THE RISE OF ACTIVE-ELEMENT PHASED-ARRAY RADAR

Ike Chang

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Preface

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Introduction

The War in the Persian Gulf has recently underscored the vast leverage of advanced electronics to U.S. military power. Advanced electronics will likely play an even greater role in the U.S. military in the future. Under declining budgets, the U.S. forces are experiencing drastic reductions in manpower and resources. To offset these reductions, the military has turned to high technology in general as a force multiplier. In terms of projecting air power, a key force multiplier involves the use of electronic sensors for reconnaissance, surveillance, and tracking. One type of sensor for tactical aircraft, fire control radar, has proven to be a crucial element in establishing air superiority over potential adversaries in war. This paper will discuss the advantages, history of development, and enabling technologies of a superior and emerging technology for fire control radars.

Newly emerging technologies have finally enabled the development of the superior radar technology of solid-state active-element phased arrays. Active-element phased-array radar employs an antenna composed of an array of elements, each with their own amplifier functions. This can be contrasted with a passive-element phased-array radar, whose elements receive microwave energy from one transmitter source. On the receive side, passive elements absorb microwaves and transfer the energy to a receiving amplifier. Hence, the term "passive element" signifies that the element apertures themselves do not generate microwaves from electrical energy and vice versa. Instead, the apertures transfer the microwave energy passing through them to and from a separate source that houses the amplification and phase control.

Numerous radar configurations are possible that combine characteristics of both active and passive phased arrays into one array. For instance, an array could have elements that are passive in the transmit mode but active in the receive mode. Thus, element apertures would not amplify the transmitted signal, but would amplify the received signals. In another case called a "hybrid" array, every column of an array would have its own amplification and phase function, but the rows within the columns would not. Such a hybrid array might be described as active along one dimension and passive along another. In yet another case, such as an array used for early warning ballistic missile detection, the U.S. has developed a semi-active array where every *two* aperture elements have their own amplification. Numerous other configurations having both active and passive characteristics are possible. To avoid confusion with these partial active-passive arrays, this paper will refer to active radars as being *fully* active where each and every element aperture has its own transmit and receive amplification and phase control.

Beam-steering capability is a required attribute for fire control radars. To search for targets, the fire control radar scans by steering its beam quickly over a search area. After sensing reflections from one or several targets, the radar must then memorize the positions and range of the targets and track them by following their movements with a narrow beam. For beam steering, most airborne fire control radars of the past have relied on physical rotation of the antenna to steer the beam. Both active and passive phased arrays are different from this in that they beam steer by modulating the relative phases among the elements. This happens because one can create a desired radiation pattern of an array antenna simply by controlling the phase distribution among the elements. Thus, the characteristics of beam shape and direction can be precisely controlled.

Beam steering with a phased array can be highly effective when controlled by a computer processor. The processor can be programmed to calculate the appropriate element phases for a given direction of the beam. Because phased arrays scan by electronic modulation of the element phases, they are also called *electronic-scan* radars. On the other hand, radars that scan by physical rotation of the antenna are called *mechanical-scan* radars. Some mechanical-scan fire control radars employ a reflecting dish or even an active or passive array. An array is not a phased array if mechanical rotation rather than phase modulation is used to steer the beam.

Advantages of an Active Phased Array

Phased Array versus Mechanical Scan

While costly to develop and produce, phased arrays offer dramatic improvements in performance over mechanical-scan radars. Phased arrays offer beam steering without inertia and can therefore scan and track multiple targets almost instantaneously. Some radar engineers have claimed this enables active arrays using advanced transmit/receive (T/R) modules to track ten to 100 times as many targets as those presently available in front-line fighters today. Not only can phased arrays track many more targets than mechanical-scan radars, they can also interleave between different radar modes almost instantaneously. For example, after a pulse in the track-while-scan mode, an array radar can generate a pulse in velocity-search mode. Also, phased array radars are more versatile in generating various beam shapes than mechanical-scan radars with reflectors. A computer controlled phased array radar can employ a variety of different beam shapes for different applications, depending on the amplitude and phase distributions among the element apertures. Unlike an array radar, a reflector radar is limited to the beam shape determined by the aperture's physical configuration.

In addition, phased array radars can be more reliable and maintainable than mechanical-scan radars. Since phased arrays scan electronically, they do not require moving parts. Thus, phased arrays can avoid the rapid physical wear that mechanical-scan radars experience under high dynamic load, giving phased arrays longer lifetimes and lower life-cycle costs.

