INNOVATING the FUTURE

INSIGHTS INTO RF & MICROWAVE DESIGN

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Editorial Statement of Purpose

This publication serves RF and microwave design engineers, engineering managers in research through production roles who design, manufacture, and specify components and subsystems used in microwave systems. Its editorial mission is to provide practical information about microwave markets, programs, and current and emerging technologies that are or will be critical for the development of the microwave industry.

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IN THIS ISSUE

A Few Words About This eBook

by **Joel Levine, Co-founder, RFMW**

The solutions offered by manufacturers represented by RFMW showcase the ongoing, remarkable advancements in RF, microwave, and millimeter-wave technology. Many of these companies document their innovations in detail, providing valuable insights for designers new to the industry and seasoned engineers. We've selected some of the best of these resources for inclusion in this eBook, ranging from advanced beamforming, surface mount components for phased arrays, filter design considerations, SWaP optimization, MEMS switches, and UltraCMOS technology for receiver front ends.

For example, although active beamforming was once the exclusive domain of advanced defense systems, it's now being integrated into many commercial wireless applications, from cellular networks to satellite communications, fixed wireless access, and even IoT. The article from Qorvo describes these advances using an X-band radar as an example. At the same time, Marki Microwave explains how surface-mount components simplify phased-array design where beamforming is fundamental.

While filters are often taken for granted, there's a lot to know about these seemingly simple devices and their types (of which there are many) that many designers have either forgotten or haven't yet become familiar with. The article we're featuring from Knowles Precision Devices goes a long way to solving this problem. It goes back to the basics of filter design that can help any designer make the best choice for a given challenge.

A decade ago, the concept of optimizing systems for Size, Weight, Power, and Cost SWaP-C was a goal fostered by the Department of Defense. Now it's a mandatory requirement for any system, not just those intended for defense systems. We reached out to Ian Dunn, chief technology officer at Spectrum Control, to describe where SWaP is today, and you can find his insights in the eBook.

MEMS switches have revolutionized RF switching and other applications. They are the size of a pinhead, handle relatively high power levels, have lifetimes at least 10 times longer than their electromechanical counterparts, and provide many other benefits as well.

Menlo Micro's article about their Ideal Switch technology describes their technology in detail and its benefits for meeting the challenges of meeting PCIe 5.0/6.0 specifications.

Silicon-on-insulator (SOI) technology has emerged as a key enabler, providing reduced parasitics, improved isolation, and superior linearity compared to traditional bulk silicon processes. The article from pSemi explores the fundamentals of SOI in RF design, highlights the attributes of their UltraCMOS technology, and discusses its applications in high-performance broadband switches, amplifiers, low-noise amplifiers (LNAs), and front-end modules.

I hope you enjoy these articles and I welcome your comments.

– Joel

The Power of X-Band Radar with Advanced Beamforming Technology

by **David Corman** *(Chief Systems Architect),* **Paul Prudhomme** *(Senior Product Line Manager),* **Andy Crofts** *(Senior Marketing Manager)* **and David Schnaufer** *(Technical Marketing Manager),* QORVO

THE DEFENSE SECTOR is constantly evolving to address the latest security challenges, one of which is the increasing prevalence of unmanned aerial vehicles (UAVs) or drones in critical areas. X-band radar systems, particularly those leveraging beamforming ICs (BFICs), advanced gallium nitride (GaN) and gallium arsenide (GaAs) components, are leading the way in providing the high-performance radar capabilities required for modern defense and surveillance. This article delves into the latest advancements in X-band radar technology (8 to 12 GHz), discusses its applications in defense, and illustrates contributions from Qorvo (Figure 1).

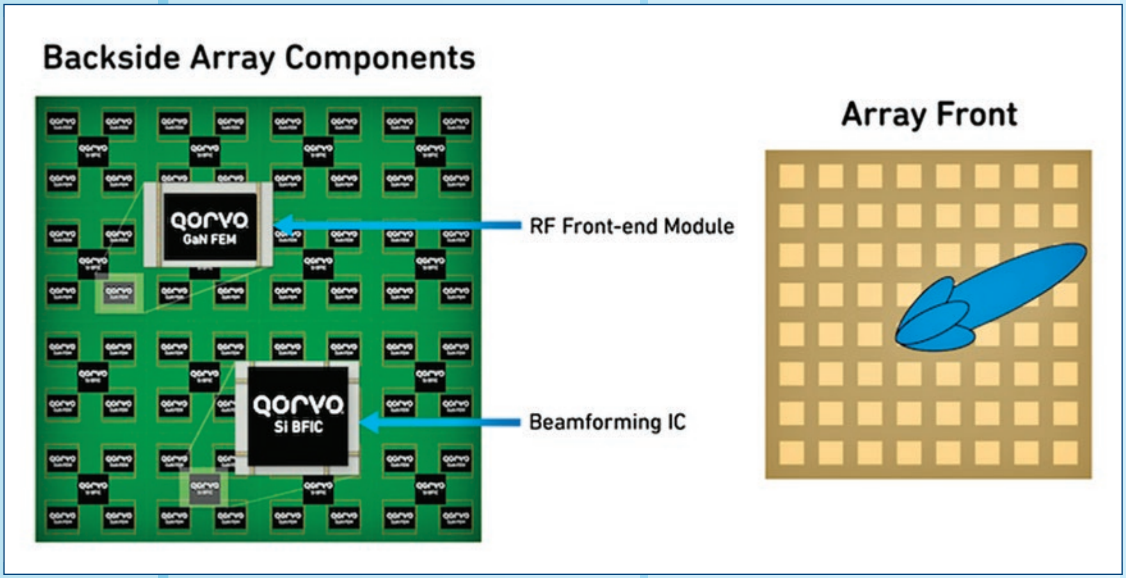

Figure 1 – AESA beamformer ICs with RF front-end modules.

Drone Detection and Tracking: A New Security Imperative

The ability to detect, track and manage drones is becoming indispensable for defense operations. X-band radar systems are uniquely suited for this task, especially in scenarios like border security, critical infrastructure protection and mobile perimeter monitoring. These radar systems provide high-resolution detection capabilities, ensuring drones can be tracked with accuracy even in cluttered environments.

The ability to differentiate drones from other small airborne objects is crucial as security demands grow around the globe. Phased array Active Electronically Scanned Array (AESA) radar systems operating at X-band offer an ideal balance of range, target resolution and size, enabling these systems to detect and monitor obstacles from significant distances. X-band radars are lightweight and self-contained, which simplifies integration into aviation systems for comprehensive aerial surveillance and threat detection (Figure 2).

AESA radar systems offer several significant advantages that enhance their operational effectiveness. One of the primary benefits is their accuracy; these systems can track multiple targets with high angular precision, even in congested airspace. Additionally, AESA radars demonstrate superior reliability compared to legacy radar technologies, largely due to their lack of moving parts, which minimizes mechanical wear and potential failure points.

They also incorporate a “soft failure” capability, allowing the system to maintain performance with only minimal degradation even if several array channels malfunction. Furthermore, AESA systems are capable of transmitting signal energy in microseconds, enabling them to detect and track targets at remarkable speeds. Their multi-functionality allows them to operate effectively in both air-to-ground and air-to-air environments simultaneously.

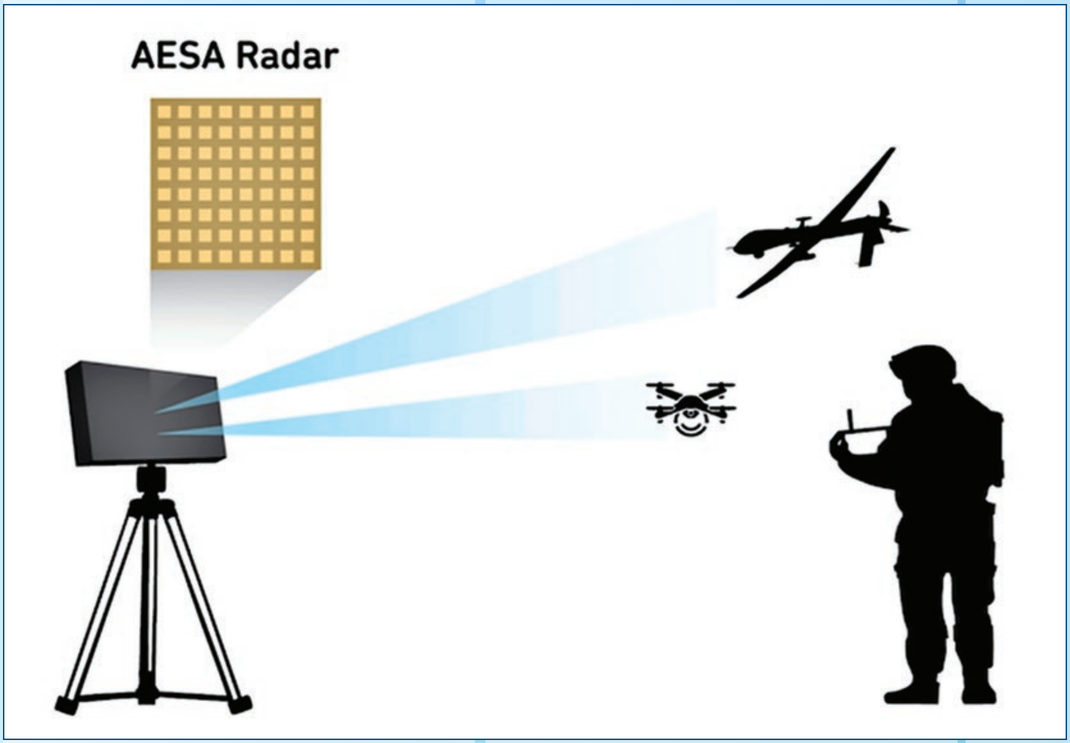

Figure 2 – X-Band AESA radar applications.

Environmentally, AESA radars excel as they can see and map the ground from great distances under various weather conditions. In terms of mobility, these systems are more portable due to their smaller size, lighter weight, and lower power consumption compared to previous X-band radar technologies. Lastly, the low physical profile of AESA electronics, which can be integrated into a planar (flat panel) antenna, contributes to a more compact design, resulting in a smaller, lighter, and more cost-effective solution.

AESAs combined with advanced X-band BFICs are pushing the capabilities of compact radar systems in the aviation and defense markets. These systems, combined with integrated software-defined radios and beam-steering controllers, provide remote sensing coverage across a wide range of applications. Additionally, these solutions provide enhanced sensitivity and lower DC power consumption than traditional radar systems.

AESA radars also benefit significantly from X-band BFICs coupled with GaN and GaAs technologies, helping to enable long radar range, high-resolution, stable phase and amplitude control needed for rapid and precise beam steering. The combination of using these technologies – silicon for the BFIC, GaN and GaAs helps achieve SWaP-C (reduced size, weight, cost and high power). This low-profile, high-performance technology allows developers to create radar systems with optimized cascade performance, achieving lower RF power emissions, reduced false detections and increased dynamic range—attributes that open new avenues in aviation radar applications while ensuring effective, energy-efficient drone tracking and threat management.

X-Band Radar Advancements: Precision Meets Mobility

Modern X-band radar systems operate between 8–12 GHz, offering an ideal balance between range resolution, size and target detection range. Compared to lower-frequency counterparts, X-band radars use smaller antennas, allowing for the development of lightweight, self-contained radar units that are easy to deploy. This compact form factor and portability make X-band radar systems versatile and effective for remote or mobile surveillance.

One of the notable advancements in this sector is the incorporation of phased-array systems with electronic beam steering. Phased-array radars allow for rapid, precise beam control without the need for mechanical components. This technological leap is particularly beneficial in dynamic threat environments, as the radar can adapt to changing conditions in real time.

The Importance of BFICs in Phased Array Antennas

A core component of X-band radar performance is precise phase control for each antenna element in the phased array. High-resolution phase and amplitude control enable fast,

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accurate beam steering, which is essential for tracking multiple objects simultaneously. Qorvo's beamformer ICs facilitate this capability by providing independent phase shift and attenuation control, enhancing the radar's ability to operate in complex environments with multiple moving targets (Figure 3).

At the core of X-band phased array radars, beamforming ICs allow precise control over each antenna element's phase and amplitude, enabling rapid, accurate beam steering. This control is especially critical in scenarios where radar systems must distinguish between multiple, fast-moving targets in congested airspace or complex urban environments.

Qorvo's X-band Beamformer IC stands out with its quad architecture featuring dual receive outputs, and it offers independent serial "SPI" control of the phase shifters and attenuators. This architecture facilitates both individual control over each channel within an IC and the daisy chaining of multiple ICs, enabling scalable radar systems that adapt to various application needs. A single positive supply further simplifies the design and reduces the overall system footprint, which is essential for low-profile deployments.

The Integration of GaN and GaAs Beamforming ICs

In today's defense landscape, radar systems must meet stringent requirements for cost-effectiveness, compactness and high performance to operate effectively in complex environments. The integration of beamforming integrated circuits (ICs), along with advanced GaN and GaAs technologies, has become essential in addressing these demands, enabling radar systems to maintain accuracy, flexibility and robustness. Electronically steered active antennas, which rely heavily on these advancements, are paving the way for next-generation radar solutions optimized for critical defense applications, from UAV detection to border surveillance.

