Phased Arrays—Part II: Implementations, Applications, and Future Trends

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Invited Paper

***Abstract*—In Part I of this paper, we presented the basic architectures and theory for passive and active phased arrays. Here, we review array implementation, state-of-the-art applications, and identify future trends in phased-array technology.**

***Index Terms*—Arrays, feed networks, phase shifters, radiators.**

I. Phase Shifters

THE key essential component of an electronically scanned array (ESA) is the phase shifter. To scan to an angle off broadside, a differential phase shift between elements is required. It is convenient to quantize the 360° differential phase shift into discrete increments. For example, a 5-bit phase shifter would have $2^5 = 32$ phase increments of 11.25°. The 32 different phase increments can be realized by cascading five phase shifters with the differential phase increments of 11.25°, 22.5°, 45°, 90°, and 180° and then switching each differential phase shift bit in and out as appropriate to realize the desired phase shift. Such digital phasers are most appropriate for ESAs because they are controlled easily by a special-purpose digital computer (the beam-steering controller).

Phase-shifter critical design parameters are RF insertion loss, amplitude variation with phase shift, switching times, power-handling capability, and the power required to shift phase. Also important are the size and weight of the phase shifter and its control circuits. Unfortunately, no one type of phase shifter has desirable properties for all of these parameters.

A variety of electronically controlled ferrite phase shifters and diode phase shifters have been investigated for use in passive phased arrays [1]–[10]. Diode phase shifters have been used because of their fast switching times, low weight, and low cost with some attendant sacrifice in performance because of their high insertion loss [11]–[14]. In passive array systems where low insertion loss is required and slow switching times are permissible, ferrite phase shifters have been used. Table I compares the performance of 5-bit diode and ferrite phase shifters.

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A. Ferrite Phase Shifters

There are four general types of ferrite phase shifters, i.e., variable permeability, toroidal, dual mode, and rotary field. In a variable permeability phase shifter, a ferrite rod is located in the center of a waveguide and magnetized longitudinally with a solenoid. The phase shift of the propagating RF wave is dependent on the magnitude of the applied magnetic field that is controlled by the current flowing in the solenoid winding. Variable permeability ferrite phasers are generally continuously variable and reciprocal, but have slow switching times, resulting from the high inductance of the magnetizing coil. Also, they require that the large control current be maintained over the operating period of the device. The nonreciprocal toroidal "latching" ferrite phase shifter eliminates the need for a constant control current. It consists of a ferromagnetic toroid centered in a waveguide, as shown in Fig. 1(a), and operates on the remenant magnetization of a ferrite material with a square hysteresis loop. A differential phase shift is obtained by switching the remenant magnetization from one direction to the other. A control wire runs through the center of the toroid to change the remenant magnetization of the toroid. The toroid remains in one state with no further expenditure of energy until a switching pulse reverses the magnetization to the second state where it remains until subsequent switching pulses are applied.

The dual-mode reciprocal ferrite phase shifter shown in Fig. 1(b) provides the benefit of a reciprocal phase shifter with the efficiency of a nonreciprocal design. The variable ferrite in the center of the assembly is axially magnetized to a level for the desired amount of phase shift. At the ends of this central section are short quarter-wave ferrite sections that are transversely magnetized with a fixed quadrapole field to achieve the function of a nonreciprocal circular polarizer. At the extreme ends of the structure are dielectric members containing thin resistive-film elements whose purpose is to absorb one sense of linearly-polarized RF energy, while allowing the orthogonal sense to pass with minimal insertion loss. The whole assembly is metallized to form a waveguide.

In operation, the input quarter-wave plate converts the linearly polarized wave into one sense of circular polarization, which propagates through the ferrite-loaded section with an insertion phase that depends on the magnitude and direction of the applied axial bias field. The output quarter-wave plate then converts the emerging circularly polarized wave back into a linearly

TABLE I
COMPARISON OF TYPICAL PERFORMANCE PARAMETERS FOR 5-bit p-i-n DIODE AND FERRITE PHASE SHIFTERS FOR PASSIVE ARRAYS

Parameter	5-Bit Pin Diode	Ferrite		
		Toroidal	Dual-Mode	Rotary Field
Loss	1.4-2.3 dB	0.6 dB	0.7 dB dB	0.7 dB dB
Size	0.6 x 1.1 inch	0.6 x 1.6 inch	1.0 x 2.2 inch	1.0 x 2.6 inch
Weight	0.6 oz.	0.8 oz.	1.0 oz.	2.8 oz.
Switching Time	50-200 nsec	2-5 μsec	50-150 μsec	50-200 μsec
Phase Accuracy	4° rms	7° rms	6° rms	3° rms
Temperature Sensitivity	Low	High	Moderate	Low
Power Handling	2 Watts	10 Watts	20 Watts	120 Watts
Drive Power	500 mW	100 mW	100 mW	2 W