Active versus Passive Elements

Active phased-array radars also offer numerous improvements over passive arrays. Active arrays are more energy efficient because amplification of both transmit and receive radio frequency (RF) signals are performed immediately behind the radiating surface. Passive systems, on the other hand, typically incur 4 to 6 dB of lost power when transferring energy from the transmitter/receiver to element surface and back.[1] Active arrays can avoid these waveguide or manifold losses by combining the energy from separate miniature modules "in space."[2] The energy emitted by the active modules combines through interference as the radar waves propagate through space. While passive arrays can compensate for the lost power by using a transmitter three to four times more powerful, such a larger transmitter and its associated cooling system would impose severe weight and size penalties.

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[1] Lockerd, p. 108

[2] Skolnik, p. 218.

In theory, active arrays can be more versatile in beam-forming than passive arrays. While passive arrays effect a beam by shifting the phase among elements, active arrays can achieve even greater beam control by also modulating element amplitudes. Additionally, active arrays can operate at wider bands than passive arrays of comparable size and power. Passive arrays require a single transmitting device powerful enough to overcome waveguide or manifold losses and still supply adequate power to several element apertures. Active arrays, on the other hand, can rely on numerous miniature devices which can collectively amplify more efficiently at wider bands than one large, high-power device.

Active phased arrays can have much higher reliability and maintainability (R&M) than passive arrays for two primary reasons. First, through the added power efficiency of combining power in space, active arrays have fewer over-heating problems than passive arrays of comparable performance. Thus, active-array radars can experience less thermal stress and can have longer lifetimes. Second, because every active-array element has its own T/R amplifier module, it is less susceptible to catastrophic common mode failures. Passive arrays generally have one transmitter supplying energy to several apertures. Since the principal failure mode is often with the transmitter, entire subarrays of passive arrays can fail at once. This could either cause severe degradation or put the whole radar out of operation. While redundant power supplies can be employed in passive arrays to reduce the likelihood of such catastrophic failures, doing so often imposes severe weight and size penalties. On the other hand, if one or several T/R modules fail in a many-element active-array, the array can still remain operationally effective. Rather than catastrophic breakdown of the entire radar with one transmitter failure, active-array radars experience gradual reduction in effectiveness even after several T/R modules fail. Radar engineers refer to this attribute as *graceful degradation*. This gives active arrays vastly larger mean-time-between-failures than passive arrays.

Performance Improvements at Systems Level

The use of phased arrays offer substantial systems level improvements over other kinds of radar for an operational system. These improvements fall under several categories--greater range, better R&M, more rapid scanning and precise tracking, greater resistance to jamming, and potentially lower radar cross section (RCS).

An airborne active phased-array radar can potentially detect targets at greater range because it can produce more power than other radars of similar size and weight. Active arrays avoid the waveguide or manifold losses of passive arrays and avoid the weight penalties of moving parts in a mechanical-scan radar. By combining energy in space, active arrays employing several thousands of solid-state transmitters arrays can emit impressively high power levels at good efficiencies. These factors imply not only the advantages of active arrays in terms of greater range but also improved detectability of stealthy targets.

Active phased arrays can also have higher reliability because they require no moving parts and have graceful degradation. The use of adaptive radar-control software can further enhance the lifetimes of active arrays. Control software can be programmed to detect module failures and re-optimize the amplitudes and phases for the remaining modules. The most notable application for this technique to increase subsystem lifetime is in satellite-based communications systems. For satellite systems, cost-effectiveness is driven by subsystem lifetime. Once a subsystem fails, the whole satellite becomes useless because of the prohibitively high cost of repairs in space. With satellites and spacecraft, the increase in subsystem lifetime justifies the high up-front cost of incorporating the adaptive software into a system computer.

Active phased arrays offer the advantage of rapid scanning and precise tracking for fire control. As mentioned above, inertialess beam steering enables scanning at near instantaneous speeds and tracking of many more targets than are possible with mechanical-scan radars. Amplitude modulation of active arrays also enables the generation of sharper beams with smaller beamwidth and higher resolution for more precise tracking of targets.

The ability to modulate element amplitudes gives active phased arrays greater resistance to jamming. Amplitude modulation can improve beam-shaping control, thereby allowing more suppression of sidelobe levels for a given beamwidth. This, in theory, enables the active array to block out jamming signals away from the main-lobe more effectively than passive phased arrays and mechanical-scan radars. In addition, by having a wider operating band, active arrays can be more resistant to jamming, as the radar can be designed to "hop" along a wider range of frequencies. This allows the radar to operate in more frequencies where an enemy jammer is weak.

