APERTURE TO DATA

The latest miniature multi-mode arrays are offering enhanced performance at low cost and with simple implementation

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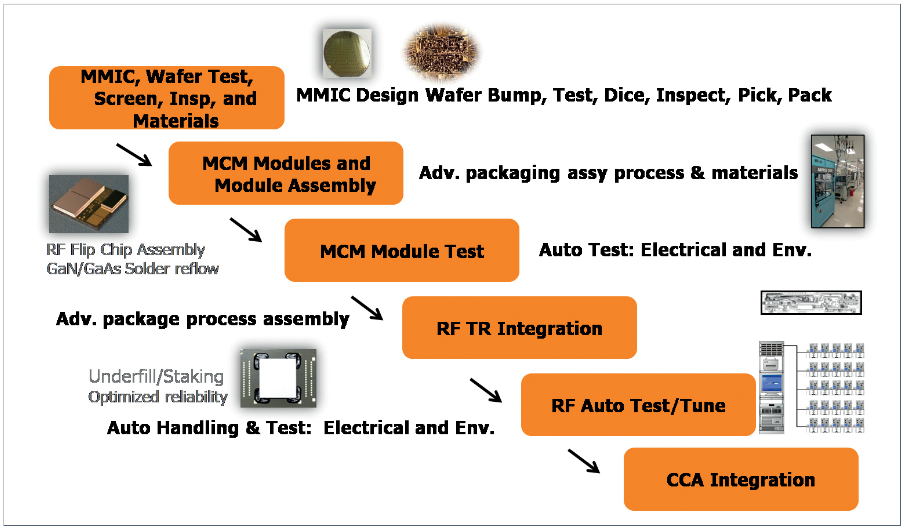


Figure 1: Vertical integration needed for small mmWave AESA
Opposite page:
Figure 2a: K-CSP Test Board (basis for 8 x 8 array) tested in 2019
Figure 2b: SiGe/GaN beam-former I/Q Performance, and RMS Phase and Amplitude Error

Most ATC radars such as ASR-9 and ASR -11 and weather radar such as WSR-88D use a continually rotating antenna. Earlier versions used a vacuum electronic device, such a Klystron, transmitter with high peak power and low duty cycle. Si bipolar transistors, and recently GaN transistors, have replaced vacuum electronic device transmitters with lower peak power levels using the pulse compression technique leveraging higher duty cycles and longer pulse widths. The solid-state transmitters provide an order of magnitude higher MTBCF resulting in a significant reduction in operation and sustainment costs.

The development of next-generation phased array radars and advent of commercial 5G wireless infrastructure is fueling considerable innovation in massive MIMO antenna designs and software-defined beamforming. The Multifunction Phased Array Radar (MPAR) program, sponsored by the Federal Aviation Administration (FAA) and National Oceanic and Atmospheric Administration (NOAA), successfully spearheaded the consolidation of multiple independent legacy radar functions into a more cost-effective, unified, multifunction platform for weather surveillance and ATC.

The planned Spectrum Efficient National Surveillance Radar (SENSR) program will replace the aging surveillance, weather and ATC radars with fewer, more advanced multi-mission systems. The Five mission areas are: near-/short-/long-range aircraft surveillance with the Department of Defense (DoD), Department of Homeland Security (DHS) and FAA “air traffic control” weather (FAA, DoD) “high resolution” weather (NOAA, FAA, DoD).

The developments for all digital array radar for the DoD and 5G have generated interest in millimeter-wave (mmW) for UAVs (unmanned aerial vehicles). Through advanced integrated circuits (ICs) and packaging, miniature multi-mode custom arrays offer customers new capabilities with “aperture to data” enhanced performance at low cost and simple implementation.

Phased Arrays and MIMO Radar

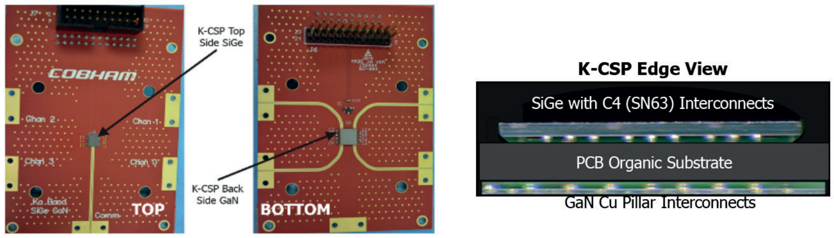
Cobham Advanced Electronic Solutions (CAES) is developing Active Electronically Scanned Array (AESA) technologies for mission-critical systems in support of radar, electronic warfare (EW), missile / munitions, space, communications, navigation, and IFF (identification friend or foe) communication navigation identification, and for UAV applications.

Investments in phased array and Multiple Inputs Multiple Outputs (MIMO) radar technologies, along with underlying IC and packaging technology are required to meet demanding threat detection requirements. Solutions for these radar products are built upon highly integrated system-on-a-chip (SoC) custom ICs and MMICs along with advanced packaging and integrated subsystem products (Figure 1). Combinations of differentiated technology aggregated with advanced package and automation is making it possible to build small lightweight integrated AESA solutions. Advanced technology integration is required to be an integrated solution provider from aperture to data.