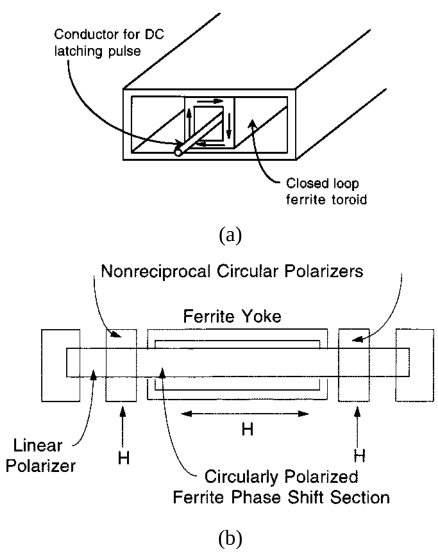

Fig. 1. Ferrite phase shifters. (a) Nonreciprocal ferrite “latching” phase shifter. (b) Dual-mode ferrite phase-shifter configuration.

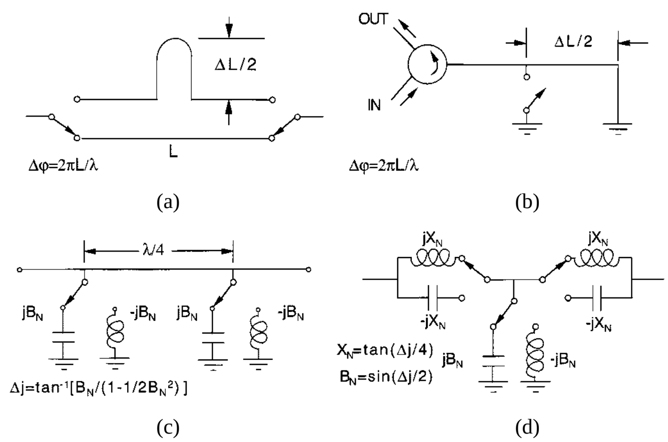

Fig. 2. Electronic switch phase shifter circuits. (a) Switched line phase shifter. (b) Reflection phase shifter. (c) Loaded line phase shifter. (d) High-pass low-pass phase shifter.

polarized wave. The two end plates also cause opposite traveling waves to propagate through the variable-field section with opposite senses of circular polarization to ensure equal insertion phases for both directions of propagation. This combination of nonreciprocal effects results in a reciprocal device without needing to reverse the direction of magnetization. Alternate designs where the variable ferrite section is controlled by a transverse magnetic quadrapole have also been developed to reduce switching times [6].

The rotary-field phase shifter is reciprocal and is an electrical equivalent to a “rotary vane” phase changer [9], [10]. It is used in applications requiring high power-handling capability. It consists effectively of a transducer from rectangular-to-circular waveguide, followed by a linear-to-circular polarizer, a transversely magnetized ferrite rod (equivalent to a rotatable half-wave plate), a circular-to-linear polarizer, and a transducer from circular waveguide back to rectangular. The center ferrite completely fills the circular waveguide and is biased with a transverse four-pole field to a level that creates a birefringence of 180° differential phase (i.e., a half-wave plate). This bias field is produced by “sine” and “cosine” windings placed on a frame that resembles a motor stator that is located outside the metallic waveguide wall next to the ferrite. Each winding produces a transverse four-pole magnetic field in the ferrite rod, and the windings are interlaced such that the principal axes of the four-pole field can be rotated to any angle by setting the currents in the two windings. The amount of phase shift is proportional to the effective angle of the principle axes of the magnetized ferrite rod.

B. Electronic Phase Shifters

Four general configurations of electronic phase shifters are shown in Fig. 2 [11]–[14]. A p-i-n diode, field-effect transistors (FETs), or microelectromechanical switches (MEMS) can be used in these circuits to electronically switch the phase state. The phase shifters in Fig. 2(a) and (b) use switches to select either of two different lengths of transmission lines. In the periodically loaded transmission line shown in Fig. 2(c), the phase velocity is increased when the inductors are switched in and is reduced when the capacitors are switched in. The quarter-wave line between the elements is used to cause a partial cancellation of the reactance mismatches. Fig. 3 presents a photograph of p-i-n diode loaded-line phase shifters encased in machined flared notch radiators. In Fig. 2(d), the elements in the T-circuit are selected so that the section is exactly matched whether the switches are in position to form the low-pass circuit or the high-pass circuit. The circuit provides phase delay in the low-pass position and phase advance in the high-pass position.