Finally, active phased arrays can be designed more compatibly within a stealthy airframe than a mechanical-scan radar for two reasons. First, arrays do not require any moving parts, and can therefore be more easily accommodated into tight constraints inside the smooth surfaces of a stealthy airframe. In addition, a mechanical-scan radar, when sweeping its reflector over a wide swath of bearings, presents a highly reflective surface for an enemy radar from many directions. Such a radar could severely compromise the aircraft's stealthiness. Second, an array antenna can be conformally-shaped to or even blend with a particular airframe skin shape for stealth purposes. For instance, a planar phased array could be bevelled at an angle so that it scatters waves downward or upward. It can also be shaped with electrical smoothness throughout to minimize edge diffractions for reduced RCS. This concept of conformal array shaping to minimize impact on RCS signature is reportedly used in the design of the AN/ALQ-181 radar antenna for the B-2 bomber.[3] Wide flexibility in shaping the array is possible because software can be programmed to take an unusual array shape into account when calculating element phases. Such flexibility permits the arrays to be shaped and oriented in a way that minimizes scattering of enemy radar waves.

History of X-Band Active Phased Array

The potential advantages of X-band active phased arrays for airborne applications have long been recognized by radar developers. Besides instantaneous scanning and tracking, X-band arrays can also have high resolution beams due to the small wavelengths at X-band frequencies. In the past, however, active arrays were deemed impractical because of the inavailability of affordable, miniaturized T/R modules that supply adequate power at X-band and higher. The technology of solid state Gallium Arsenide (GaAs) Monolithic Microwave Integrated Circuit (MMIC) T/R modules in the 80s and 90s

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[3] Aerospace Daily, May 16, 1991, pg. 272.

has led to the development of power-efficient active-element phased array radars.

Advanced development of X-band active phased arrays for airborne applications goes back to the early 1960s, when Texas Instruments began development of the Modular Electronics for Radar Applications (MERA). The first generation MERA employed GaAs devices to switch between transmit and receive circuitry and to control the phase shifts of elements, but used silicon transistors for both transmit and receive amplification. MERA demonstrated a capability to scan a pencil beam pattern, but had very low power efficiency due to limitations of silicon transistors in amplifying at X-band. In the 1970s, TI continued active array work by developing the reliable advanced solid-state radar (RASSR), which demonstrated an ability to form and scan variable shaped radiation patterns. Like its predecessor, however, RASSR still could not generate adequate power due to the limitations of its silicon amplifiers.

Beginning in 1983, the solid-state phased-array (SSPA) was developed under an Air Force program. The technology of producing GaAs amplifiers had become available, enabling SSPA to realize higher power efficiencies that previous active phased arrays could not. GaAs field-effect transistors were used inside hybrid amplifier circuits for both transmit and receive functions. SSPA used over 2000 GaAs hybrid T/R modules, and demonstrated not only good performance but also high reliability.

Presently, several programs are striving to develop X-band active phased arrays using T/R modules made of advanced, state-of-art GaAs MMICs. These programs include the ATF radar program, DARPA's Project MIMIC, and the Japanese Air Force's FS-X fighter/support program. MMICs are used to build the modules because of the high levels of integration of power-efficient GaAs transistors in a more compact form than hybrid modules. These programs hope to increase performance and at the same time, decrease size and cost of each finished module package. For all three programs, reducing cost of their MMIC T/R modules is considered the single most important factor determining program success. If successful, these programs could lead to the first operational airborne active phased-array radar by the year 2000.

Enabling Technologies

Digital Signal Processors

The development of fast digital signal processors (DSPs) has provided strong impetus for the development of sophisticated fire control radar. Powerful DSPs are also indispensable for the efficient operation of active phased arrays. Active phased arrays require instructions on what phase and amplitude each element aperture is to have. Such instructions can be controlled using a DSP, thus enabling high-level processing of information needed to search and acquire targets. In addition, DSPs enable active phased arrays to perform many radar modes at high performance, such as multiple track-while-scan, velocity search, and ground mapping. They can also extend system lifetime by sensing any module failures and re-optimizing with the remaining modules still working, thereby enhancing graceful degradation.

