 Ω line widths on thinner substrates better accommodate the small geometries of mmWave components, although one trade-off is thinner materials with narrower microstrip lines will have more loss.

With Signal Microwave's new 2.92 mm edge connector, no soldering is required to mount the connector. The design has a 12 mil center conductor and a 39 mil outer conductor, and a 6 mil pin sits on the top of the printed circuit board, creating an offset toward the top. On an 8 mil test board, there is a slight step of 3 mils between the substrate ground and the coaxial ground.

For the individual connector, the VSWR specification is 1.15:1 maximum (i.e., 23 dB return loss). Two edge-launch connectors mounted to a 1 in. long, 50 Ω microstrip line on an 8 mil RO4003 substrate with an FR-4 backer has a measured maximum VSWR of 1.2:1 through 40 GHz. The corresponding insertion loss gradually increases with frequency to less than 3 dB at 40 GHz, including the loss of the 1 in. microstrip line.

Signal Microwave can provide design support to optimize the interface on the board for best performance. Connector samples with data and test boards are available for evaluation.

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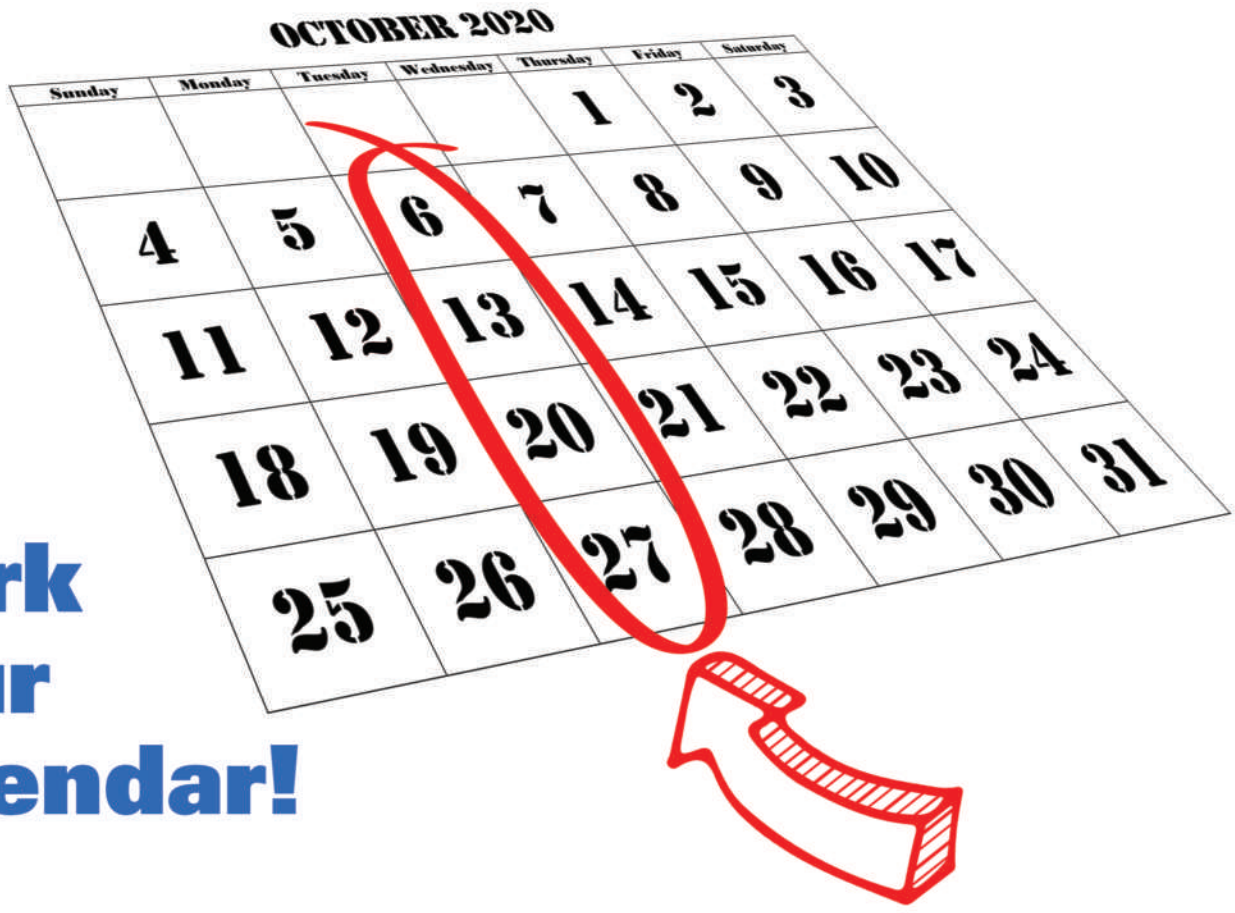