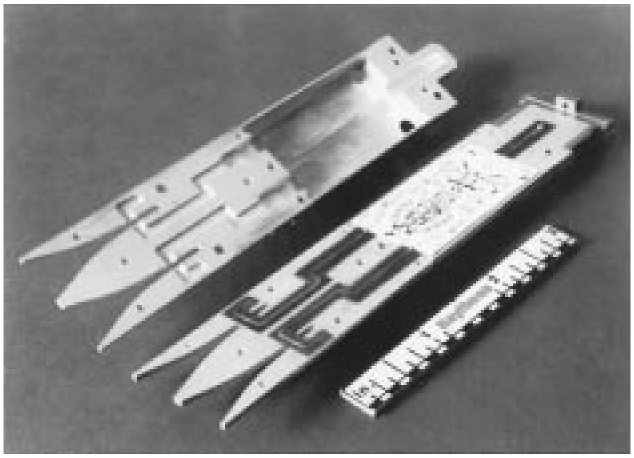

Fig. 3. Two p-i-n diode phase shifters mounted inside the housing of two machined-metal flared-notch radiators. The phase shifters are of the loaded-line type.

MEMS phase shifters offer an alternative for passive array applications where the radiated power per element is relatively low. MEMS technology is still immature, but a five-bit MEMS phase shifter with an insertion loss of only 1 dB and a power-handling capability of 1 W has been demonstrated. Due to their small size, low weight, low insertion loss, and low power consumption, MEMS phase shifters have potential application in space-based arrays.

In the 1990s, monolithic microwave integrated circuit (MMIC) phase shifters were developed for transmit/receive (T/R) modules (TRMs) because of their small size, fast switching speeds, low power consumption, and low cost. Their high insertion loss of 4–9 dB is acceptable because they are used on the low power side of a TRM and after the receive low-noise amplifier (LNA).

II. Array Feed Networks

Techniques for feeding the elements of an array are many and varied; there are two general types, i.e., constrained and unconstrained or space-fed [15]–[23]. There are several variations of semiconstrained feeds between these two basic types. In a constrained feed, the microwave energy is distributed via transmission lines and power dividers to the array elements. Usually, these feeds are one-dimensional, but by interconnecting arrays of these feeds, one can excite the elements in planar arrays. In an unconstrained feed, the energy is distributed through free space or in transmission medium using principles of microwave optics. A constrained feed is usually mounted on the back of a planar array and requires low depth. On the other hand, unconstrained feeds require depths equal to about one-half the array diameter.

A. Parallel Feeds

Constrained feeds are further characterized as either series or parallel depending on the method of power division to each element. In a parallel (or corporate) feed, there are repeated junctions of power division from the input port to each element so that the electrical path length from the input port to each element is the same. Shown in Fig. 4 is a corporate feed for an eight-element linear array. In general, a corporate feed is used in arrays with a binary number (2^n) of elements and requires $2^n - 1$ junctions. The feed network in Fig. 4(a) uses "lossless" reactive power dividers, whereas the feed in Fig. 4(b) uses matched hybrid junctions. Reactive feeds are satisfactory if the input impedance of every antenna element is identical. They are a potential problem if there are any element-to-element impedance imbalances because the power divider mismatches will create feed resonance. In a corporate feed, all the power dividers are the same for a uniform aperture distribution. For arrays with tapered aperture distributions, unequal power dividers are required.

In passive phased arrays, low-loss feed networks are essential and usually waveguides are used. In active arrays, some loss in the feed network can be tolerated and stripline or air-stripline medium is used to reduce array depth, weight, and cost. Fig. 5 presents a photograph of a 19-way air-stripline feed network that utilizes Wilkinson matched power dividers.

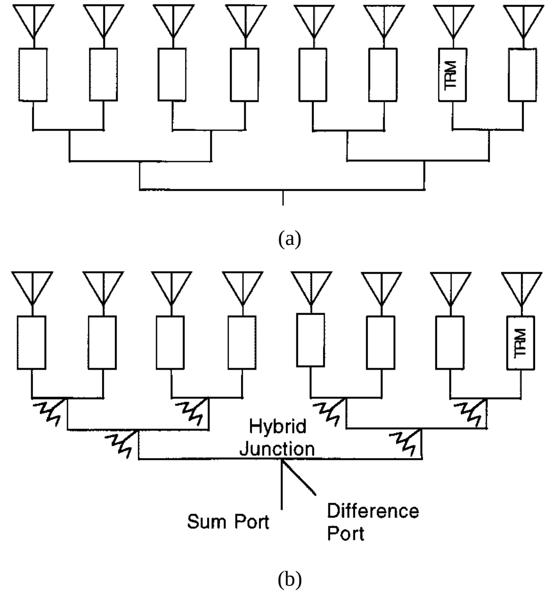

Fig. 4. Constrained parallel (corporate) feed networks. (a) With reactive power dividers. (b) With "matched" power dividers and monopulse network.