GaAs MMIC

GaAs MMIC technology represents the final step in achieving system efficiency and affordability of active phased arrays. MMIC is the integration of several analog microwave/mm-wave circuit devices onto one chip. Instead of silicon, GaAs is used as the basic material for MMIC because its higher electron mobility allows GaAs transistors to switch fast enough to operate at X-band and above. Therefore, GaAs achieves efficient, high power amplification as well as wideband, low-noise amplification at higher frequencies than silicon. Also, GaAs has lower conductivity at radar frequencies. This minimizes electromagnetic power loss within the microwave circuitry and increases overall power efficiency of the devices.

Given these properties, GaAs MMIC technology is now removing the last performance bottlenecks of active phased arrays. T/R modules can be made small enough with MMICs so that arrays of thousands of elements can fit inside an aircraft radome. So far, MMIC has achieved T/R module miniaturization down to a few centimeters in length. This in turn permits the use of more modules within a constrained volume. More modules are needed to achieve higher beam control and more transmit power, a necessity for increasing the detection range and beam-forming precision of the radar.

The most crucial bottleneck remaining is MMIC T/R modules unit production cost. The main reason for this bottleneck is the large number of modules per array. At the moment, a T/R module costs in the thousands of dollars. An array of several thousand modules puts the modules' cost per radar in the millions of dollars. A notable example of where modules drive the entire subsystem's cost is the ATF active array radar. Even if DoD's cost goal for T/R modules is met, the cost of the thousands of modules needed for one ATF array could still comprise about one-third the cost of the entire radar system, including the array, the fire control computer, power supply, and cooling system.

Cost drivers for unit production cost include yield and testing costs. As a measure of manufacturing quality control, yield refers to the ratio of non-defective chips to the total number of manufactured. Increasing yield rates as a way to reduce costs is a key goal for almost every semiconductor program, including the ATF radar program and the DARPA-sponsored Project MIMIC. One Project MIMIC contractor claimed to have increased yield of simple, .5μm field-effect transistor test chips from 10% to over 90% over two years, thereby reducing unit costs an order of magnitude.[4] To increase yield, various fabrication techniques are under development to reduce the number of faults per chip. A second cost driver is test cost. To reduce testing costs, techniques are being explored by MMIC producers to increase automation and decrease testing time. In addition, efforts are being made at collecting a database of test results and interpreting how these results could be used to fine-tune the overall manufacturing process. Such fine tuning helps perfect MMIC manufacturing processes to increase fabrication yields and chip performance.

Conclusion

An active phased array radar employs an antenna containing an array of transmit and receive apertures, each containing its own amplifier. Active phased-array radars offer tremendous advantages over mechanical-scan or passive arrays, especially for airborne fire control. Phased arrays can perform inertialess beam steering and scan at near instantaneous speeds while tracking multiple targets at the same time. The lack of moving parts makes phased arrays less prone to physical wear. With modulation of element amplitudes, active element arrays can offer added beam-forming flexibility, bandwidth, and

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[4] Adams, p. 24.

resolution over passive element arrays. Active arrays are also more power efficient, because the microwave energy is combined in space rather than through a lossy microwave network or manifold. Finally, active arrays can be more reliable because of graceful degradation and multiple, redundant failure modes. Graceful degradation can be further increased using adaptive software to re-optimize around failed modules. These numerous technical advantages of active phased arrays translate to improved overall systems-level performance, such as greater range, better R&M, rapid scanning and precise tracking, improved low-observable detection, resistance to jamming, and lower RCS.

Radar engineers have long recognized these potential advantages of solid-state active arrays, and have attempted to develop them as early as the 1960s with MERA and the 1970s with SSPA. The 1980s have seen the emergence of several development programs geared toward developing more efficient systems using GaAs amplifiers within T/R modules. Three of these programs extending well into the 90s include ATF radar program, Project MIMIC, and FS-X radar program. All three are striving to develop affordable and compact GaAs MMIC T/R modules for active arrays.

Two technologies, digital signal processors and GaAs MMICs, have enabled the development of efficient and affordable active phased arrays. Powerful DSPs have made a tremendous contribution to radars in general, and are indispensable for the operation of active arrays. GaAs MMICs have made possible the development of miniaturized, yet efficient, T/R modules, many of which can fit within tight size constraints. The high production cost of MMIC modules continues to be a problem, and stands as the final obstacle to more widespread use of active arrays in deployed systems. Manufacturers are presently working to reduce MMIC T/R module unit costs by increasing the semiconductor chip fabrication yields and decreasing testing costs. Substantial gains in GaAs MMIC production processing so far give great hope that active phased array radar will soon become a staple for all U.S. tactical combat aircraft developed into the 90s and beyond.

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