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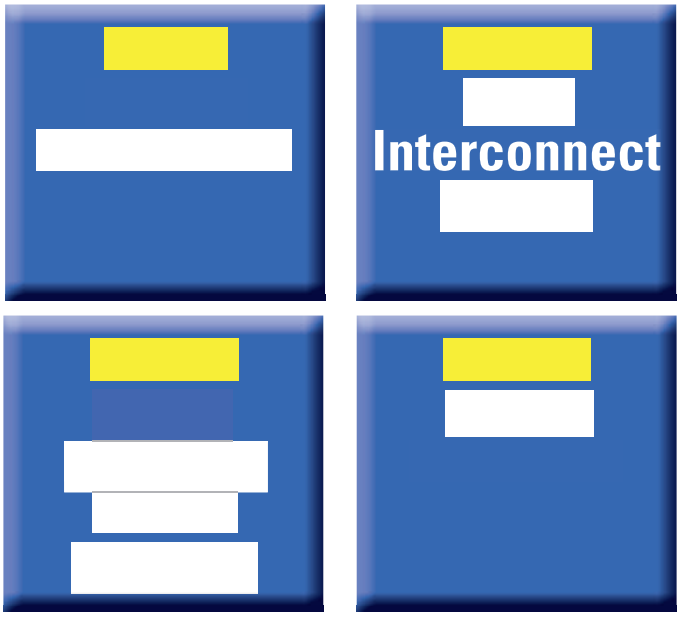

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18 GHz Flexible Coaxial Cable Assemblies Replace Semi-Rigid

L-com has introduced a new series of flexible coaxial cable assemblies designed to be used instead of 0.141 semi-rigid (RG402) cable in applications requiring increased flexibility. The LCCA series cable assemblies feature 402SS cable and are produced using high quality components to create a rugged, flexible and versatile interconnect. These assemblies exhibit performance characteristics very similar to semi-rigid and offer flexibility without compromising performance.

The 402SS coax cable features a solid center conductor, PTFE dielectric and silver-plated copper braid outer shield over a silver-plated copper spiral strip inner shield. This multi-layer shield construction provides increased flexibility, maintaining excellent insertion loss and shielding performance to 18 GHz, to support many lab, test and automated test equipment applications.

The LCCA series has heavy-duty booting to extend the life of the flexible assembly and uses precision stainless-steel connectors, offering multiple connector options: male and female SMA and Type N connectors, Type N female bulkhead and male SMA right-angle connector combinations.

Custom versions of the LCCA cable assemblies, as well as L-com's entire RF cable assembly line, can be built and shipped the same day. Other available RF cable assembly value-added services available from L-com include connector orientation or clocking, heat shrink booting, custom labeling and RF testing to document the electrical performance of the cable assembly.

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Anoison, known not only for the best solutions for your RF and Microwave interconnect requirements, but also the most value for your dollar with outstanding quality and fast delivery has them both. As you've come to expect, Anoison's 1.0mm and 1.85mm adapters and connectors offer the best specifications in the industry with frequency range up to 110 GHz; low insertion loss (0.9 dB) and great VSWR, all at the best prices and fastest delivery.