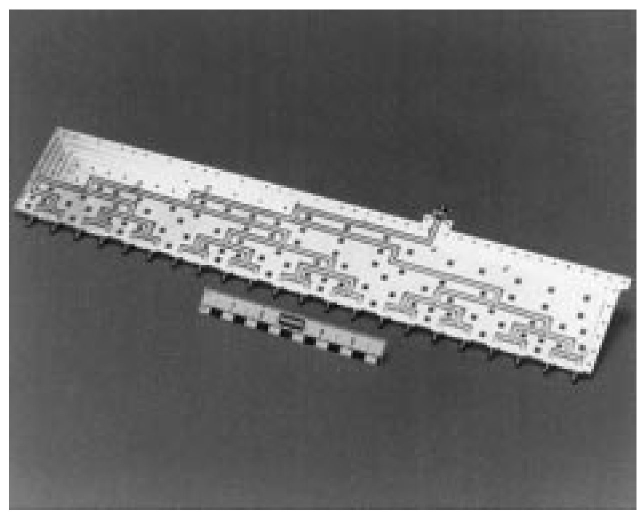

Fig. 5. 19-way air-stripline feed network that utilizes Wilkinson matched power dividers. The ohmic insertion loss is less than 1 dB over a broad band.

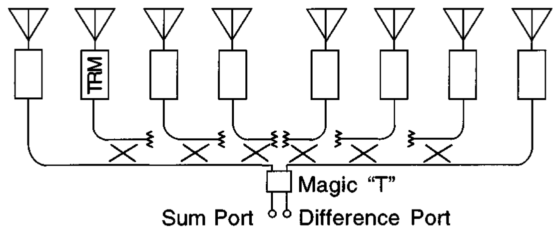

Fig. 6. Constrained series (traveling-wave) feed with "matched" power dividers and monopulse network.

The feed networks for radar antennas must provide for both the sum and difference patterns. A simple means to achieve this is to use the difference port in the highest level hybrid of the parallel feed, as illustrated in Fig. 4(b). The sum port combines the two halves of the array in phase and the difference port combines the same two halves of the array in phase opposition. With this type of configuration, sum and difference patterns are achieved on a pulse-by-pulse basis, and the scheme is referred to as a monopulse-beam network. Patterns achieved in this way are a compromise between the desirable low-sidelobe characteristics of a sum beam and the high error-slope sensitivity for a difference beam. The more taper that is applied to improve sum beam sidelobes, the wider the null and less sensitive is the difference beam. To achieve desirable characteristics in both the sum and difference beams, separate feeds must be used and optimized independently. Various techniques have been developed for both parallel and serial feeds [16], [17].

B. Serial Feeds

Serial feeds are composed of a cascade arrangement of junctions such that the energy to the first output port traverses only one junction, the energy to the second output port traverses two junctions, and so on to the last output port whose energy has traversed all junctions. Shown in Fig. 6 is a diagram of traveling-wave series feed that has terminated directional couplers and a monopulse network at its input. Fig. 7 presents a photograph of an 18-port serial feed that uses crossed slot couplers to realized the matched power division. This feed has very low loss and excellent power division. A disadvantage of serial feeds is that each coupler requires a separate design.

C. Multiple-Beam Feeds

For space-based communication arrays, multiple-beam antennas are desired. A parallel type of feed network developed to provide multiple beams from a single aperture is the Butler matrix [18]–[22]. This type of network will produce as many independent beams as there are elements in an array. Fig. 8 shows the feed configuration for an eight-beam eight-element Butler matrix. A Butler matrix feed requires 2^{n-1} couplers at each of its n levels or a total of $n(2^{n-1})$ couplers. Additional phase shift is required in some of the interconnecting paths in order to realize the independent beams. The unit of phase shift is π/N, where N is the number of elements in the array. For the example in Fig. 8, the unit of phase shift is 22.5°. It is evident that a Butler matrix becomes very complex for a large number of elements.

Advantages of unconstrained feeds are lightweight and lower cost. An example of an unconstrained feed is a space-fed lens illuminated by a feed horn. One surface of the lens is an array of antennas, each feeding a phase shifter or TRM that is connected to a corresponding radiator on the output surface of the lens. The setting of the phase shifters controls the direction of the radiation from the lens. A transmission lens must be totally edge supported since the region between the feed horn and the back face of the lens must be clear of reflecting obstructions.

The Rotman lens is a constrained quasi-optical multiple-beam feed [23]. The electromagnetic field is constrained between parallel plates whose boundaries are shaped to provide the proper phase distribution from an input port to all of the output ports. Multiple input ports, one for each beam, are on one side of the lens and the output ports on the opposite side. Either multiple beams can be excited simultaneously or the beam position can be switched by switching the signal among the input ports.

Cascading sets of a Rotman lens or Butler matrix can feed a two-dimensional (2-D) planar array. The first set of lens is stacked parallel to each other. The second set of parallel lens is oriented orthogonal to the first set so that the output ports of the first set excite the inputs to the second set of lens. This approach has application in multibeam communication satellite systems where there are very stringent conditions on the beam shapes, beam-pointing locations, and beam switching in order to maintain links with the Earth as the satellite traverses its orbit.