New technology roadmaps coupled with close relationships with fielded applications offer a fresh new look at the AESA technologies advanced packaging of system-on-a-chip solutions with fully integrated subsystems. This widens opportunities to deliver a strategically important supply to system primes and key subsystem providers.

Recent FCC (Federal Communications Committee) news regarding the multi-billion dollar bids for mmWave frequency bands along with expansive 5G rollout indicates long-term technology development. Connector and waveguide technologies are improving to support the growing need for and uses of mmWave frequency expansion.

Leveraging long-standing RF expertise, CAES can offer broad solutions and capabilities including antenna systems, transmit/receive (T/R) electronics and beam-formers, up/down converters, digitizers, interconnects, and positioners. Through the use of advanced packaging technologies, digital and direct conversion technologies have become part of the signal chain. The



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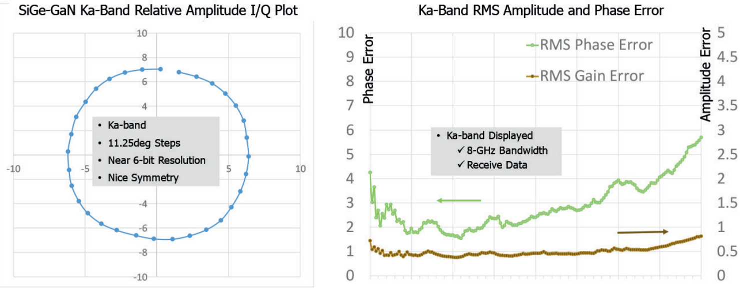

result is an integration of the complete signal chain into an integrated mmWave solution with higher power, wider bandwidth, and high reliability in austere environments. Integration lowers size, weight, power, and cost while meeting stringent application requirements for highly sensitive solutions with optimum probability of detection.

A tailored approach to building AESA systems using new technology offers cost, size, reliability, and performance advantages. Frequencies under consideration include Ka-band and W-band. These mmWave steerable systems track target range, position, and velocity vectors. Target detections must be resolvable from each other, even when targets are substantially contrasting in reflection cross-sections at variable range. Key performance criteria include simplifying the array control and system interfaces with higher levels of integration.

Technology application

mmWave phased array dimensions with typical λ/2 element spacings are very small (approximately 5mm at 30GHz to 1.9mm at 80GHz). Therefore, placing T/R elements at the aperture is feasible and is nearly ideal for T/R electronics at lower mmWave frequencies using quad-channel MMICs and Silicon ICs. Communication arrays are well suited for these form factors with transmit power at less than 0.2- W/element where silicon technologies are well suited. Phased array with transmit powers greater than 0.75 W/element require more sophistication in TR electronics and often require active cooling within the array. Fortunately, advance cooling substrate materials and techniques are not required for power densities lower than 10 Watts/element.

The total transmit power for small arrays is primarily limited by available prime power and the dissipated power in the form of heat generated from each element's T/R amplifiers RF conversion efficiency. At mmWave frequencies, the factor limiting operation is typically heat dissipation. Power added efficiency (PAE) at mmWave - established by semiconductor technology and circuit implementation – should be near 25% or higher for a multi-stage MMIC amplifier.

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

When building arrays within the Ka-band frequency range, it has become increasingly obvious that higher levels of integration with customized system-on-a-chip and automated assembly processes drive performance and affordability towards planar phased array architectures.

Ka-Band Phased Arrays

Key pieces of the development in this area include: Multi-channel Silicon-Germanium (SiGe) beam-former ICs; multi-channel Gallium Nitride (GaN) T/R MMIC with PA, LNA, switches; chip-scale flip-chip packaging (K-CSP) for both die on organic substrate; integrated heat sink, and I/O RF, DC, and control signals. The silicon die utilizes C4 solder bump flip-chip technology, and the GaN MMIC die utilizes Cu pillar flip-chip technology. The K-CSP configuration leverage production qualified flip-chip process developments based upon maturing processes qualified to QML Class-Y processes that use automated processes and are environmentally rugged.