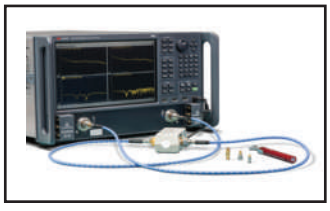
Anoison Electronics LLC
www.anoison.com

COBHAM RF CABLES

VENDORVIEW

Cobham Advanced Electronic Solutions RF Cables include a wide range of assemblies with a clear focus on military and high performance commercial applications as well as a long-standing commitment to the space market. Known for their excellent electrical performance, proven reliability and overall mechanical strength, Cobham Advanced Electronic Solutions' cable portfolio ranges from 0.09-inch (2.3 mm) diameter FZ09 to 0.92-inch (23 mm) diameter FE92 flexible cables with extremely low insertion loss for special ground-based applications.

Cobham Advanced Electronic Solutions
www.cobham.com/rfcables

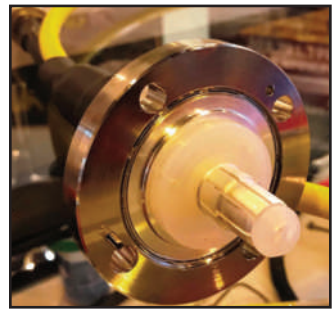


SUCOFLEX 500

VENDORVIEW

SUCOFLEX 500 test leads are suitable for a vast-range of applications including bench top testing, RF production, automated test equipment, vector network analyzers (VNA), portable testing equipment and RF module testing up to 50 GHz with a lifetime of more than 100,000 flex cycles. When tailored performance is needed, HUBER+SUHNER can offer a quick turn manufacturing (10 business days) on a wide selection of customized SUCOFLEX assemblies.

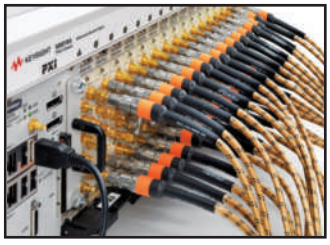
HUBER+SUHNER
www.hubersuhner.com/en



1-5/8 EIA FLANGE

IW offers a 1-5/8 EIA flange for use with 4806 cable. Cable attachment method is solder clamp to ensure minimal impedance variation and low VSWR, and body material is brass to provide optimum thermal performance. Flange assemblies can be supplied with the interface bullet if required. Customer testing has proven 4806 capable of handling 17 KW at 13.56 MHz for semiconductor material processing and is also widely used for EMC testing and other high-power commercial and military applications.

IW Microwave Products Division
www.iw-microwave.com



MAURY STABILITYPLUS™ MICROWAVE/RF CABLE ASSEMBLIES

Maury StabilityPlus cable assemblies provide industry-leading phase and amplitude stability performance. These cables are armored to last under demanding conditions while remaining extremely flexible. Excellent electrically and mechanically durable, StabilityPlus cables are ideal for testing in the lab or in the field. Uses include precision VNA measurements, production testing, antenna range testing, EMC/EMI chambers. Standard StabilityPlus cable configurations are in-stock and available to ship today.

Maury Microwave
www.maurymw.com

NMD PRECISION ADAPTERS FOR VECTOR NETWORK ANALYZERS

MIcable develops a series of NMD precision adapters for Vector Network Analyzers (VNA). These adapters have 1.15:1 max VSWR and over 1000 mating cycles. They can effectively protect VNAs and save the use of expensive VNA test cables. The adapter models include almost all type of connectors that you can use, all models are in stock sales. The prices are very competitive. The customer can contact the company's sales team at sales@micable.cn or visit their website to get the related information.