III. RADIATING ELEMENTS

Several types of radiators have been used in phased arrays. Six of the more widely used radiating elements are dipoles above a ground plane, open-ended waveguides (both rectangular and ridged) in a ground plane, multimode horns, dielectric-loaded circular waveguides, flared notch radiators, and patch radiators. Bandwidth, maximum scan angle, polarization, radar self-signature, installation environment, and cost are but a few requirements that must be taken into consideration when selecting a radiator.

A dipole above a ground plane is perhaps the simplest configuration and of relatively low cost, but it has limited bandwidth. Crossed dipoles have been used for dual-pole applications. Open-ended waveguides in a ground plane provide reasonable bandwidth and the bandwidth can be extended with ridged-waveguide radiators. For satellite-to-Earth communication applications where dual polarization is required and large element spacing is possible, multimode square horns are used.

The dielectric-loaded circular waveguide excited with a pair of orthogonal dipoles was used in the ground-based radar (GBR) active array and in the B-1 radar passive ESA to provide dual polarization. The circular guide is loaded with dielectric to reduce the size of the radiator to accommodate the required tight lattice spacing.

As radar systems have demanded more bandwidth, the flared-notch radiator has been a radiator of choice. Multiple octaves of bandwidth are possible with the flared-notch radiator. To meet the requirements for increased uniformity in low self-signature

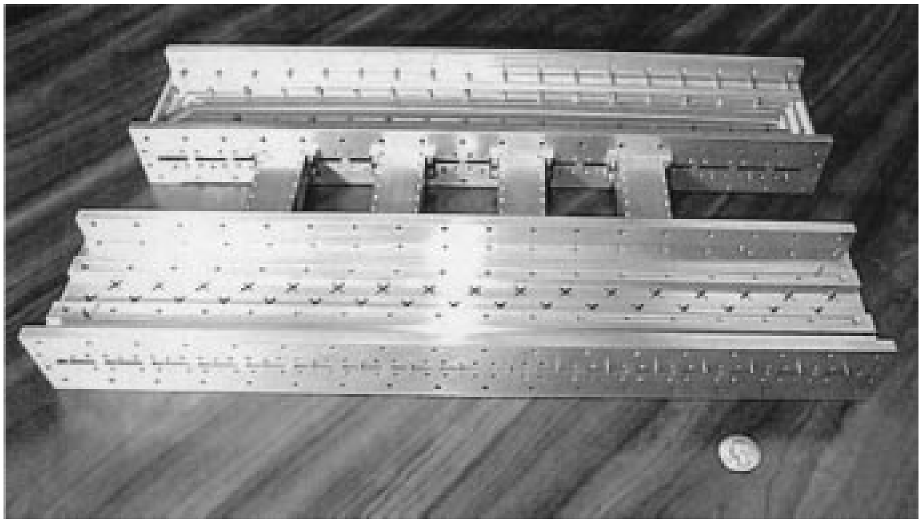

Fig. 7. 18-port series power divider and combiner connected together for testing. The power division/combining was realized with matched crossed-slot couplers and the circuits were fabricated in reduced-height waveguide.

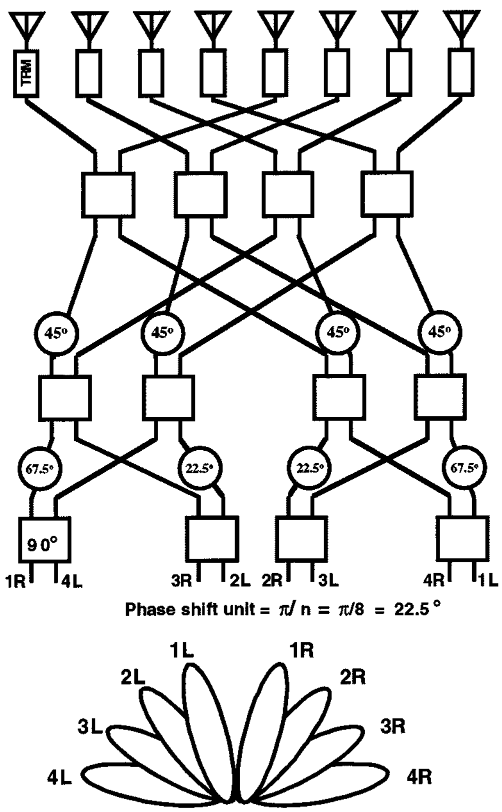

Fig. 8. Butler matrix feed produces a number of beams equal to the number of radiators.

apertures, metal flared-notch radiators that are precision machined have been developed, as shown in Fig. 9. The radiator feed is low-loss air-stripline and the circulator used to duplex T/R signals is buried inside the radiator.

For those applications where one desires a very low profile or low cost, patch radiators, like that shown in Fig. 10, have an application [24]. Patch radiators tend to be narrow band; although by stacking disks of radiators, octave bandwidths can be approach.