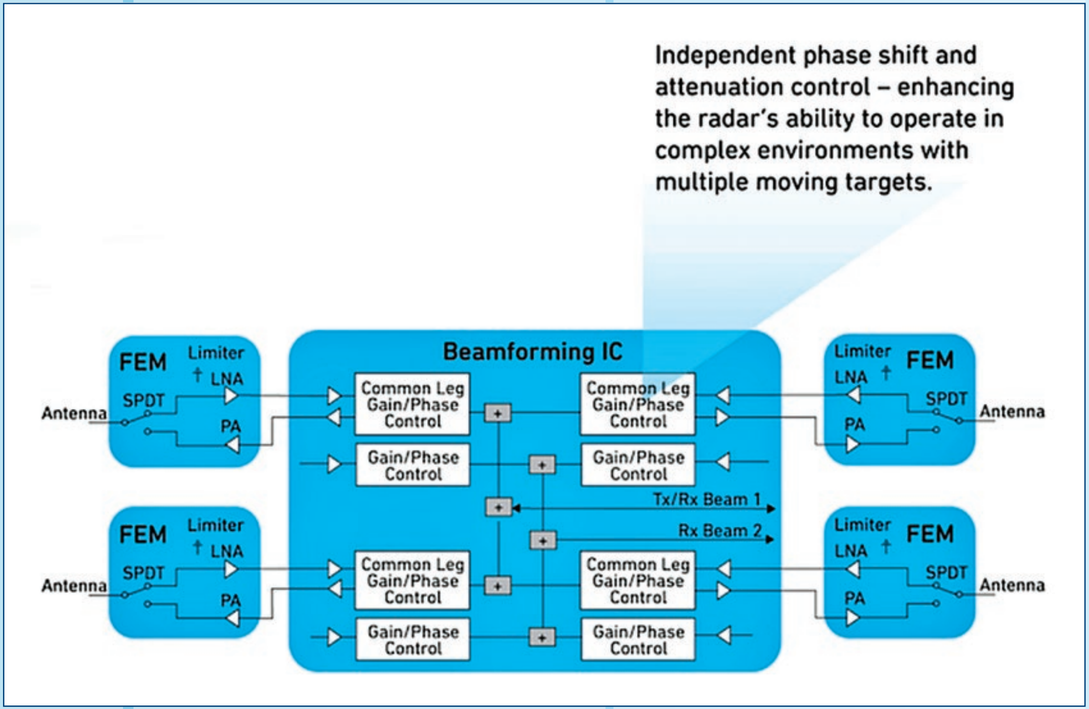
Independent phase shift and attenuation control – enhancing the radar's ability to operate in complex environments with multiple moving targets.

Figure 3 – Block diagram of Qorvo AESA array antenna design.

Incorporating GaN and GaAs technology into radar systems enhances performance by enabling high power output with superior thermal management. This combination is particularly advantageous in AESAs, where low-profile and lightweight designs are essential. AESA radars built with Qorvo's X-band beamformer ICs and GaN/GaAs-based front-end modules can fit compactly within the radiating lattice of a planar antenna, making it possible to create portable yet high-performance radar units for defense applications.

The use of GaN-based technology extends beyond sheer power; it also improves efficiency. GaN's high breakdown voltage and efficiency support the design of radar systems with longer operating life and lower heat dissipation, a vital feature for defense-grade equipment that must endure extended deployments in challenging environments.

Qorvo's GaN and GaAs front-end modules (FEMs) complement the beamforming ICs by delivering high output power with exceptional thermal efficiency and low noise performance. The GaN/GaAs-based modules provide the necessary flexibility to adapt radar performance based on the specific threat environment. The low noise figure and over-drive protection of these FEMs ensure that radar systems can maintain signal integrity, even in high-density RF environments.

The synergy between Qorvo's beamforming ICs and advanced GaN and GaAs modules is transforming defense radar capabilities, making high-resolution, electronically steered active antennas a viable, practical solution for today's defense challenges. This complete X-band solution not only meets the modern requirements for performance and profile but also makes phased array technology accessible and deployable in critical surveillance and air defense applications.

For example, in AESA radar systems, each transmit/receive (TX/RX) module consists of a power amplifier (PA) along with other components. One critical requirement in AESA design is reducing overall power consumption, as these systems use numerous TX/RX modules, resulting in high energy demands. This challenge becomes more acute at higher operational frequencies, where PAs consume most of the the system's energy. To meet these stringent power requirements, PAs in AESA systems must operate with high power-added efficiency (PAE) and gain across a broad input frequency range while still delivering sufficient output power. In this context, Qorvo has designed a highly efficient PA tailored to meet the demanding performance standards required by AESA systems, ensuring both energy efficiency and robust output.

Qorvo's silicon-based BFIC smart antenna solutions deliver optimized performance and cost-efficiency, meeting commercial and defense market demands. These products, refined over several generations, incorporate a unique architecture that enables manufacturers to build scalable arrays with effective isotropic radiated power (EIRP) ranging from 30 dBmi to greater than 70 dBmi.

Key performance features of advanced radar systems include lower energy consumption, achieved through dynamic array control and fast attenuator adjustments that allow for the selective deactivation of elements and rows. This capability shapes beams while significantly reducing direct current (DC) power, which is essential for the energy-conscious radar industry. The use of (GaN) high-power technology further contributes to lower power consumption. Additionally, the systems incorporate patented ultra-fast beam steering technology, which supports radar timing protocols and enables antennas to quickly shift beam directions.

Another important feature is the variable maximum linear power (vMLP), which allows the system to flexibly adapt its power output to meet varying operational requirements, thereby preventing interference. The integration of smart arrays with embedded digital cores facilitates real-time performance monitoring and adjustment, ensuring that the array maintains peak functionality. Furthermore, the systems offer polarization flexibility, enabling the generation and control of various polarizations to meet diverse operational needs.

Qorvo's full radar array solution supports dual-polarization feeds of four antenna elements from a single IC, offering simplified integration with phased array terminals through features like low voltage supply and integrated logic control. Fabricated using silicon, GaN and GaAs technology, Qorvo's solution perfectly balances performance and cost-effectiveness.

Qorvo's X-Band Applications

Qorvo's X-band radar solutions offer a complete package for defense clients. These systems are optimized and pre-configured for low-cost and low-profile deployment, ensuring that radar arrays can be installed with minimal footprint and maximum operational effectiveness.

Qorvo's integrated radar solutions play a crucial role in supporting key defense applications. They enable long-range, high-resolution monitoring of sensitive areas, making them ideal for border and critical infrastructure surveillance. Additionally, these solutions are effective in detecting, tracking, and managing (UAVs) and other aerial threats, enhancing air defense capabilities. Furthermore, Qorvo's radar systems can be rapidly deployed for mobile perimeter security, ensuring the protection of mobile assets and temporary installations.

Qorvo's X-band solutions also integrate advanced GaN and GaAs (FEMs) that offer power options from 2 to 12 watts, providing users with flexibility in power output without compromising noise performance. These modules also include overdrive protection, which is essential for radar systems operating in unpredictable or high-risk environments where signal integrity is critical.

Summary

The advancements in GaN and GaAs technologies are dramatically expanding the capabilities of X-band radar systems, making them indispensable for modern defense applications. GaN-based transmit/receive modules offer higher output power and improved efficiency, while GaAs contribute essential low-noise performance for precise target detection, even in congested spatial environments.

Together, these materials are setting new standards for radar performance, enabling highly configurable, multi-functional systems that meet the sophisticated demands of today's defense industry. With a modular, scalable approach, X-band radars leveraging these technologies allow defense agencies to rapidly deploy versatile solutions in various mission-critical applications.

The rapid evolution of X-band radar, powered by advancements in Beamforming ICs, GaN and GaAs materials, is transforming defense capabilities. From drone detection to border surveillance, these compact, powerful systems are essential to the defense landscape. With companies like Qorvo advancing radar technology, the industry now has access to sophisticated, reliable tools that deliver high performance and operational flexibility, paving the way for the next generation of defense applications. ■

Enhance Phased Array Systems with Innovations in Surface Mount Components

by **Doug Jorgesen,** *Vice President of Applications Engineering,* MARKI MICROWAVE

OVER THE PAST 50 years, mechanically steered antennas have largely been replaced by phased array architectures, which are particularly beneficial in densely populated signal environments. These advancements necessitate a significant increase in the channel count of the underlying RF systems, putting pressure on RF components to become increasingly smaller. This paper will explore phased array architectures and examine how technological advancements have led to the development of smaller RF and microwave components that maintain exceptional performance in surface mount packages.

Phased arrays operate on the principle that when multiple antennas radiate at the same frequency and are placed close together, their radiation patterns exhibit peaks and nulls due to interference. The radiation pattern can be manipulated by dynamically controlling the phase of the radiated signals. Most phased arrays consist of a linear or triangular arrangement of equally spaced, identical, fixed antennas, with the phase between each element adjusted to create a focused radiation pattern known as a beam. However, this pattern also includes undesired sidelobes. If the phase shift remains passive, the structure is reciprocal, meaning the transmitted radiation pattern will match the antenna's sensitivity to received signals.

The increase in the focus of transmission or reception is described by the antenna gain G, and to first order, it increases linearly with increasing number of antenna elements N: $G \propto G0 \cdot N$

When individual power amplifiers are used on each transmitter element, the radiated power increases linearly with N, so the effective isotropic radiated power increases as N2. $P_{effective} \propto P0 \cdot N2$

The combined system improvement per element is theoretically proportional to N3 for a combined transmit/receive system with phased arrays on both sides.

Phased Arrays Vs. Mechanical Steered Antennas

The realistic comparison system for a phased array isn't a single radiating element but a single parabolic dish antenna with high gain fed by a large transmitting amplifier and receiving with a single low-noise amplifier.

A single antenna offers several advantages for the same aperture size, including fewer components, the absence of beamforming network losses, and consistent gain during mechanical scanning, unlike phased array scanning, where gain drops. However, phased arrays present several significant benefits contributing to their widespread use in various applications. One of the primary advantages is electronic scanning, which allows a phased array to be scanned quickly and to jump discretely from one location to another. This capability is essential for tracking multiple simultaneous objects in radar systems and servicing multiple users in communication applications. Additionally, phased arrays feature a flat or low-profile form factor, critical for airborne applications to reduce drag and enhance mechanical reliability.

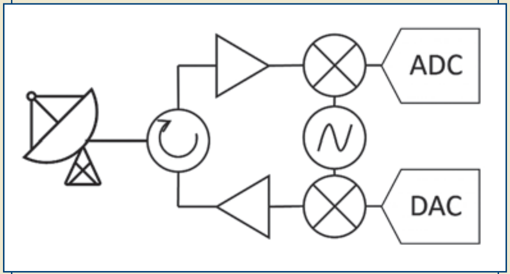

Figure 1 – Core Elements of a Traditional Transceiver.

For ground-based military vehicles, large mechanically scanned antennas can make the vehicle a target for enemy fire, whereas phased arrays can be concealed more effectively. Reliability is another key factor; applications that require tracking often face significant reliability issues with motor controllers, particularly in terrains with high sand or dust content.

Phased arrays mitigate this risk through graceful failure, meaning that losing a small number of elements does not significantly impact overall array performance. Furthermore, specific implementations of phased arrays enable multi-beam solutions, which are necessary for multifunction phased array radar (MPAR) applications, such as adaptive search and track solutions and support for multi-user satellite communications.

A key consideration in designing a phased array is determining how the tasks of generating the transmit signal and processing the received signal are allocated among the electronic components associated with each radiating element. To better understand this, it's helpful first to examine the operation of a traditional rotating dish transceiver, such as those used in radar systems (Figure 1).

The core elements of the transmit system are a digital-to-analog converter to generate the transmit signal, an upconverting mixer, a power amplifier, and a duplexer to feed the antenna. The core elements of the receiving system are an antenna duplexer, a low noise amplifier to boost the signal above the noise floor, a downconverting mixer, and an analog-to-digital converter to receive and process the signal. In addition to these core components, additional components are added to improve bandwidth and spur free dynamic range of this system and add extra protection.

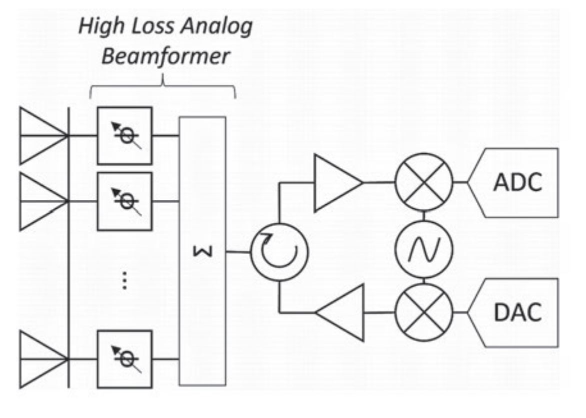

Figure 2 – **Passive Beamforming Architecture.**

Additional components can include limiters, which protect the low-noise amplifier (LNA) from high-power transmit signals. Filters are also essential, as they help reduce received noise, eliminate transmitted harmonics, and remove blockers and interferers while addressing spurious products generated by mixers or amplifiers. Additionally, attenuators, equalizers, and further amplification are utilized to adjust the signal level entering the analog-to-digital converter (ADC) to maximize its dynamic range. Couplers play a role in monitoring the transmitted or received power levels, and baluns are used to convert the differential signals from the ADC or digital-to-analog converter (DAC) into single-ended signals. As we'll discuss later, miniaturization of these components is critical for high channel count receivers. Consider now a phased array implementation of the same system.

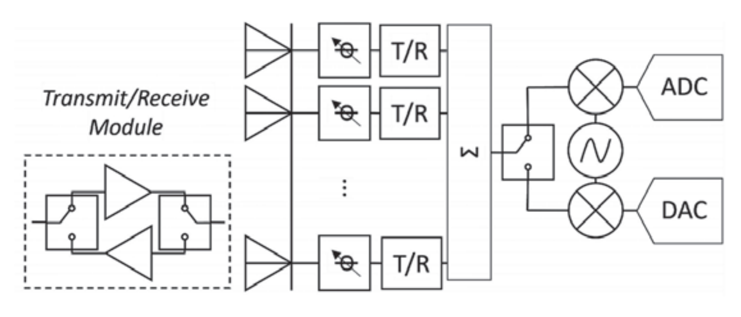

Figure 3 – **Active Beamforming Architecture.**

Passive Beamforming

The most straightforward way to move to a phased array implementation is to change only the antenna and leave the rest of the system intact. This requires a distribution manifold and a series of phase shifters, as well as radiating elements (Figure 2):

With the addition of phase shifters, the beam can be steered as quickly as the phase shifters can tune. This is on the order of nanoseconds vs. several seconds for a mechanically steered antenna. This allows the antenna to track multiple simultaneous targets nearly instantaneously.