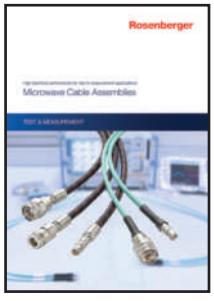
MIcable Inc.
www.micable.cn

MINI-CIRCUITS BLOG OFFERS NEW ACCESS TO CORPORATE KNOWLEDGE AND INSIGHTS

VENDORVIEW

Mini-Circuits is proud to announce the launch of its new corporate blog! The blog is now open to the public, offering a variety of valuable content including technical articles and reference for RF engineers, executive insights and thought leadership on market trends, and stories about the people, culture and values that make Mini-Circuits unique in the industry.

Mini-Circuits
https://blog.minicircuits.com/



MICROWAVE CABLE ASSEMBLIES UP TO 110 GHz

The revised Rosenberger standard portfolio of flexible microwave cable assemblies with improved armour and optimized designs includes ultra-low-loss and phase stable variants for frequencies up to 18, 26.5, 40, 50 GHz and even 70 GHz. VNA test cables for metrology grade performance applications up to 110 GHz are also available. Outstanding product features are high phase stability, low insertion and return loss values, crush resistance up to 1000 N. The portfolio covers RTK 081, RTK 092-70, RTK 106, RTK 125 and RTK 162 high-quality cables, assembled with SMA, RPC-N, RPC-3.50, RPC-2.92, RPC-2.40 or RPC-1.85 high-precision connectors. A brand new catalog with detailed information is available cost-free.

Rosenberger
www.rosenberger.com/0_documents/de/catalogs/ba_tm/TM_MicrowaveCableAssemblies_Flyer_2020.pdf

EXTREME FREQUENCY CABLE ASSEMBLIES

SV Microwave offers a complete line of fixed length, high frequency (26 GHz and above) cable assemblies utilizing SMA, 2.92mm, 2.4mm, SMP, SMPM & SMPS connectors on flexible 0.047 and 0.085 cable types. SV Microwave's cable assemblies feature low solder wicking and the high flexibility allows for tight bends behind the cable ferrule. SV's low loss is your gain. Order from a variety of RF cable assembly options COTS today.

SV Microwave
www.svmicro.com

COMPREHENSIVE RF INTERCONNECT PRODUCT & VENDOR PORTFOLIO

Richardson RFPD stocks all major transmission line components for 5G, wireless infrastructure, telecom, military and commercial radar, satcom and navigation systems applications. High-end, space-qualified coaxial cables; connectors; attenuators; terminations and low-cost, commercial-grade solutions. Richardson RFPD combines this extensive interconnect portfolio with its extensive applications engineering experience, product knowledge, technical aptitude and flexibility to supply all your RF interconnect product needs.

Richardson RFPD: Interconnect Portfolio
www.richardsonrfpd.com/interconnect

RF/MICROWAVE COMPONENTS AND SUBSYSTEMS

VENDORVIEW

Smiths Interconnect is a leading provider of technically differentiated electronic components, subsystems, microwave and RF products that connect, protect and control critical applications in the commercial aviation, defense, space, medical, rail, semiconductor test, wireless telecommunications and industrial markets. Smiths Interconnect offers proven quality and innovative connectivity solutions, constantly adapting our products to tomorrow's needs while meeting our customers' requirements. The company leverages its application specific expertise to design and manufacture superior RF components, connectors, interposers and cable assemblies.

Smiths Interconnect
www.smithsinterconnect.com

CLARITY™ SERIES 40 GHz TEST CABLES

Times Microwave introduces its new Clarity Series of 18, 26.5 and 40 GHz coax test cables. Clarity boasts steel torque, crush and overbend protection with abrasion resistance yet does not compromise flexibility. The cable is ultra stable through 40 GHz with exceptionally low attentuation. An industry first includes an ergonomically designed injection molded strain relief and Times' new, SureGrip™ coupling nut to significantly improve the user's everyday experience. Clarity is appropriate for use as VNA test port extension, R&D lab, production test and even system interconnect cables.