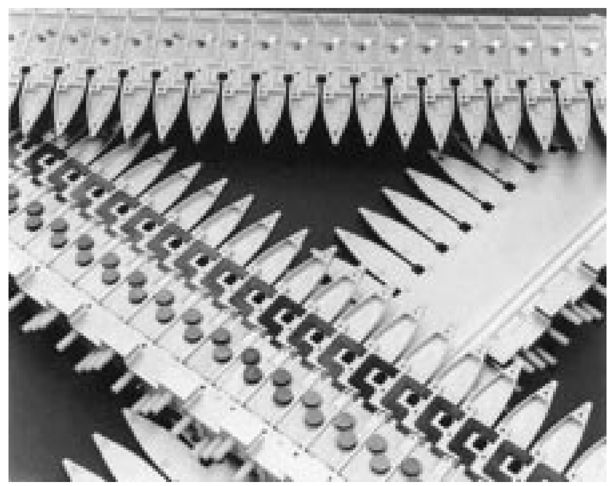

Fig. 9. Machined flared-notch radiators with embedded four-port circulators.

IV. Applications and Future Trends

Until recently, most phased-array applications used passive arrays because active array technology was not mature and arrays were too expensive. With the advent of GaAs MMIC technology, extensive effort has been expended to develop active arrays. The use of MMICs coupled with automated module assembly techniques have reduced the cost of active arrays at least an order of magnitude and have made them practical for airborne, surface-based, and ground-based radar applications. Significant additional reductions in cost and weight are necessary to make active arrays viable for space-based radar (SBR) and tactical missile applications.

A. Passive Arrays

1) ANSPY-1 Radar: The AN/SPY-1 antenna used in the AEGIS system is an S-band passive hybrid phased array [25]. The basic building blocks of the array face are termed array modules each having 32 radiating elements. A photograph of the array face is shown in Fig. 11. Two array modules constitute a receiving subarray, of which there are 68 for the

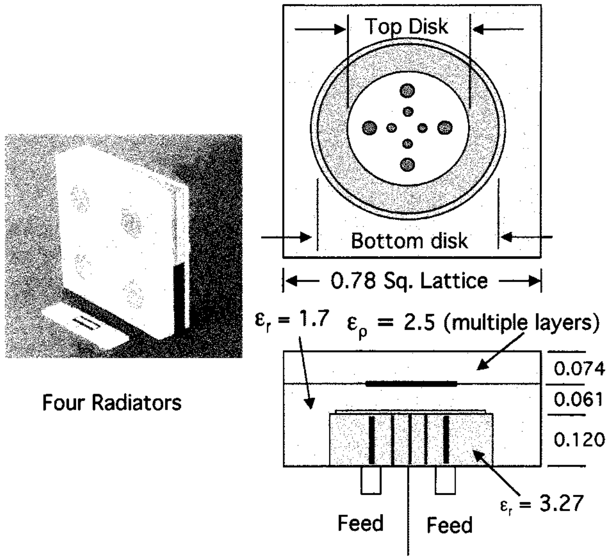

Fig. 10. Dual-polarized stacked disk radiators.

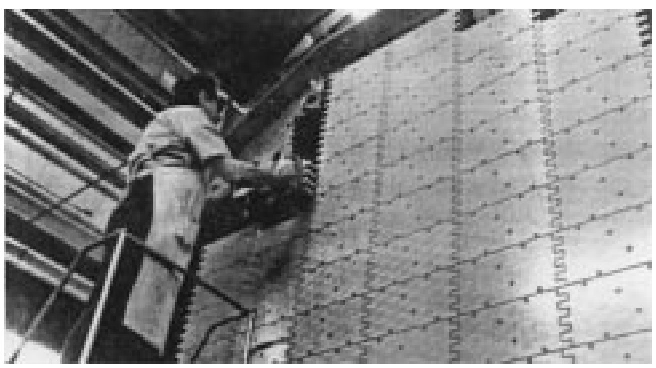

Fig. 11. AN/SPY-1 S-band passive array. The 32-element array modules are evident in the aperture face.

main array function and two others that are separately utilized for auxiliary functions. Four array modules (two receiving subarrays) constitute a transmitting subarray, of which there are 32 corresponding to the number of high-power traveling-wave tube (TWT) amplifiers in the transmitter sub-segments.

On each array module are 32 phase shifters integrated with a 32 : 1 power divider and eight phase-shifter driver boards. These modules plug into assemblies of 32 rectangular horn radiating elements arranged on a triangular lattice.

Nonreciprocal toroidal ferrite phase shifters are used to provide the phase-shift functions.

The array module power divider/combiner feed assembly is a corporate structure of coaxial transmission line consisting of circular center conductor and planer outer conductors. A reactive divider network rather than a network employing loaded hybrid junctions is used to gain the advantages of compactness and minimum cost.