In addition to phase shifters, individual tuning of the amplitude of each radiating element is frequently performed with variable attenuators at each port. By varying the power of each element (more in the middle, less on the outside) the undesired grating lobes of the antenna pattern can be reduced significantly. For the remainder of the paper, it is assumed that each element-level phase shifter includes a fixed or variable attenuator to correct the amplitude to the desired level for the required antenna beam. The major downside of this system is that there are significant excess losses (in addition to the splitting loss) in the beamforming network. While the centralized high-power amplifier can be a very high-power tube amplifier, the receiver's sensitivity is directly reduced by the excess loss of the manifold.

Active Beamforming

To overcome these losses, we can (if we have the amplifier technology available) place a low-noise amplifier on each element to improve sensitivity. If also available (as it is with GaN technology), we can place a transmit amplifier on each element as well (Figure 3).

This is referred to as active beamforming since there is an active amplifier on each element, as opposed to passive beamforming. Since the loss of the beamforming manifold directly degrades the receiver's sensitivity, these manifolds were large, heavy, expensive waveguide components. Putting the LNA before the manifold significantly reduces the loss requirements, and a simple power splitting/combining network can be used. The cost, in terms of going from a single RF front end to one RF front end per element, depends mainly on the cost of the RF front-end components, particularly the transmit power amplifier.

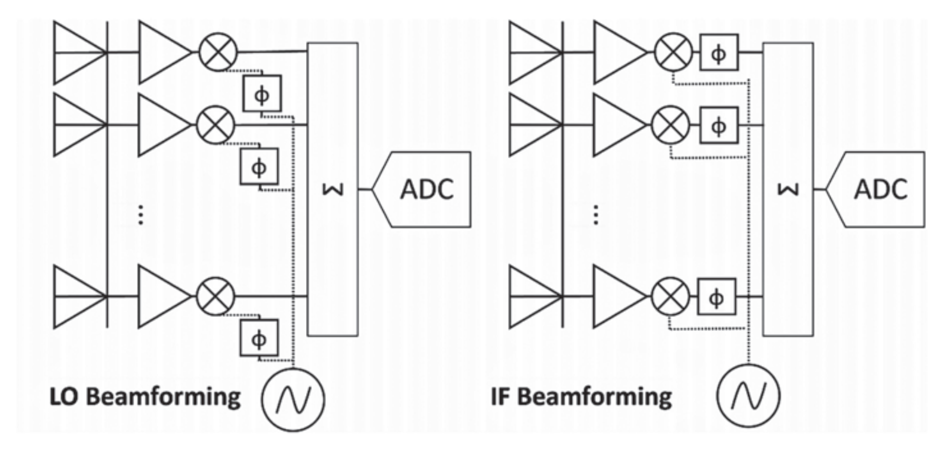

Figure 4 – **IF and LO Beamforming Receiver Architectures**

Instead of applying the phase shift to the signal directly at the RF frequency,

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it is also possible to downconvert each element and apply a phase shift to the LO instead, with an amplitude shift at baseband. This is called LO beamforming. The phase and amplitude shift can also be applied at baseband instead of at the RF frequency, which is called IF beamforming (Figure 4).

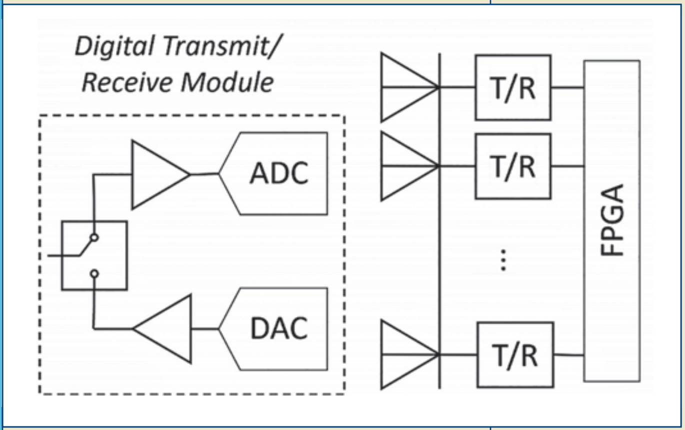

Figure 5 – Digital Beamforming Architecture.

RF beamforming has the best signal integrity of these options since it occurs prior to the mixer. Additional interfering signals in the mixer create spurs that must be subsequently filtered, so RF beamforming is the most linear option.

Digital Beamforming

Active beamforming has one major drawback: it is very difficult to realize multiple simultaneous beams. Each beam pattern requires a different setting of the analog phase shifters and variable amplifier/attenuators. While the transmit function may be able to scan to different locations, this is a major limitation for the receive function. For applications like electronic warfare where determining the location of unknown incoming signals is the main function, this temporary blindness is unacceptable.

Resolving this issue requires processing the same incoming signals but with different amplitude and phase weightings to resolve different beams. This is possible by using an ADC on each channel instead of a single ADC for the entire array. The same input signal to each ADC can be processed using different weightings in digital signal processing to resolve different locations. These calculations are performed simultaneously in a high-speed FPGA fed by the ADC output (Figure 5).

By receiving the data directly into an ADC and applying the phase and amplitude weighting digitally, multiple incoming array patterns can be resolved. Instead of the limitations being in analog hardware, the limitations are now in analog-to-digital conversion and digital signal processing. This amplitude and phase modulation can be performed at baseband after a conventional downconversion, but it will be subject to the limitations of IF beamforming mentioned above. It can be performed immediately after the antenna element if a sufficiently capable (high frequency and high resolution) ADC is within the power and cost budget of the system.

The advent of GHz frequency ADCs and DACs with 10+ bit resolution has made this capability a reality despite significant power expenditure and cost. Requiring a high-speed, high-dynamic-range ADC in front of every element in an array with hundreds or even thousands of elements is cost-prohibitive for many applications. Additionally, the power consumption of the FPGA network required to combine all the high-speed outputs from these elements contributes further cost and power consumption.

Hybrid Beamforming

The most common implementation of phased arrays for many applications is a compromise between active beamforming and element-level digital beamforming, referred to as hybrid beamforming. In a hybrid system, there are both digital and analog beamforming elements (Figure 6).

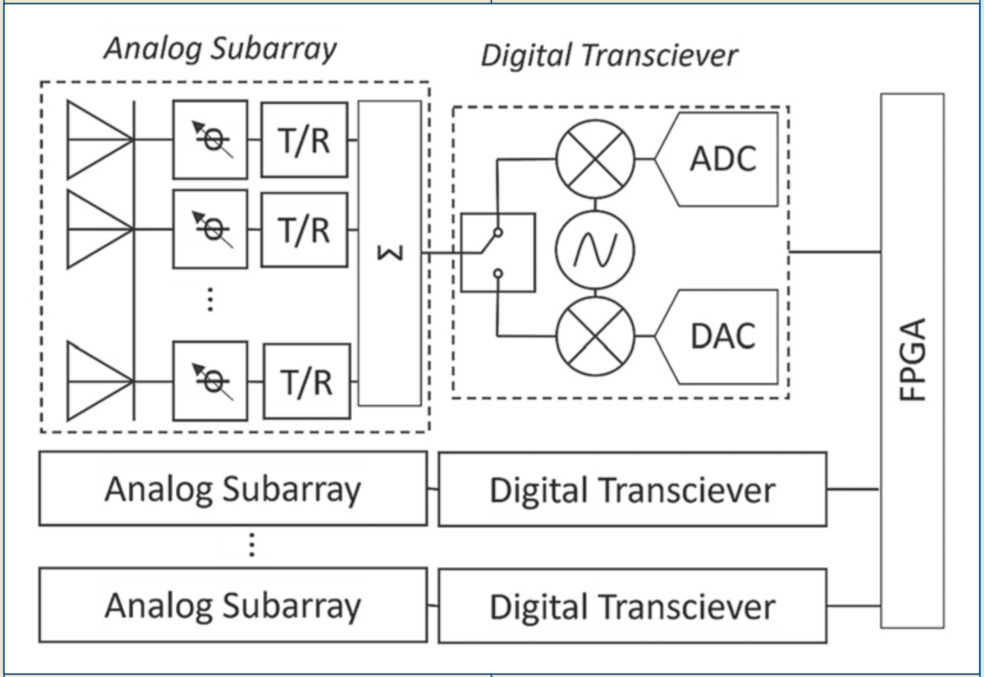

Figure 6 – Hybrid Beamforming Architecture.

Each analog subarray acts as a radiating element, and the digital beamformers process the data from these subarrays to detect signals from multiple different directions. The benefit of this is clearly that the number of elements in each subarray reduces the cost and power consumption of the ADC and FPGA. For example, a 32x32 element array (1024 total) may be divided into 8x8 element subarrays (64 elements per subarray) for 16 subarrays. Each element will require its own analog phase shifter and variable amplifier/attenuator. Only 16 DAC/ADCs are required instead of 1024, reducing the power consumption by 90%. Again, the digital beamforming can be performed at either the RF or IF frequency. Still, the linearity of a subarray after downconversion can be much better than the linearity of a single element since there is some rejection of interferers and jammers. This provides more flexibility, furthers cost, and reduces power.

Component Miniaturization and Phased Arrays

The capability and cost of digital and analog electronic components are used to realize a phased array form a critical part of the engineering tradeoffs in designing a system. Another critical factor for phased array systems is the size of the components. The sidelobes created in addition to the main beam in a phased array are called 'grating lobes', and they limit the highest frequency (or minimum spacing) possible in an array. This is given by:

$$D_{max} = \frac{c}{f_{high}(1+\sin\theta_{max})}$$

where D_{max} is the maximum antenna spacing and c is the speed of light, (f_{high}) is the maximum operating frequency and θmax is the maximum scan angle. For a full scan angle of 90 deg. this is the same as half the wavelength in free space at the highest operating frequency. For a receiver that operates at 12 to 18 GHz, 6 to 18 GHz, or 2 to 18 GHz, this will always be the same 8-mm array spacing.

Considering that standard component sizes range between three and 6 mm2, this is too small to accommodate conventional discrete components. Two primary solutions to this problem have been proposed: one for high-cost systems and one for high-volume systems.

GaAs ASICs and Multichip Modules

For ultra-high-performance systems (major radar and electronic warfare systems), which cost millions of dollars, the solution has been to create application-specific semiconductors in GaAs and multi-chip modules that can be tightly integrated. This technique has several limitations. Integration of multiple functions in GaAs leads to suboptimal component performance metrics as compromises must be made between the optimal process (HBT, power pHEMT, high-frequency pHEMT, PIN diode, etc.) to enable integration on a single die. These tradeoffs are eliminated in multi-chip modules, which allow a system designer to pick and choose individual components with the highest performance for their application.

The issue with multi-chip modules is the assembly cost. Bare die components are not environmentally robust, so they must be assembled into an environmentally protected package. The assembly process is intrinsically serial, using specialized equipment. It can be automated and companies with the required processes can produce multi-chip modules in high volumes at reasonable costs, but the capabilities are not widely available. In contrast, surface mount assembly is a low-cost, parallel process that is widely available from many contract manufacturers. For this reason, surface mount assembly is the preferred implementation for many modern RF and microwave systems in both high and low-volume production.

Silicon And SiGe Beamformers

The obvious choice for small-size, small-cost electronics is integration in silicon. Indeed, silicon beamforming products have proliferated in recent years (as of 2024), and many products are available from numerous companies. These chips integrate a power amplifier, LNA, phase shifter, variable amplifier, power splitting, sometimes up/downconversion, and other functions in a single chip. As with GaAs ASICs, however, integration leads to degradation of performance specifications. This is more pronounced in Silicon as its fundamental RF performance is inferior to III-V compounds for most functions. Integration also leads to limited flexibility, so many systems that would benefit from a phased array implementation cannot utilize the Silicon chips due to operating frequency, bandwidth, or performance limitations. The development of a custom silicon beamformer will take many years and millions of dollars.

For applications where a Silicon chip is available and meets the performance requirements, it is the obvious choice. An additional III-V power amplifier and low-noise amplifier are almost always preferred, and other discrete components are required to meet system-level performance specifications. There is still a need to miniaturize the discrete components in the system without sacrificing the performance advantage provided by these components. Fortunately, component manufacturers continue to make advances in size reduction while maintaining electrical specifications.

The Chip Scale Package for Discrete Components

Industry-standard QFN packages have significantly reduced size from previous generations of microstrip carrier packages. The construction of a QFN consists of a monolithic microwave integrated circuit (MMIC) die wire bonded to transition pads at the bottom of the package. This wire bond–pad transition adds parasitic inductance, capacitance, and significant extra size to the package, especially for small dies. Marki Microwave's chip scale package eliminates the need for these wire bonds and places the landing pads under the MMIC die, enabling significant size reductions (Figure 7).

While QFN packaging typically compromises the performance of the MMIC die inside (particularly for high frequency or low loss components), CSP components offer performance nearly identical to the comparable MMIC die. As an example, consider various limiter options available. A limiter is a component placed before the LNA in a receiver to protect it from the high-power transmit signal. Insertion loss of a limiter directly degrades the sensitivity of the receiver. Poor return loss in a limiter will cause signal degradation due to reflections between the limiter and the antenna.