The MMIC and mmWave SoC combination was designed a few years ago with specific features needed for phase array operations. Currently, the GaN T/R MMIC is a multi-channel mmWave RFIC with approximately 15% bandwidth with electrical channel-to-channel symmetry with ≥ 1-W/channel transmit output power and ≤ 5.5-dB receive noise figure as integrated with low insertion loss T/R switches. PA efficiency, LNA noise figure, and TR switch power handling and loss were optimized to near

Characteristics	Performance Goals
Operating Frequency	Ka-Band, 15% BW
Instantaneous Bandwidth	> 500 MHz
Scan Volume - Azimuth	+/- 60˚
Scan Volume - Elevation	+/- 60˚
Scan Loss (+/- 60°)	< 3 dB estimated
Azimuth and Elevation Beam Width (3dB)	+/- 5 degrees
Noise Figure	5.5 dB @ 64 elements sub-array
Antenna Gain	23.3 dB @ 64 elements sub-array 29.2 dB @ 256 elements (4 sub-arrays)
EIRP (sub-array/array)	71.3 dB @ 64 elements sub-array 83.3 dBm@ 256 elements (4 sub-arrays)
Input Voltage	28 V DC
Cooling	Liquid Cooled
Operating Temperature	-20 to +85˚ C
State Switching Speed	2.5 uS

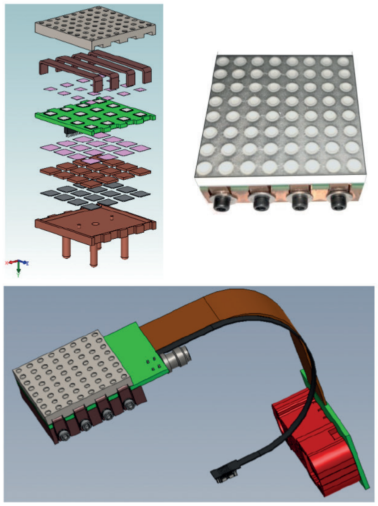

Figure 3: 64-element planar Ka-band test sub-array and performance goals

Figure 4: AESA topology scalable from a few elements to 1,000s of elements with LRU building blocks.

performance limits offered by short gate length GaN technology. The SiGe SoC was set up for an analog beam forming to work specifically with the GaN T/R MMIC in a 3-D stack. The SiGe SoC has 30-dB amplitude control, and near 6-bit phase control. The I/Q performance plane is corrected with a built-in 8-bit coefficients for small and simple calibration stored into on-chip register space. Calibration tables are very small and allow a single 64-bit serial beam-steering command to repoint the entire array with potentially many hundreds or thousands of elements.

Figure 2 shows the SiGe / GaN test boards used to characterize the channel characteristics, RF and thermal performance, and is the basis of the ongoing 8 x 8 phased array modules optimized for organic substrates to be tested in late 2020. With nearly 6 bits of phase resolution channel performance, the test demonstrated RMS error of 2.4-degrees mid-band phase error and 0.36-dB of mid-band gain error.

Figure 3 illustrates a 64-element sub-array and vertically integrated assembly. Extensive reliability analysis (including solder stress and mechanical stress predictions) and environmental test verification, offer a path to reliable automated assembly processes for IC integration. These small integrated arrays (1.5in x 1.5in x 0.8in) are assembled to withstand austere environments with reliable operation both mechanically and thermally. The use of commonly available organic substrates provides the opportunity to tailor array pattern variation with custom printed circuit board (PCB) shapes such as round, rectangular and octagonal. The GaN MMIC has fractional-power modes and may be scaled up in output transmit power to 8-W/element or more for array architectures with a limited number of elements.

The array has a 120˚ field of view (FOV) with 3-dB beam width of ± 5 degrees and less than 3-dB of scan loss at ± 60-degrees. The effective isotropic radiating power (EIRP) for a 256 element array is approximately 83.3-dBm (≥ 200kW) with beam state switching speed of less than 2.5 µs.

The radiating elements are circularly polarized and the current demonstration array is half-duplex. Dual polarization configurations are also under development for assembly in 2021. The arrays are liquid cooled—with PAO or other suitable cooling liquids—to maintain a uniform temperature and low thermal gradients across the array. Integration of the Ka-band AESA architecture may be scaled up into large arrays or scaled down into arrays with fewer elements as shown in Figure 4.

Aperture to data

Performance advancements in recent years in small geometry Silicon CMOS technology (including RF CMOS), have allowed higher levels of integration to become a reality. Work extending the multi-channel planar approach of the Ka array to include other key pieces of the radar is underway with architecture studies and demonstrations. This new integration will make ultra-small advanced capability arrays with digital conversion a reality in the coming months, with mmWave radar demonstrations planned for the fall of 2020.

Developments are currently underway to evolve the up/down converters, transmit signal synthesis (DAC) and receive digitization (ADC) at rates exceeding 1 GS/s, and to include radar detection and digital-signal-processed datasets directly in the aperture electronics. This architecture enables multi-beam software-defined digital beamforming (or mixing of digital and analog beamforming). This capability enables digitally modulated radar sensor operation utilizing beamforming and code division multiplexed MIMO radar capabilities. The MIMO feature offers extended virtual receive channels, improved angular resolution, and interference immunity associated with digitally coded channels. These extended capabilities also offer improved range resolution, better signal to noise ratio (SNR) at similar frame rates, and faster updates with short system cycles. The system can also switch between phase array modes and massive MIMO processing mode or a combination thereof. Advance digital processing ICs utilizing these capabilities result in four-dimensional (4D) detection datasets with spatial position and velocity for many targets. This is the new world of aperture to data. ❖