The receiver beamforming network utilizes reduced height waveguide as a compromise between space and weight considerations and RF loss characteristics.

2) B-1 Radar: Westinghouse developed a passive array for the B-1 bomber. The array uses a waveguide corporate feed. The phase control modules consist of "latching" ferrite phase

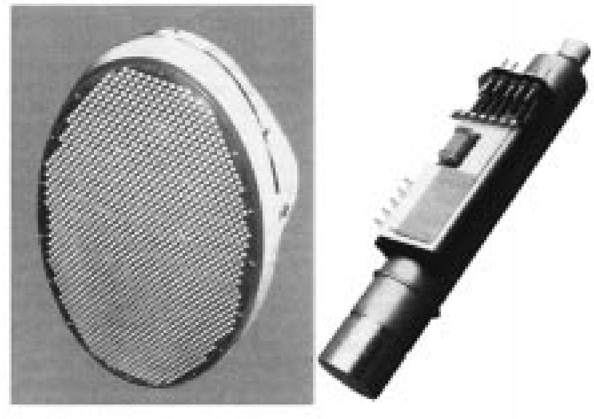

Fig. 12. B-1 passive ESA and phase control module with dielectically loaded circular waveguide radiator.

shifters at each element of the array. The radiators are dielectric-filled circular waveguides. Fig. 12 is a picture of the B-1 array and a phase control module with integrated radiator.

3) ASARS ESA: Hughes Aircraft Company developed a passive ESA for the Advanced Synthetic Array Radar System (ASARS) used in reconnaissance. This array is an X-band 1-D ESA consisting of 2400 open-ended rectangular waveguide radiators and has corporate feeds in both azimuth and elevation. Both air-stripline and waveguide feeds provide low loss and light weight. Azimuth scan is effected with analog-controlled ferrite rotary-field phase shifters in each column of the array. Fig. 13 presents a photograph of the back view of the ASARS antenna partially assembled; it shows the feeds, phasers, and power converters loaded into the array.

B. Active Arrays

The U.S., Sweden, The Netherlands, and a U.K. consortium of France, Germany, and Britain are all developing active arrays for various applications. Until recently, array designs have been based on the "brick" architecture. The array for the AMSAR radar briefly described below is representative of brick array designs.

1) AMSAR: GEC Thompson Das Airborne Radar EEIG (GTDAR) is developing an airborne multirole solid-state active array radar (AMSAR) on behalf of the French, German and U.K. Ministries of Defense [26]. The X-band active antenna being developed as a demonstrator has approximately 1000 T/R modules within a diameter of about 60 cm. The TRMs use MMICs of advanced design provided by the industrial members. High electron-mobility transistors (HEMTs) front ends, integrated core chips for amplitude and phase control, and high-efficiency high-power amplifiers (HPAs).

The brick T/R modules are mounted on linear vertical cold plates that are perpendicular to the array face. The modules are connected to corporate power splitters or manifolds made of soft board stripline that are also mounted on the cold plates. The same manifolds are used on T/R. The cold plates with assembled modules and manifolds constitute a linear subarray. These subarrays are stacked together to form the array. Each TRM is connected to a dual-polarized radiating element. The elements are

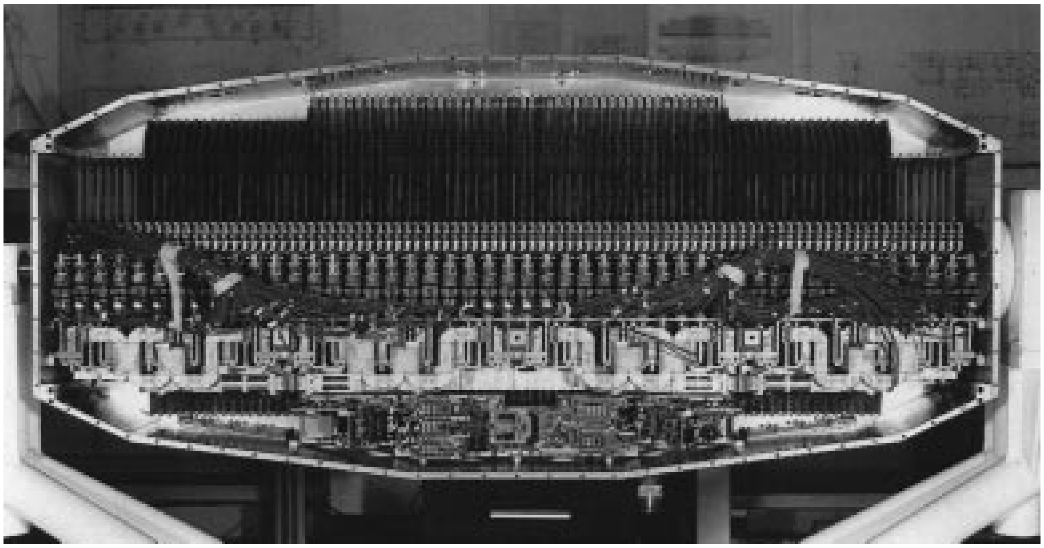

Fig. 13. Backside of an ASARS antenna partially assembled. Visible subassemblies are the vertical air-stripline feeds and horizontal waveguide feeds, column phase shifters, and power converters.