The HLM-40CH bare die limiter has excellent performance to 40 GHz, with insertion loss below 1 dB and return loss below 12 dB. When placed into a QFN (as the HLM-40PSM), the parasitic capacitance and inductance cause reflections that appear as degraded return loss and insertion loss. When this limiter is modified into the CSP package (as the HLM-8010CSP1), the insertion loss and return loss return to the same or even superior performance compared to the bare die version. At 1.5 mm2 , the

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HLM-8010CSP1 is seven times smaller than the HLM-40PSM, which is critical in an 8mm grid spacing. The CSP package brings bare die performance and size to customers and projects that require surface mount packaging.

We have shown that the CSP package reduces the footprint of high-performance electronic components enough that they can be used within the spacing of a microwave phased array system. To understand how this capability can be used, we need to consider various system-level architectures. In doing so, we will understand the importance of various component performance parameters and their impact on system-level performance.

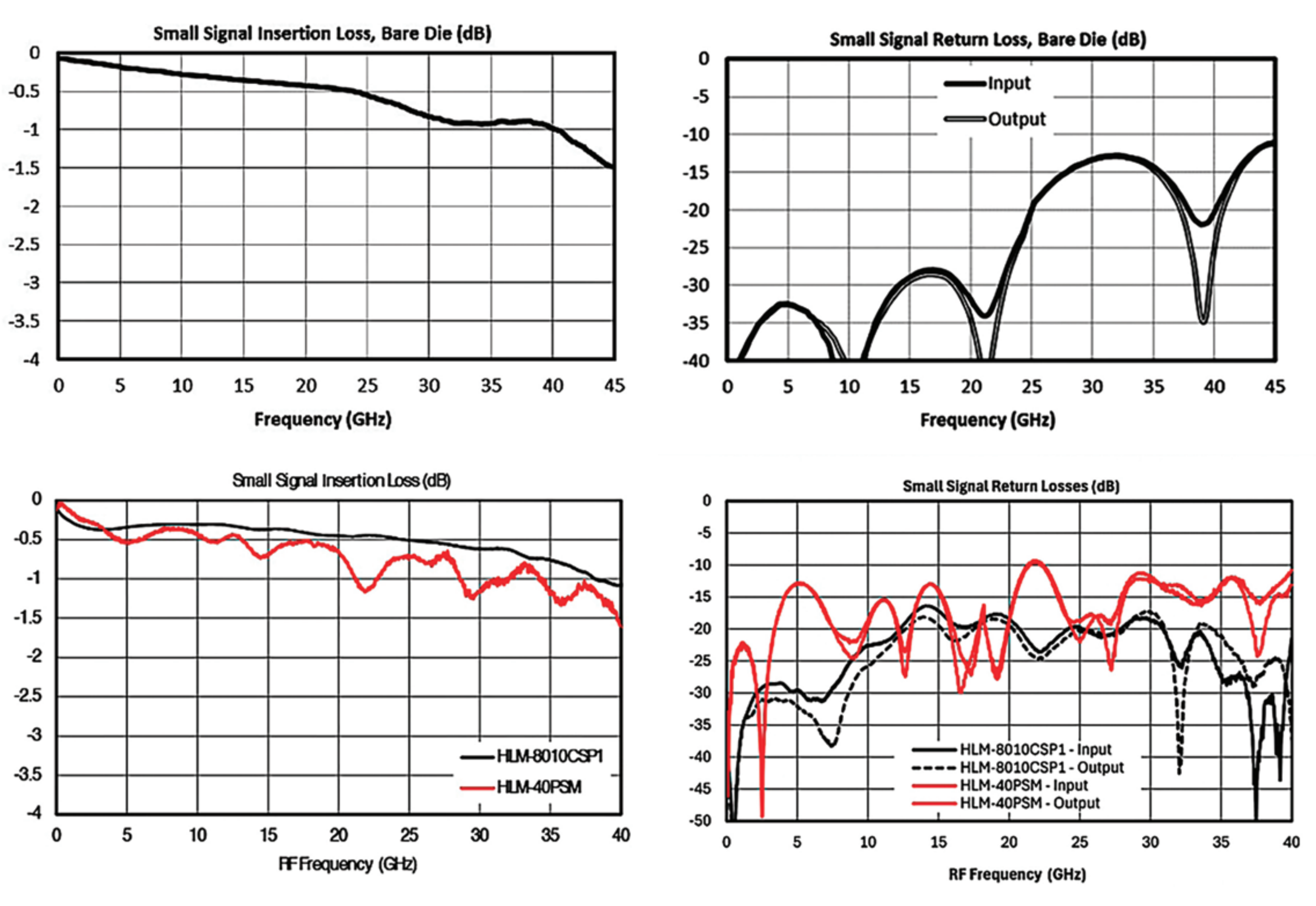

Figure 7 – Small signal performance of bare die, QFN, and CSP packaged limiters.

For simplicity we will only consider broadband receivers. In the following architectures it is assumed that each receiver is a hybrid beamforming network where each block of 8 antenna elements would actually represent an analog subarray that would be combined with other subarrays using digital beamforming to create a receiver that can simultaneously receive signals from multiple different directions with beamsteering and adaptive nulling.

In the first architecture, each receiving antenna element feeds directly into a low noise amplifier to set the noise figure and maximize the sensitivity. A variable phase shifter and attenuator tuned to the desired beamshape follow the LNA. Three sections of power combiners and a filter precede a mixer, which downconverts the signal. The IF signal is filtered to remove spurs, and the amplitude is conditioned with a variable amplifier and attenuator to compensate for losses and maximize the dynamic range before passing through a balun into the ADC.

Benefits:

- Putting the LNA first means no loss contributes to the noise figure, so very low-level signals can be detected
- Since the LNA sets the noise figure, the losses of the phase shifter, power combining network, and filter are not critical specs if the gain of the LNA is sufficient

Drawbacks:

- No protection for the LNA, so nearby transmitters can permanently damage the LNA
- The spatial discrimination of the phased array does not occur until after the LNA, so interfering signals from undesired directions can saturate the LNA and create two-tone intermodulation that will obscure the desired signal.
- Other than the antenna frequency

response, no frequency filtering occurs before the LNA. Signals at undesired frequencies can also damage, saturate, or cause intermodulation in the LNA.

This architecture trades everything for sensitivity. It is best for narrowband applications where low signal levels are expected, such as communications links in sparsely populated areas. The burden for electrical performance specifications is placed squarely on the LNA, which must be both highly linear and robust to damage from interfering signals. While these LNAs may be available, the power consumption, heat management, and cost of putting such an LNA on each antenna element may be prohibitive for many systems.

The remaining components' electrical performance specifications are relieved, but the size requirements remain. All the electronics must fit within the spacing of the antenna array. This is particularly challenging for the power combiners since N-1 is required for an N-element array.

In this architecture, undesirable jamming and interfering tones are eliminated in several ways before the low-noise amplifier. The phase and amplitude shifters and power combining network provide gain to the desired spatial direction and null undesired jamming locations. A filter removes undesired frequencies, and a limiter protects the LNA from destructive-level jammers.

The system's benefits include the complete suppression of signals from undesired directions before they reach the low-noise amplifier (LNA) and the filtering of signals at undesired frequencies, which reduces distortion and minimizes the risk of damage from these interferers. Additionally, the LNA is safeguarded from potential damage by a limiter. However, there are drawbacks to consider; the loss of all elements preceding the LNA, such as the phase/amplitude shifter, power combining network, filter, and limiter, directly contributes to the receiver's noise figure, ultimately degrading its sensitivity.

This architecture trades everything for linearity. It is best for wideband systems operating in dense signal environments, such as electronic warfare and communication in crowded environments. The phase/amplitude shifter, power combiners, filter, and limiter bear the burden of component performance.

Real systems are unlikely to follow either the maximum sensitivity or maximum linearity scenarios but make individual tradeoffs depending on the required system-level specifications for sensitivity, immunity to jamming signals from undesired directions or frequencies, and protection from high-power transmitters. These tradeoffs will depend on the performance parameters available for small form factor components, which we will consider now on an individual component basis.

Desired signals will be in phase when they meet in the power combiners, so they will only be subject to the excess insertion loss of the combiner. This will contribute to the receiver's noise figure, so it should be as low as possible. The isolation of the power combiners will terminate undesired signals, so this should be as high as possible. Both desired and undesired signals will reflect from each level of the power-combining network, so return loss must be excellent, or reflections will distort the signal. Again, the size of each combiner must be small enough to fit into the antenna grid spacing. Marki Microwave offers a full line of high-performance CSP power splitter/combiners in both 2- and 4-way combinations ranging from 400 MHz to 50 GHz.

Filter requirements vary widely by application. This is likely to be a relatively narrowband filter for a communications link that requires sharp rejection, low loss, and good return loss to prevent degradation in sensitivity and signal distortion. This may be a switched filter bank, a tunable filter, or some other adaptive filter for a wideband electronic warfare system. Loss and return loss remain important components. Size is particularly critical for filters, as conventional filter technologies (such as laminate or thin film) are prohibitively large for use within phased array antenna spacing. Marki Microwave offers a complete line of MMIC CSP bandpass, lowpass, and high pass filters with sizes as small as 1.5 x 1.5 mm and frequency coverage to 70 GHz. Additionally, custom filter designs are available with short lead times.

The flat leakage of the limiter must be below the damage threshold of the LNA, the power handling must be sufficient to handle the combined effect of the power combined array input, and the linearity must be sufficiently higher than the LNA so as not to degrade the system linearity. As with previous components, loss and return loss must be excellent in preventing sensitivity degradation and signal distortion. Marki Microwave offers CSP limiters as small as 1.5 x 1.5 mm, various flat leakage and power handling values, instantaneous recovery time, and no spike leakage. These small, lower power limiters are ideal for phased array applications where transmit power levels are lower than in traditional systems with very high-power traveling wave tube amplifiers.

In addition to the stringent size requirements imposed by the phased array antenna spacing, modern RF and microwave systems use multi-channel ADC/DACs that feed directly to FPGAs to perform the complex calculations required for digital beamforming and other digital signal processing, such as digital downconversion and filtering. These chips may have 16 or more microwave channels in a ball grid array package with a pin-to-pin pitch of less than 1 mm. This means that the size of each analog signal processing component must be narrower than 3 mm to fit all components in a linear array in front of the ADC. Size is a constant concern in high channel count systems regardless of the implementation of the antenna.

Conclusion

Phased array technology is a useful tool for many applications. How it is implemented depends on the desired tradeoffs in size, power, cost, and system performance goals such as sensitivity to blockers, ability to detect low-power signals, and antenna scanning range. Advancements in surface mount technology from Marki Microwave (such as the chip scale package) enable system designers to maintain high-performance signal receivers while adding the advanced capabilities of high element count and high channel count arrays. ■

RF and Microwave Filter Terminology and Specifications

by KNOWLES PRECISION DEVICES

TO CHOOSE THE RIGHT FILTER for your application, you must evaluate the filter type, identify the specific filter technology that best suits your application, and ensure the filter meets your required specifications. This article quickly references the standard terms used to discuss filter type, technology, and specifications.

The four key filter behaviors are low pass, high pass, band pass, and band stop (Figure 1).

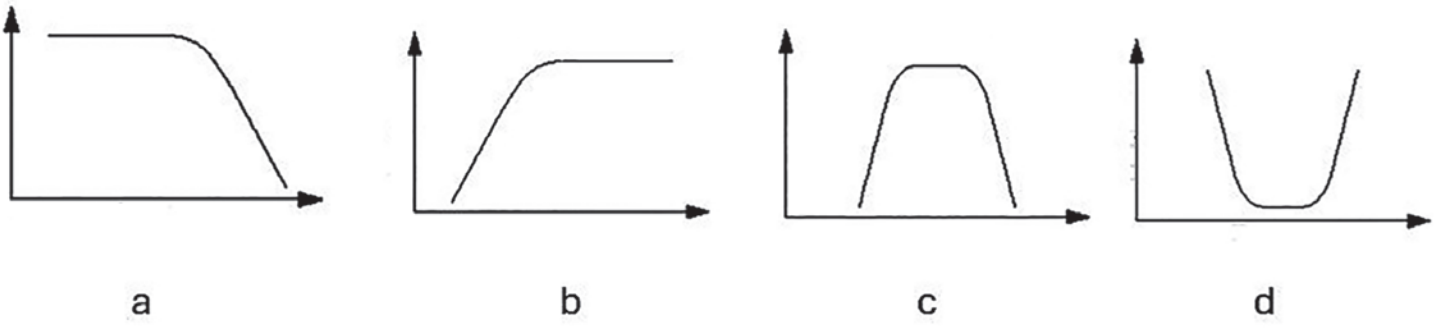

Figure 1 – The four key filter behaviors

Low Pass filters allow frequencies below a given frequency to pass (to be transmitted or received) while rejecting frequencies above the given frequency.

High Pass filters let frequencies above a given frequency pass through the filter while rejecting frequencies above the given frequency (opposite of low pass).

Band Pass filters pass frequencies between two frequencies while rejecting all others.

Band Stop (or Band Reject) filters prevent all frequencies between two frequencies from passing while allowing all others to pass (opposite of band pass)

FILTER TECHNOLOGIES

Crystal Filters: This type uses a quartz crystal as the resonant element. The high Q of a quartz resonator makes for a very steep band-pass. These filters are usually implemented at IF frequencies of 10 MHz and have Q factors of 10,000 to 100,000.

Surface Acoustic Wave (SAW) and Bulk Acoustic Wave (BAW) Filters: These filters cover a range of up to 6 GHz and provide a good performance/cost tradeoff, making them the dominant off-chip filter approach in mobile devices.

Ceramic Filters: These filters are useful for frequencies ranging from about 100 MHz to 8 GHz and offer performance similar to discrete lumped element inductor-capacitor (LC) designs. However, they can be implemented in small form factor surface-mount packages. Performance and package thickness can be limiting factors when comparing ceramic filters.