Times Microwave
www.timesmicrowave.com

Cables and Connectors

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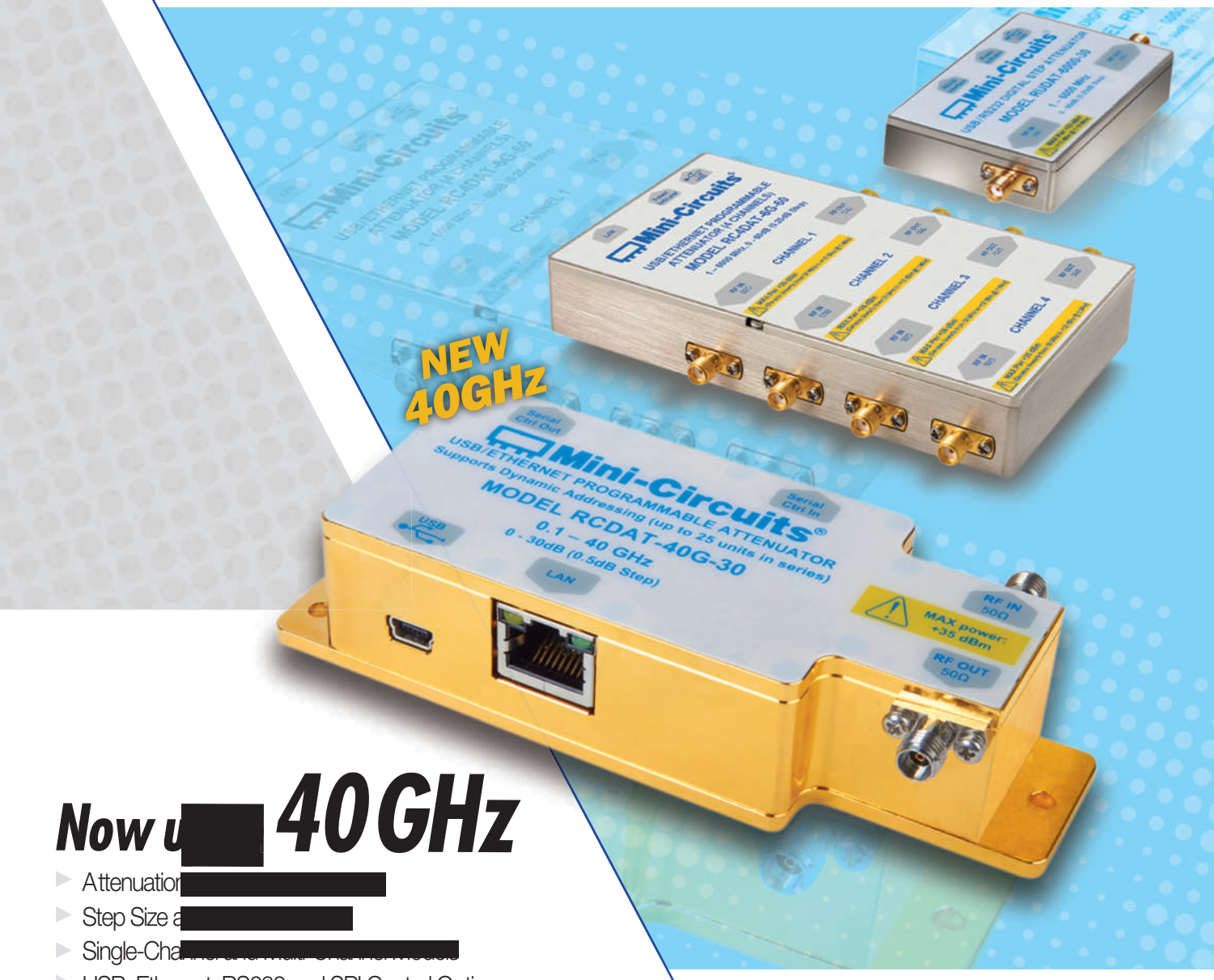
PROGRAMMABLE ATTENUATORS



Now u[redacted] 40 GHz

- Attenuation[redacted]
- Step Size a[redacted]
- Single-Cha[redacted]
- USB, Ethernet, RS232 and SPI Control Options

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