Lumped Element: The discrete LC approach provides a low-cost solution for implementing a filter, but the attainable Q factors are limited. They are usually employed at frequencies ranging from 30 to 300 MHz but can theoretically be built for frequencies up to 40 GHz. At millimeter-wave frequencies, discrete lumped element filters are very hard to implement because of the dimensional limitations imposed by the frequency since the filter elements must be much smaller than the wavelength of the transmission lines. Discrete LC designs are performance and repeatability limited by the tolerances of the discrete components.

Cavity Filters: This approach is very common between 40 MHz and 960 MHz and offers high selectivity and high power handling capability. However, they are inherently large, which makes them suitable primarily for infrastructure applications such as adding filtering at a cell site.

Planar (typically Mmcrostrip) Filters: These filters are made using a thin-film process and, depending on the filter topology, can offer high Q and a reasonable approach to achieving performance in a small footprint compared to discrete lumped element designs. In the thin-film umped-element approach, the filter's transmission lines are printed in various configurations, depending on the required performance. Filter elements are realized through discrete resistive, capacitive, and inductive elements. Planar distributed element filters rely on carefully distributed transmission lines to create resonant structures and can be designed to tighter tolerances than a lumped-element filter. These designs are more practical than lumped-element designs at higher frequencies.

Waveguide filters: This type of filter has very high power handling ability, which is why it is widely used in radar applications. We also provide very low loss, high selectivity, and rejection. As the size of a waveguide filter decreases with frequency, it is desirable for use at millimeter-wave frequencies.

FILTER SPECIFICATIONS

Regardless of the type of filter, the following parameters are the most important:

Attenuation: Measured in dB, the degree by which a signal sees a loss in amplitude after passing through the filter.

Bandwidth: The width of the passband of a band-pass filter expressed as the frequency difference between lower and upper 3-dB points.

Cut-off: Usually, the point at which the response of the filter has fallen by 3 dB from the passband level.

Group Delay: A measure of how different components of a modulated signal (a sum of sine waves at various frequencies) would propagate through the filter. Measured in units of time (seconds) and is a derivative of the filter's phase with respect to frequency.

Insertion Loss: The ratio of a signal level in a test configuration without a filter present (|V1|) to that when the filter is present (|V2|). When discussed, this typically refers to the loss in the passband.

$$Insertion\ loss\ (dB) = 20log_{10}\frac{|V_1|}{|V_2|}$$

Passband: The portion of the spectrum the filter allows to be transmitted.

Percent Bandwidth: relative figure of merit that compares bandwidth with carrier frequency. Commonly calculated as 3dBW/(center frequency).

Resonator Quality factor (Q): the ratio of stored versus lost energy per oscillation cycle. Overall losses through a resonator increase as Q factor drops and will increase more rapidly with frequency for lower values of resonator Q. As a result, the edges of the passband becomes more rounded, and the bandwidth narrows as the Q decreases.

Rejection: Attenuation of signals outside the passband. Typically measured in dB or dBc if referenced from IL of the passband.

Return Loss: A measure of the amount of the signal returned or reflected by the filter. Measured in dB, it is the negative of the magnitude of the reflection coefficient expressed as power.

$$RL(dB) = -20log_{10}|\Gamma|$$

Passband Return Loss: The return loss in the filter's passband.

Ripple: The variation of insertion loss within the passband measured in dB.

Scattering Parameters: The scattering parameter S11 represents the reflection coefficient (Γ) at the input and is related to return loss. The S21 scattering parameter is a measure of insertion loss (if the measurement ports are the same impedance).

$$IL = -20log_{10}|S_{21}|$$

Selectivity: The ability of the filter to pass or reject specific frequencies relative to its center frequency. Selectivity is typically stated as the loss through a filter that occurs at some specified distance from the center frequency. A filter with high selectivity exhibits a high slope in the transition from pass to stop. Selectivity is crucial in environments where adjacent channels are close together, and high selectivity enables designers to make good use of available bandwidth.

Shape Factor: The ratio of a filter's stop band to pass cand. The higher the shape factor, the closer the filter is to theoretical performance.

Stopband: The band where the filter has reached it requires out-of-band rejection

Temperature Stability: How performance varies with temperature. An approach is to define in ppm/°C the frequency shift of the filters, cutoff, passband, etc., as temperature varies.

Voltage Standing Wave Ratio (VSWR): The filter's match to a given impedance (such as 50 ohms) is calculated from S11 (Γ).

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$$

You can learn more about Knowles Precision Devices filter technology by reading our filter brochure or visiting the microwave products page. You can learn more about how our RF and microwave filter technology fits into 5G and millimeter-wave applications there. ■

Integrated Miniaturization: Optimizing Size, Weight, Power, and Cost

by **Ian Dunn**, *Chief Technology Officer,* SPECTRUM CONTROL

WIRELESS communication advances are shaping nearly every aspect of the RF spectrum and its underlying technologies. Commercial and defense applications demand ever-increasing data throughput, reduced latency, and greater connectivity to access cloud-based large language models (LLMs) for AI, automation, and autonomy. Integrated miniaturization, which unites various functions within a single, compact component, is the most promising, necessary, and powerful approach to meet this imperative.

Integrating GaN, SiGe, optical, MEMS and other technologies has become increasingly common, especially in high-performance communications and cloud acceleration applications. Packaging technology and high-frequency or wideband substrates continue to evolve to keep pace. Investments in material science, design, and component integration can achieve new levels of miniaturization for system designers who must efficiently meet demanding market conditions (Figure 1).

Integrated Miniaturization Benefits

Performance: Traditional SWaP-C benefits of integration can degrade RF performance with increasing levels of analog bandwidth processed. New substrates and manufacturing techniques need to be developed to enhance and promote better analog segmentation, isolation, miniaturization, and integration of passive and active RF components.

Speed and Scale: The design, verification, and testing of integrated RF modules is generally a more time-consuming process than their digital counterparts in a mixed system. While high levels of integration can optimize size, weight, and power for a given amount of performance, the absence of interoperable interfaces between components and modules can add risk to the development timeline. It can also hinder broader system compatibility and long-term adaptability in rapidly evolving technological landscapes.

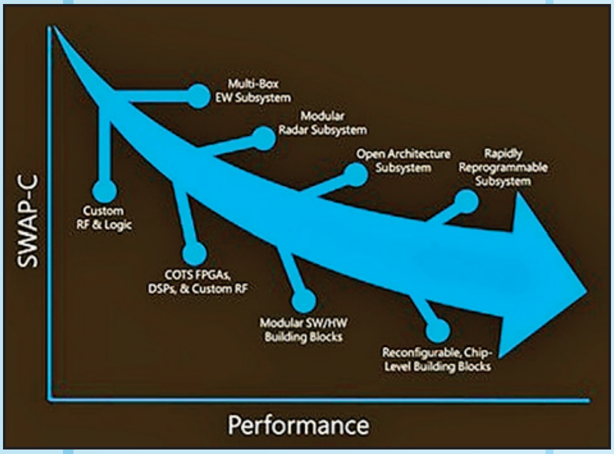

Figure 1 – Trends in RF Miniaturization

Reliability and Environmental Benefits: Integrated miniaturization plays a crucial role in building robust systems. Component reliability is improved by reducing the size and number of discrete elements in a system. And integrated modules provide reduced performance variability as each block functions optimally within its specified parameters.

Embedding multiple functions into a single chip or module allows engineers to design packaging that is better tailored to the device rather than the underlying technology and components. The reduced footprint also minimizes the component count for greater durability. Innovations such as wafer-level packaging further enhance reliability by encapsulating sensitive circuitry in a compact, resilient form factor that safeguards against environmental challenges. This level of packaging facilitates using coatings instead of hermetically sealed, larger housings.

Thermal Management: Smaller components generate less heat and enable more efficient heat dissipation pathways within the integrated design. The close proximity of elements facilitates advanced thermal management techniques that can be embedded in the substrate and packaging, forming an element of the overall interoperability architecture. This integrated approach helps maintain optimal operating temperatures while reducing thermal stress on the components extending the system's life and performance stability.

Key Enabling Technologies

3D Integration and Advanced Packaging: Enabling technologies for integrated miniaturization in RF systems hinge critically on advanced substrate materials and complimentary 3D manufacturing and packaging. Low-loss, high-frequency substrates offer controlled dielectric properties that are essential for minimizing signal attenuation and maintaining performance at millimeter-wave frequencies.

Equally important is the evolution of via technologies. Microvias and via-in-pad structures, reduce parasitic inductance and capacitance compared to traditional vias, supporting high-frequency operation with minimal losses. Blind and buried vias also contribute to improved electromagnetic performance by minimizing unwanted interference and ensuring efficient routing of RF signals. Advanced plating and filling techniques further enhance the reliability and performance of these vias in demanding RF applications.

The combination of low-loss substrates with precision via fabrication reduces the overall footprint of RF components and improves thermal management and mechanical reliability. This synergy allows engineers to design compact, high-performance RF frontends.

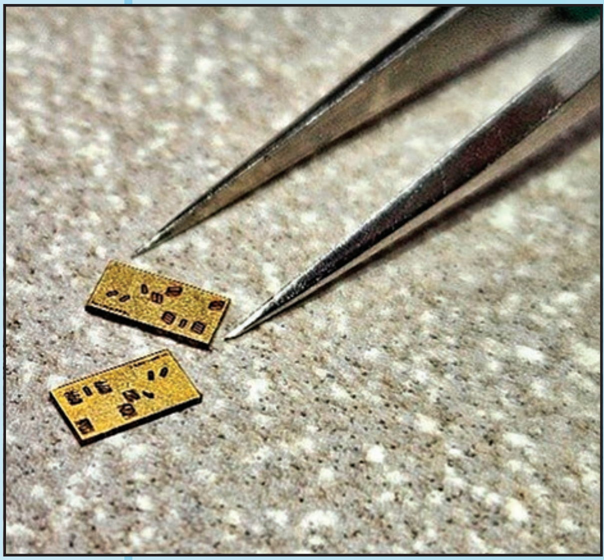

Figure 2 – **Advances in substrate technology, simulation & modeling, 3-D manufacturing, and packaging have led to significant reductions in the size of integrated microwave assemblies.**

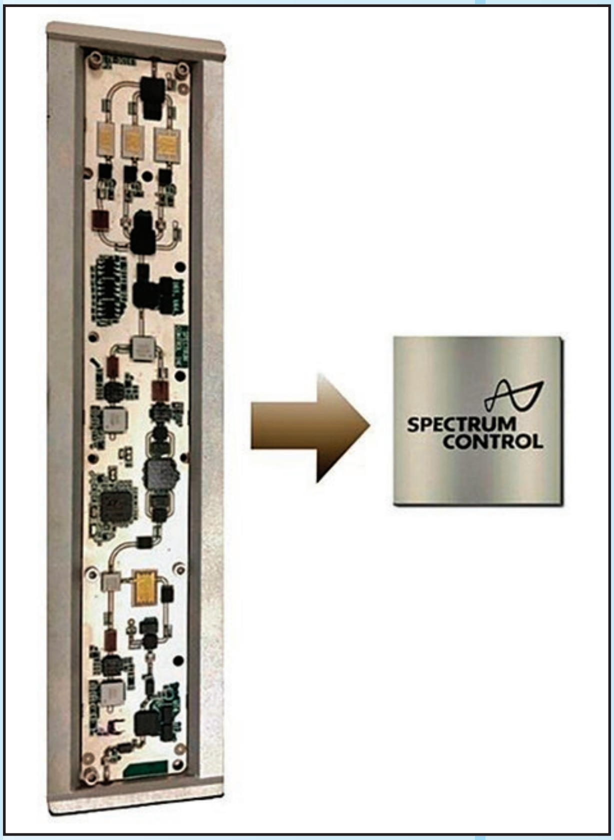

Figure 3 – **Fabricating 3D solenoid inductor structures in glass substrates helps achieve significant size reductions for lumped element filters while maintaining high performance ncy operations.**

Integrated Passives and Filters: Integrated passive structures, such as inductors, capacitors, and resistors, play a pivotal role when integrated on low-loss substrates, achieving compact and efficient RF designs. This approach can reduce the number of discrete components and interconnects, leading to lower electromagnetic interference (EMI) and improved thermal management. This can also be particularly beneficial in high-frequency applications where the size of the passive structure is proportionally smaller to the higher frequency operations. Spectrum Control team has found that via modeling is a fundamental success strategy for designing passive structures and interconnects.

Integrating passive structures within low-loss substrates also supports design flexibility and scalability. It enables the development of complex, multi-layered circuits with precisely controlled impedance characteristics, essential for advanced filtering and matching networks. Manufacturing costs are lowered by minimizing assembly steps and materials. Long-term reliability is enhanced, as well.

Challenges in Integrated Miniaturization

Supply Chain and Manufacturing Scalability: Ensuring stable, high-yield sources of advanced substrates, materials, and specialized packaging services is essential to an efficient, high-performance outcome in integrated miniaturization. Spectrum Control spent two years building a new supply chain with a special focus on next-generation substrates and high-Q micro-miniature filters. The supply chain transformation, combined with upgrades to internal design, simulation, and manufacturing processes, has been essential to the development of the company's SiP platform.

Thermal Management: Integrated miniaturization usually increases power density. Consequently, thermal management is often less concerned about power dissipation

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and more about the overall thermal environment and the mitigation of that environment in normal operation. Ensuring thermal energy is well-distributed across a device, accurately sensing the device temperature, and compensating for performance changes as a function of temperature, is critical to success.

For high signal power devices, ensuring efficient heat dissipation in a small space is crucial to prevent performance degradation and reliability failures. Spectrum Control has incorporated a scenario-planning strategy into thermal simulations, replacing low-power devices with high-power alternatives in simulation to replicate the full capability of the manufacturing stack-up and provide proper guidance to customers.

Testing and Verification: Segmenting an RF design into small building blocks with integrated power and control circuitry can significantly streamline testing and production tuning. Engineers can perform targeted tests on each block, quickly identifying and correcting issues without contending with the complexities of the full system. Integrated power and control enable precise real-time adjustments during testing. Calibration accuracy is improved, and component tuning is simplified. This leads to enhanced reliability, reduced debugging time, and a more efficient production process, with each block independently optimized and verified before final assembly.

Applications for Integrated Miniaturization

Wireless communication has been the driving force behind integrated miniaturization at volume, bringing to fruition the necessary transformation in manufacturing capabilities across the RF industry. Integrated miniaturization brings design benefits to numerous applications, including:

- **5G/6G Antenna Arrays:** With the rollout of 5G, and R&D for 6G well underway, base stations require massive MIMO antenna arrays. Integrating miniature RF transceivers and power amplifiers with on-board filtering and control circuitry allows infrastructure components to be more compact and power efficient.
- **Medical Wearables and Implantables:** Ultra-low-power, small-form-factor RF components are fundamental to ensuring continuous monitoring capabilities enabling patient comfort and device longevity.

Aerospace and Defense: Phased array antennas require increasingly dense RF frontends for beamforming and communication at Ka-band or higher. Military applications in general demand lightweight, ruggedized systems for portable and airborne platforms. Integrated miniaturized RF solutions support mission-critical communications and advanced sensing while reducing payload weight.

What the Future Holds

RF systems will increasingly incorporate analog and digital components, as well as MEMS sensors. This convergence will enable reconfigurable RF frontends, tunable filters, and advanced sensor fusion in smaller, smarter modules in RF-to-bits devices.

By consolidating multiple functions into smaller packages, manufacturers can deliver high-performance solutions that meet the stringent demands of 5G, 6G, IoT, autonomous systems, and beyond.

The potential for machine learning algorithms to tune and re-program edge infrastructure is an increasingly attractive rationale for more modular, intelligent, and of course, miniature RF frontends. The potential for AI-driven adaptation to permeate the entire design flow could be revolutionary, rapidly exploring design permutations and optimizing performance, power, and area. AI-driven tools will reduce development cycles for complex integrated systems, helping designers create innovative RF solutions faster and more reliably.

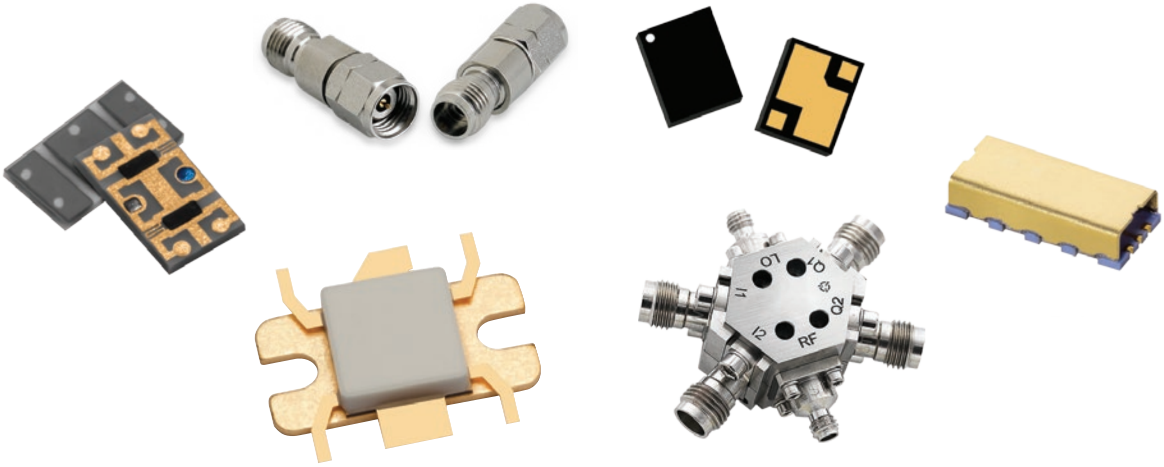
Conclusion

Integrated miniaturization is now a fundamental requirement for next-generations RF components and small form factor modular solutions. By consolidating multiple functions into smaller packages, manufacturers can deliver high-performance solutions that meet the stringent demands of 5G, 6G, IoT, autonomous systems, and beyond.

Spectrum Control has leveraged many of these advances to develop a system-in-package (SiP) platform approach to miniaturization including, a library of components and functions that can be rapidly simulated and aggregated into larger functions, a standard form factor with supporting power and control embedded in the architecture, and a packaging design process and stack-up that provides 70 dB of channel-to-channel isolation inside a standard one-inch square surface- mount BGA package.

While challenges must be addressed, technological advancements are rapidly evolving to meet these needs. For designs in need of innovative performance and smaller footprints, the future of RF components lies in highly integrated, miniaturized architectures – a critical ingredient for the seamless connectivity and pervasive sensing expected in the coming decades. ■

For more information visit spectrumcontrol.com.



High-Speed Loopback Applications with a Differential DP3T MEMS Switch

by **Stewart Yang and Ian Burke,** *Systems Applications Engineering,* MENLO MICRO

A LOOPBACK TEST for Automated Test Equipment (ATE) using the PCIe (Peripheral Component Interconnect Express) standard is a diagnostic procedure that routes data signals from a PCIe device's output back to its input, allowing the device to verify its functionality and performance. High-speed switches are essential in this context, as they support PCIe's rapid data transfer rates, which can reach several gigabits per second. Performing loopback tests at these high speeds is crucial for identifying issues like latency, signal degradation, and timing errors that may arise under real-world conditions. This capability enables engineers to accurately assess the performance and reliability of PCIe devices, making it a vital part of the testing process in modern electronic systems.

As data rates surpass 64 Gb/s and protocols like PCIe 5.0/6.0 become standard, test engineers face mounting challenges when validating these high-speed interfaces on design-in boards. Traditional electromechanical relays (EMRs), once the backbone of external loopback testing, have reached their practical limits with the PCIe 4.0 specification.

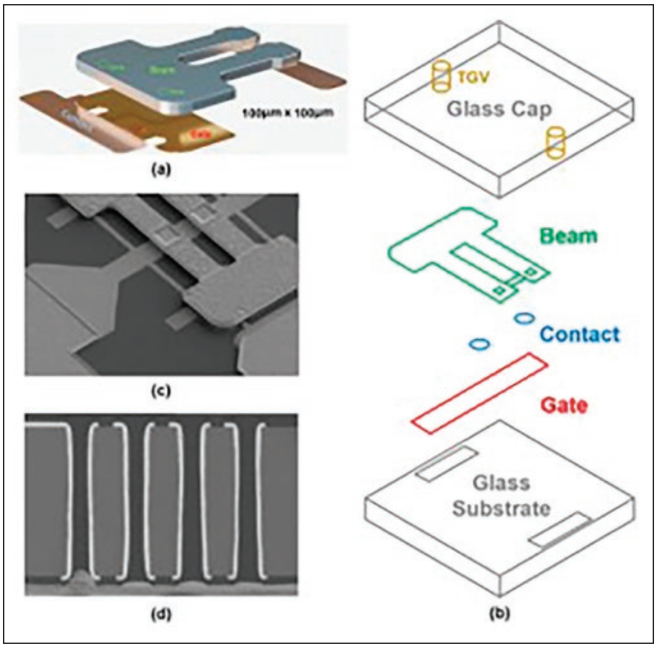


Figure 1 – The Ideal Switch consists of a glass substrate and a glass cap (a and b), a through-glass via, a beam, a contact, and a gate (c) The unit cell is only 100 µm × 100 µm (d).

One of the limiting factors with the PCIe 5.0/6.0 specifications is switch performance at higher frequencies. Historically, EMRs have been used to implement an external loopback test for ATE applications, but it has become difficult to use the relays to support testing above PCIe 4.0 specification. Menlo Micro's MM5620 Differential DP3T MEMS Ideal Switch addresses this issue as it switches in microseconds versus the milliseconds required by EMRs, which substantially increases test throughput. It also dramatically reduces form factor, allowing for higher test site density and durability measured in billions of cycles rather than millions as with an EMR.

Diving Into the Switch

As shown in Figure 1, the Ideal Switch consists of a glass substrate and a glass cap (b), a through-glass via (d), a beam, a contact, and a gate (b). The unit cell is only 100 µm × 100 µm (a and b). MEMS switches are activated via electrostatic force and require a high-voltage source for the switching operation. When the gate of the switch is set for a bias of 0 VDC, it places the metal cantilever beam in a non-deflected (off) state. Thus, the RF input and output path is isolated with an air gap, like a traditional mechanical relay. When the gate is set to its required actuation voltage of +89 VDC, the electrostatic force between the gate and the cantilever beam is strong enough to cause it to deflect downward, forming a connection with the contact and closing the switch (in the on state).

Because the field is static, the current and power consumption is extremely low. The metallurgy in this beam and contact area is highly reliable, with a minimum of 3 billion cycles and a typical performance of closer to 50 billion cycles at room temperature. Menlo's glass packaging provides better power handling and improved RF performance, and as it is fabricated on a glass substrate, parasitics are reduced, increasing overall RF performance. The switch cavities are hermetically sealed with a glass cap to enable stable resistance and switching performance. Through-glass vias provide a low resistance path to get the electrical signals in and out of the package.

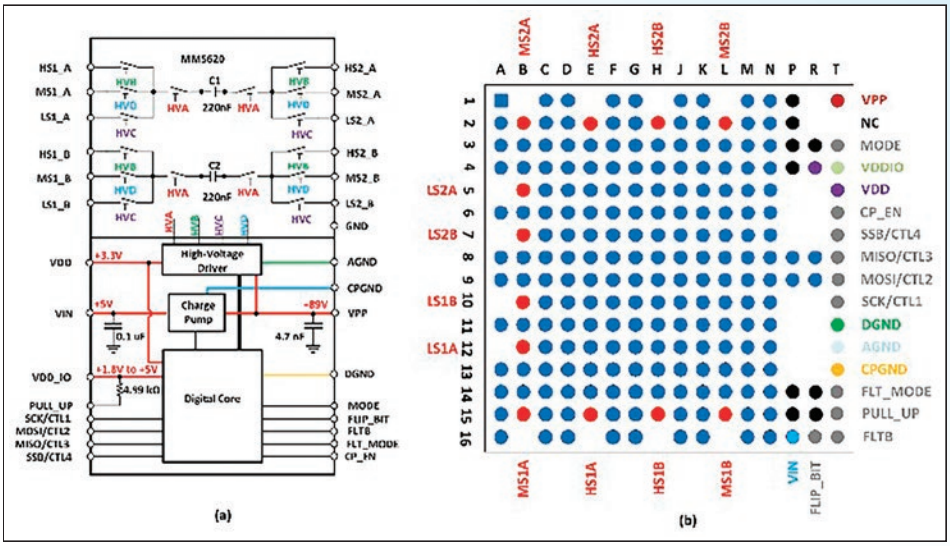


Figure 2 – **A functional block diagram of the device.**

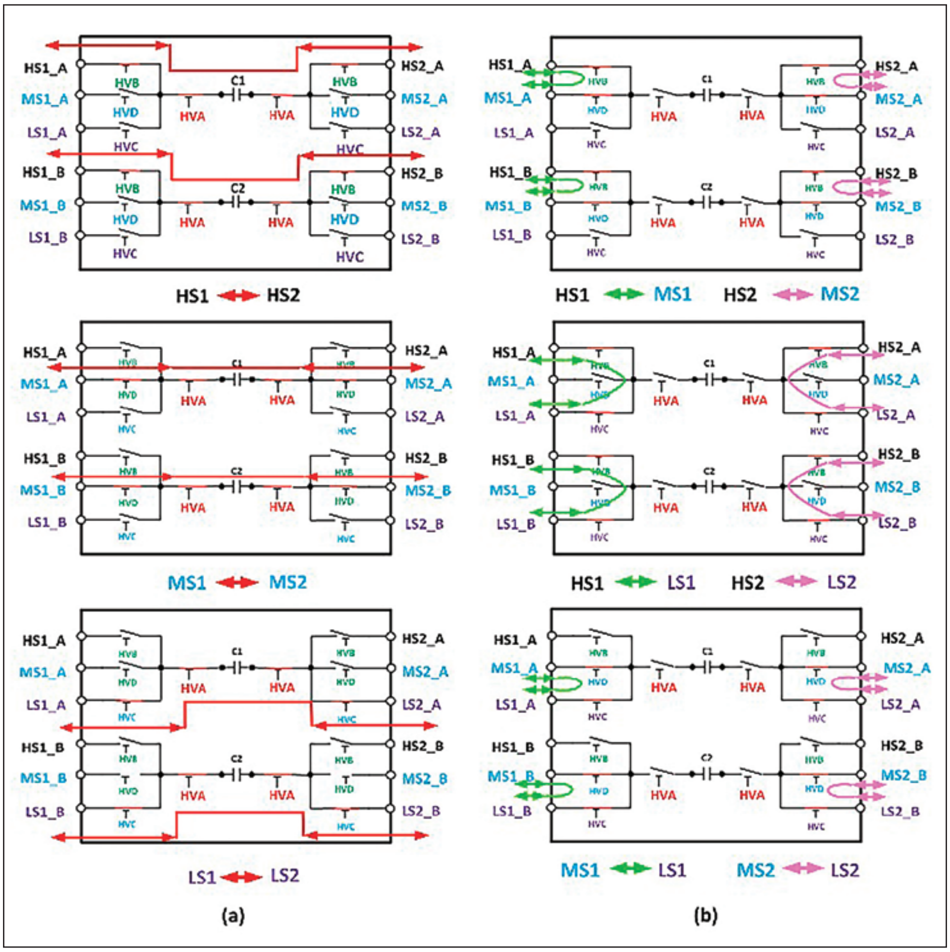


Figure 3 – **Signal paths through AC coupling capacitors (a) and loopback signal paths without AC coupling capacitors (b).**

Loss and linearity are the fundamental differences between one of Menlo's Ideal Switch products and semiconductor or solid-state switches. These can be traced back to a key figure of merit for switches called Ron Coff. This value is the on-resistance when the switch is turned on multiply the off-capacitance when the switch is turned off. Given our metal-to-metal contact, glass-insulating substrate, and air-gap open circuit, Menlo has demonstrated Ron 5 to 10 times lower than semiconductor switches.

The Ron Coff value for the MEMS switch is typically 18 fs, owing to very low off-capacitance in the femto-farad range. In addition, the switches have higher breakdown voltages than semiconductor switches and can handle higher power. When comparing our products to conventional mechanical relays, the Ideal Switch enables significantly smaller products, in many cases more than 50 times smaller in volume. The smaller size and mass of the mechanical actuator achieve switching times 1000 times faster than conventional mechanical relays.

Figure 2 shows a simplified functional block diagram and pinout of the MM5620. The upper part is the switch units, and the lower part is the charge pump and high-voltage driver. As shown in Figure 3, there are six possible controls. Three are loopback signal paths through AC coupling capacitors, and the other three are loopback signal paths without AC coupling capacitors.

Three possible signal paths pass through the AC coupling capacitors: high speed 1 to high speed 2, medium speed 1 to medium speed 2, and low speed 1 to low speed 2. Six more supported signal paths do not pass through the internal capacitors. Four high-voltage outputs from the built-in switch control module control these switches.

These switches are controlled by four high-voltage outputs from the built-in switch control module. There are many differential signal paths supported, and it gives flexible functionality. The switch re-

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quires high voltage to drive the gate to control the switch on and off. The device has an internal charge pump and a high-voltage driver. The charge pump input voltage is 5 VDC, and an additional digital supply is required. This is selectable within the 1.8 to 5 VDC range on the VDD_IO pin and sets the level for digital communication with the device. The switch can be controlled using either GPIO or SPI mode.

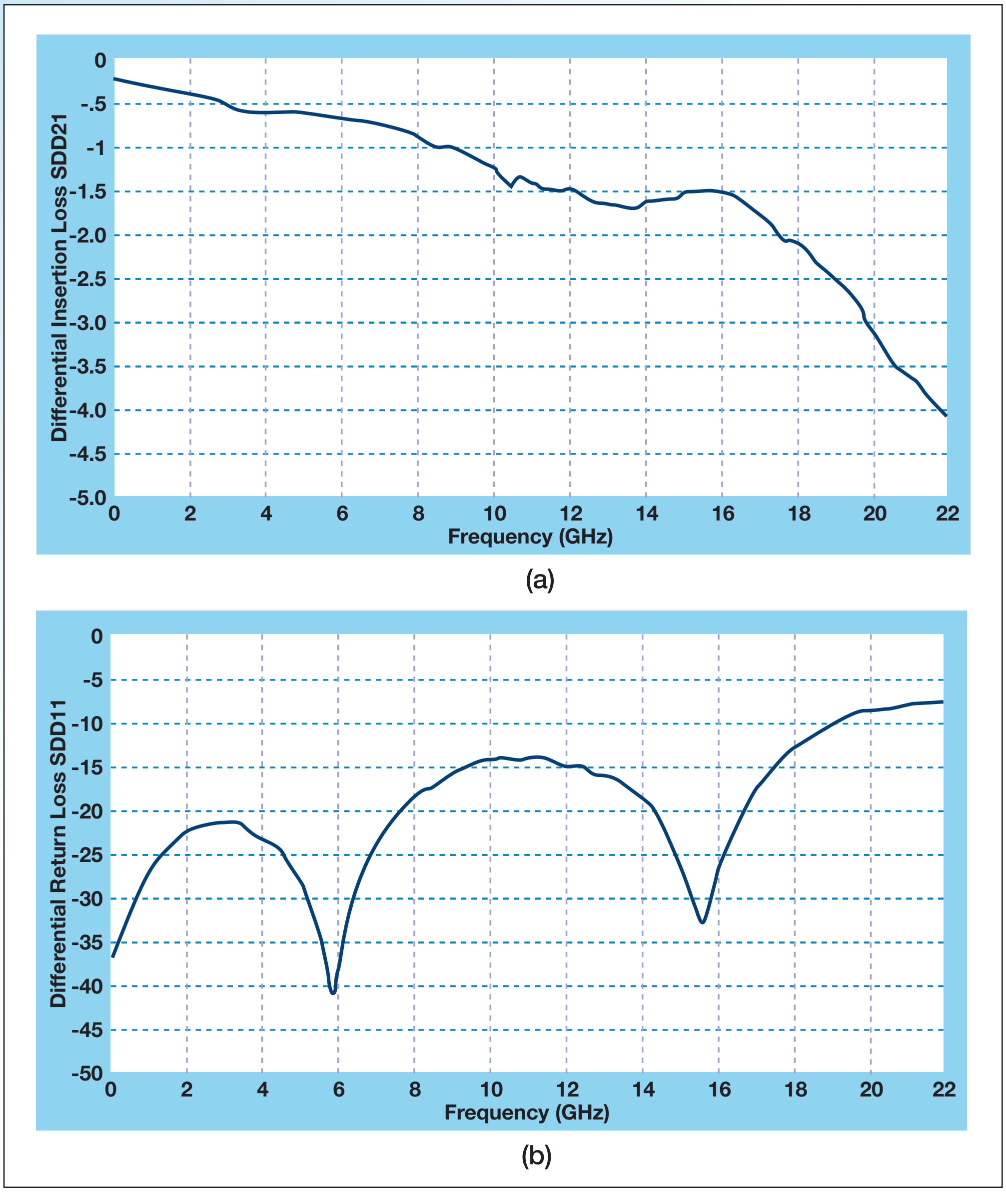
Figure 4 shows differential insertion loss (SDD21) and differential return loss (SDD11) for the high-speed loopback path. For the AC coupling signal paths, the high-speed one to high-speed two path shows a low insertion loss of about 1.49 dB and 28 dB of return loss at 16 GHz. The mid-range return loss is close to 15 dB, but it can be improved by optimizing the PCB to PAD launch using a tear-drop transition. S-parameter files are available to assist in the simulation of the board transition and overall performance during the design phase.

Figure 5 shows an eye diagram at 64 Gb/s and Table 1 shows eye-diagram performance, which was post-processed based on measured S-parameter performance. The three eyes are wide open and clean.

The switches enable single insertion testing, covering the at-speed, 64 Gb/s signal loopback test, providing access to the tester's high-speed instruments and DC instrumentation for parametric measurement. Figure 6 shows an example of how to perform these three tests using a single MM5620.

High-Speed Digital PCB Design

To achieve a good high-speed PCB design that meets the specific design target, it is very important to understand your fabrication houses' capability and details of their design rules in advance and then work closely with them. Most high-speed differential lines use either an edge-coupled microstrip or an edge-coupled stripline. A differ-



(a)

(b)

Figure 4 – Differential insertion loss SDD21 (a) and differential return loss SDD11 (b) for the high-speed loopback path.

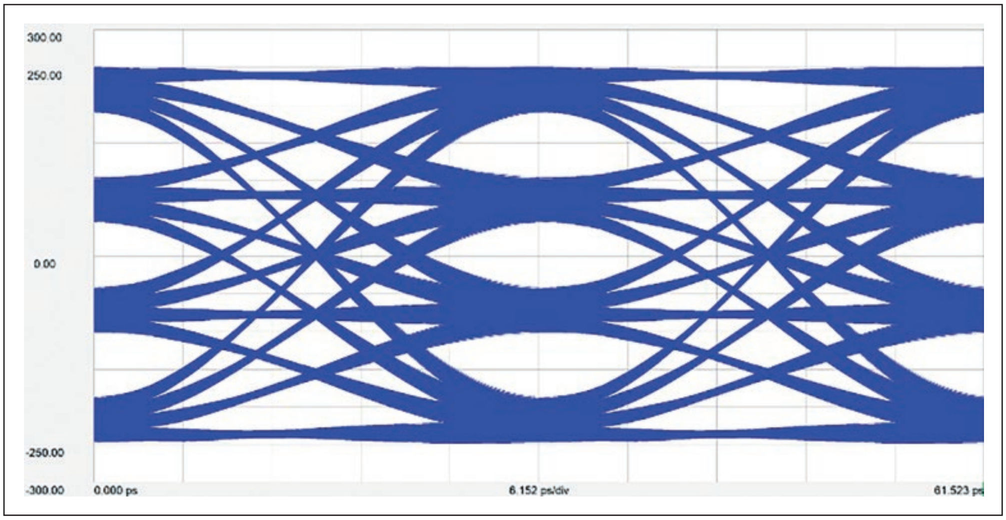


Figure 5 – Eye diagram performance.

ential pair can be implemented as loosely or tightly coupled. Figure 7 shows differential microstrip vs. differential Stripline construction, and Table 1 describes the pros and cons between the loosely and tightly coupled trace routing options.

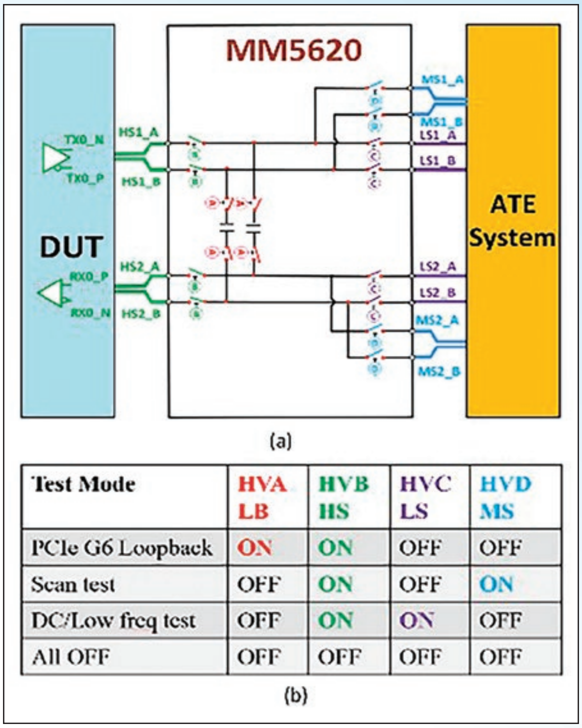
PCIe Gen6 uses the Nyquist frequency of 16 GHz, the material choices, their properties, and their manufacturing tolerances must be carefully considered and modeled as they can lead to signal integrity issues. The signal attenuation from the substrate material includes dielectric loss, conductor loss, reflections due to mismatched impedance, and radiation loss. Losses due to radiation are usually minimal and negligible. The remaining losses can be attributed to the various properties of the substrate material choice. Material properties that directly affect the link performance include:

- Loss tangent (tan(δ)/Df)
- Dielectric constant (Er/Dk)
- Fiberglass weave composition
- Copper surface roughness

The skin depth also needs to be considered; at RF and microwave frequencies, the current is conducted at the surface of the transmission line, and that depth of current flow is called skin depth. For low-loss designs, avoiding Nickel in the plating (ENIG/ENEPIG) is best. Even a very thin layer of nickel will cause high loss due to its low skin depth, and most of the current is carried in the high-loss nickel layer.

If the design has high-speed routing on the top or bottom layer it is important to choose a better dielectric material with a low dielectric constant, low-loss tangent, better surface roughness, reverse-treated copper foil, and a better plating method such as EPIG, ISIG, EPAG.

For the differential signals, routing should be smooth with minimum bends, and tight length matching is required. Stitching vias must be placed along all high-speed routing from DUT to connectors. If space allows, it is desirable to implement two rows of stitching vias along the RF signals routing as the operating frequency approaches 20 GHz. Optimizing via transitions is necessary to minimize the impedance mismatch.



Test Mode	HVA LB	HVB HS	HVC LS	HVD MS
PCIe G6 Loopback	ON	ON	OFF	OFF
Scan test	OFF	ON	OFF	ON
DC/Low freq test	OFF	ON	ON	OFF
All OFF	OFF	OFF	OFF	OFF

Figure 6 – **PCIe G6 loopback test block diagram (a) and truth table (b).**

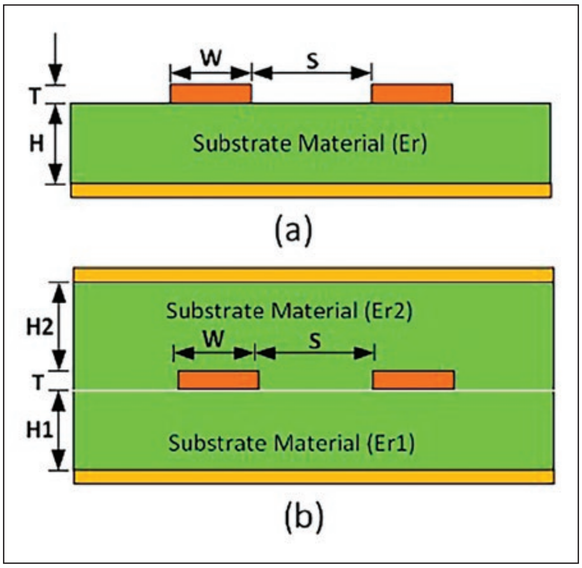


Figure 7 – **In differential microstrip (a) vs. differential stripline (b) construction: T is copper thickness, W is trace width, S is spacing, and H is substrate height.**

A TDR simulation using 3D EM tools is a good method to check the impedance of vias and optimize it. The solder mask needs to be removed on high-speed traces. Confirmation by running post-layout full 3D EM simulation to obtain s-parameter, TDR, and eye diagram results is a must to ensure that the board layout can meet the requirements. Although it takes additional time, confirmation by running post-layout full 3D EM simulation to obtain s-parameter, TDR, and eye diagram results is a must to ensure that the board layout can meet the requirements.

Conclusion

Menlo's differential DP3T switch can support the PCIe Gen6 loopback test and can be used for PCIe Gen5 applications for improved performance and reliability by replacing EMR relays on the existing load boards. Excellent eye-diagram performance is achieved at 64 Gbps signal without pre-emphasis or equalization enabled. Test engineers requiring an RF switch that meets the requirements for PCIe Gen5/6 performance while saving crucial space in the load board and improving reliability will appreciate a MEMS-based approach solution that is also cost-competitive to EM and solid-state solutions. ■

TABLE 1

Eye	Bit Rate (Gbps)	Eye Height (mV)	Eye Width (ps)	Total Jitter (RMS, ps)
0/1	64	83.6	11	10.2
1/2	64	84.2	13	8.5
2/3	64	84.2	11	10.4

Advancing RF Front-end Design with UltraCMOS® RF SOI Technology

by **Payman Shanjani,** *Director of Product Marketing,* **pSEMI CORPORATION**

THE EVOLUTION OF WIRELESS communication systems, including fifth-generation (5G) networks and the Internet of Things (IoT), demands radio frequency (RF) front-end solutions with enhanced performance, higher integration, and improved efficiency. Silicon-on-insulator (SOI) technology has emerged as a key enabler, providing reduced parasitics, improved isolation, and superior linearity compared to traditional bulk silicon processes.

pSemi's proprietary UltraCMOS® technology builds upon these SOI advantages through innovations in material processing, device architecture, and monolithic integration. This paper explores the fundamentals of SOI in RF design, highlights the attributes of UltraCMOS technology, and discusses its applications in high-performance broadband switches, amplifiers, low-noise amplifiers (LNAs), and front-end modules (FEMs). It also discusses the future directions of UltraCMOS for sixth-generation (6G) wireless systems.

The global demand for high-speed data transmission, low-latency communication, and ubiquitous device connectivity is transforming RF system design. Central to these advancements is selecting semiconductor materials capable of meeting stringent performance requirements. SOI technology has become a critical substrate for RF design due to its ability to minimize parasitic effects, enhance isolation, enable higher frequency operation, and improve signal integrity. pSemi's UltraCMOS technology represents a significant advancement in RF SOI, offering industry-leading performance for RF switches, tuners, amplifiers, and integrated front-end components.

Fundamentals of SOI Technology

In traditional bulk CMOS processes, devices are fabricated directly on a silicon substrate, introducing significant substrate losses, parasitic capacitances, and noise coupling at high frequencies. SOI technology addresses these limitations through a layered structure consisting of a silicon base substrate, a buried oxide (BOX) insulating layer, and a thin top silicon device layer, as shown in Figure 1.

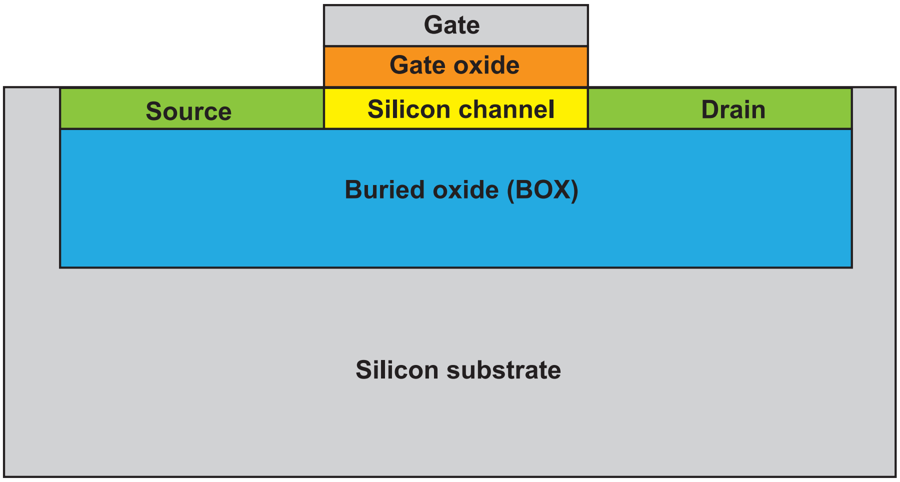


Figure 1 – Using a buried oxide layer to improve the isolation in SOI process technology

Key benefits of SOI in RF design include:

- **Reduced parasitics:** Lower capacitance between active devices and the substrate enhances high-frequency performance.
- **Improved isolation:** The insulating layer reduces substrate coupling, critical for maintaining signal purity in dense circuit layouts.
- **Enhanced linearity:** SOI devices exhibit superior linearity, minimizing distortion and intermodulation.
- **Lower power consumption:** Devices achieve better electrostatic control, enabling operation at lower voltages.
- **Integration potential:** SOI facili-

tates monolithic integration of RF, analog, and digital functions on a single chip.

These attributes make SOI technology well-suited for RF front-end components like switches, tuners, amplifiers, and LNAs.

UltraCMOS Technology Overview

UltraCMOS technology extends the fundamental advantages of SOI with proprietary enhancements in material processing, device design, and circuit innovation.

High-performance RF Switches: UltraCMOS RF switches exhibit low on-resistance (RON) and low off-capacitance (COFF), achieving minimal signal loss and high isolation over broad frequency ranges. These switches outperform conventional GaAs and standard SOI devices in linearity and power handling, essential for modern mobile and infrastructure applications. pSemi's UltraCMOS technology platform has been at the forefront of RF SOI performance, maintaining the lowest RON.and COFF in the industry.

Analog and Digital Function Integration

UltraCMOS enables the integration of RF analog circuitry with digital control logic. This monolithic integration simplifies system design, reduces component count, and conserves board space without compromising performance.

Superior Linearity and Harmonic Suppression

UltraCMOS technology delivers outstanding third-order intercept points (IP3) and minimizes harmonic distortion even under high-power conditions. High linearity enhances spectral efficiency and reduces signal degradation in dense communication environments.

Reliability and Ruggedness

UltraCMOS devices are engineered for durability and can withstand high voltages, electrostatic discharge (ESD) events, and wide temperature variations. These attributes ensure long-term stability and reliability in consumer, automotive, and industrial systems.

Applications for High-performance RF Components

UltraCMOS technology's versatility extends to a wide range of RF components, each benefiting uniquely from the intrinsic properties of the SOI-based platform.

Broadband RF Switches: UltraCMOS is optimized for high-frequency, broadband RF switch applications. Key advantages include:

- **Low insertion loss:** Enables minimal signal degradation across the DC to 60 GHz frequency range.
- **High isolation:** Critical for preventing leakage between the transmit (Tx) and receive (Rx) paths in complex RF chains.
- **Excellent linearity:** Supports coexistence of multiple radio standards without introducing intermodulation distortion. UltraCMOS switches are ideal for applications in 5G handsets, infrastructure beamforming networks, and reconfigurable RF front-ends

Power Amplifiers: Although historically dominated by III-V materials, UltraCMOS enables highly linear, efficient driver amplifiers and power amplifier modules through:

- **Superior linearity:** Reduces adjacent channel leakage ratio (ACLR) in high-power transmission.
- **Thermal stability:** Maintains consistent performance over varying temperature and power conditions. UltraCMOS PAs are well-suited for compact, integrated RF front-end modules in smartphones and small cells.

Low-noise Amplifiers (LNAs)

UltraCMOS LNAs leverage the low-noise characteristics of SOI to enhance receiver sensitivity:

- **Low noise figure:** Improves the signal-to-noise ratio (SNR) at the receiver front end.
- **High gain and linearity:** These advantages enable UltraCMOS LNAs to achieve high performance in size—and power-constrained wireless devices. They support low-distortion amplification of weak signals, essential for IoT and satellite communications.

Integrated Front-end Modules (FEMs)

UltraCMOS technology allows the integration of switches, amplifiers, and tuners into single-die RF FEMs, offering:

- **Reduced PCB footprint:** Essential for compact mobile devices.
- **Simplified RF system design:** Facilitates lower component count and enhanced system reliability. UltraCMOS-based FEMs streamline the development of multi-standard, multi-band wireless platforms.

System-level Applications

UltraCMOS technology finds widespread deployment across multiple sectors where high performance, integration, and reliability are critical.

Mobile Devices

Compactness, integration, and multi-band support make UltraCMOS critical for smartphones, tablets, and wearables operating across 4G, 5G, Wi-Fi®, and Bluetooth® standards.

5G Infrastructure

Massive multiple-input, multiple-output (mMIMO) base stations and small cells benefit from UltraCMOS components with high linearity and robustness, enabling efficient beamforming, signal routing, and antenna tuning.

Recent pSemi products, including the PE42443 and PE42444, support power handling up to 50 dBm, exhibit insertion loss below 0.5 dB, and deliver linearity up to 85 dBm. These features have enabled analog beamforming in front of the power amplifiers (PAs), eliminating the need for additional filters. As a result, customers benefit from

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reduced system costs and improved overall base station performance. See Figure 2.

Automotive and IoT

In automotive and industrial environments, UltraCMOS components deliver high isolation, ruggedness, and long-term reliability for telematics, V2X communications, and connected sensor networks. In addition, before being approved for automotive use, components must undergo rigorous qualification processes to ensure they meet the industry's demanding yield and reliability standards. UltraCMOS has proven to be robust technology capable of meeting these stringent requirements.

Cable Modems (DOCSIS)

UltraCMOS technology plays a critical role in next-generation cable modem systems, particularly in the Data Over Cable Service Interface Specification (DOCSIS) 3.1 and 4.0 standards:

- **High linearity and isolation:** Essential for upstream and downstream channel integrity.
- **Broadband performance:** Supports wide frequency bands up to 1.8 GHz and beyond.
- **Robustness:** Switches connected to the antenna port, also called the F connector, must withstand stringent surge requirements—often exceeding several kilovolts—which can be reliably met thanks to the inherent robustness of UltraCMOS technology.

Test and Measurement

UltraCMOS devices are well-suited for RF test and measurement equipment requiring precision, repeatability, and broadband operation:

- **Low insertion loss and high isolation:** Critical for accurate signal characterization across a wide frequency range. Recent advancements in UltraCMOS technology have demonstrated strong switch performance at frequencies up to 100 GHz.
- **High linearity:** Minimizes measurement distortion in vector network analyzers (VNAs), signal generators, and spectrum analyzers. UltraCMOS technology enables next-generation testing platforms to be used in the wireless, aerospace, and defense industries. Recent research using UltraCMOS technology has demonstrated linearity performance exceeding 93 dBm, comparable to the highly linear MEMS-based switches commonly used in test and measurement applications.

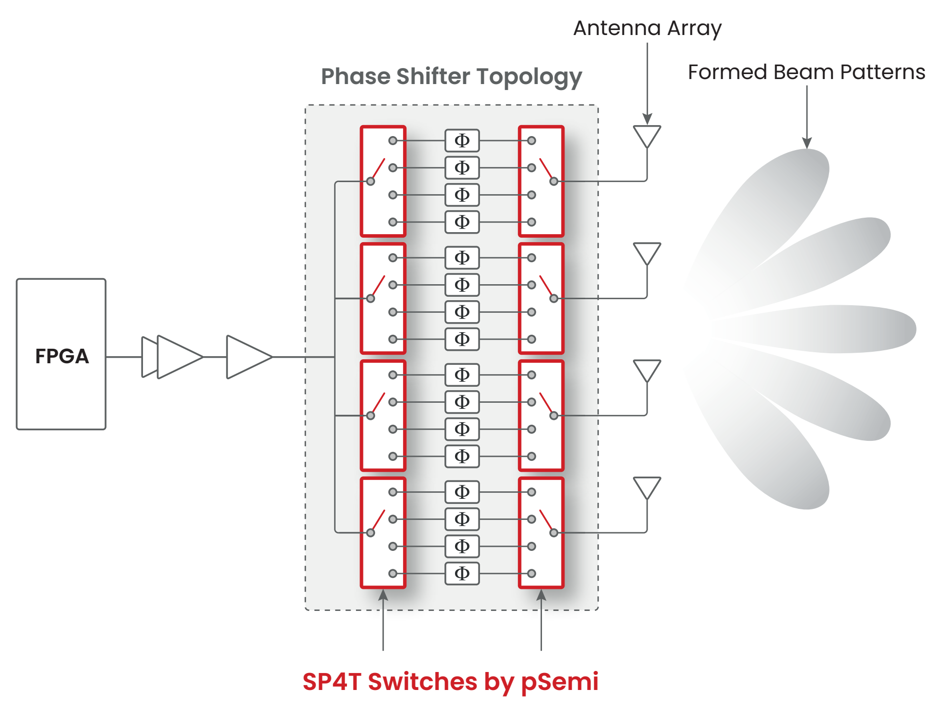

Figure 2 – Using high-power and high-linearity switches for beamforming in 5G mMIMO systems

Future Directions

The wireless industry is progressing toward 6G networks, with operating frequencies extending into the sub-terahertz (THz) range. UltraCMOS technology is well-suited for these future demands due to its low parasitic, superior isolation, and scalability.

Future advancements in UltraCMOS technology are expected to include direct integration with advanced phased-array and beamforming systems, ultra-low power consumption for battery-constrained applications, and intelligent RF front ends with embedded AI-driven optimization. pSemi continues to invest in material engineering, process optimization, and design innovation to extend the capabilities of UltraCMOS technology.

Conclusion

Modern wireless systems require RF FEMs that can accommodate high power levels, stringent linearity requirements, multi-band operation, and aggressive size constraints. Traditional technologies such as GaAs or GaN offer high performance but are expensive and complex to integrate. Bulk CMOS technologies provide integration but often fall short in RF performance and ruggedness. A balance is needed between high performance, integration capability, and cost-effectiveness. pSemi's UltraCMOS platform elevates the benefits of SOI, offering superior RF performance, high integration, and robust reliability. From mobile devices to 5G infrastructure and automotive communications, UltraCMOS is enabling the next generation of connected technologies. As the industry moves toward 6G and beyond, UltraCMOS is poised to continue leading innovation in RF system design. ■