Fig. 14. 18 operational F-15Cs have been refitted with Raytheon's APG-63(v)2 AESA.

arranged in a triangular lattice compatible with the frequency band for wide-scan angles.

2) F-22 Active Array: The F-22 radar has an X-band active array comprised of separate transmit and receive brick modules mounted on opposite sides of a linear cold plate with associated RF manifolds and signal and dc power distributions networks. Separate transmit and receive modules were used in the design to provide high isolation between T/R functions and to provide increased yield and lower cost in manufacturing.

3) F-15C: The Boeing Company recently announced the delivery to the U.S. Air Force of the final three 18 F-15C aircrafts refitted with Raytheon's APG-63(v)2 active electronically scanned array (AESA) that has significantly improved performance. This antenna, shown in Fig. 14, mounted in the nose of an F-15C, uses "brick" architecture, and it provides the U.S. Air Force with the world's first operational fighter jets using AESA technology.

4) GBR: The theater high altitude area defense (THAAD) X-band solid-state active array shown in Fig. 15 is the largest most complex yet developed [27]. At 9.2 m^2, it has 25 344 dielectically loaded below cutoff circular waveguide radiating elements each fed by a high-power TRM. The array consists of 72 subarrays each containing 352 active elements and each subarray is made up of 11 T/R element assemblies (TREAs), a subarray module (SAM), and an ac/dc converter. A TREA contains 32 active T/R modules and radiating elements, eight dc/dc con-

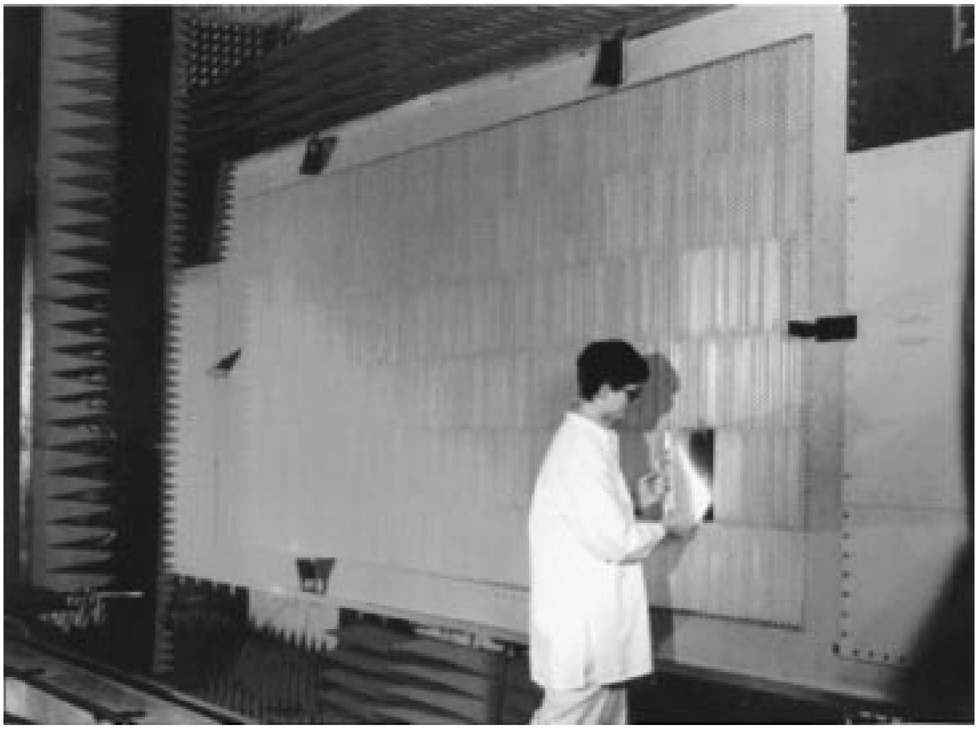

Fig. 15. GBR solid-state array for the THAAD radar. This active array has 25 000 elements each fed by a high-power T/R module.

verters, four beam-steering controller application-specific integrated-circuit (ASIC) chips and random access memory (RAM). Within the TREA are RF and power distribution, logic, and cooling functions, and the TRMs are mounted back to back over a built-in cold plate in two columns of 16 elements. Each SAM drives a complete subarray and contains a subarray-level beam-steering controller circuit card, time delay units (TDUs) for each T/R channel, LNAs, amplifiers, and switches. The TREA and SAM assemblies were designed to be modular for ease of installation and field repair. The TREAs are inserted into the array from the front and the SAMs from the rear.

C. IRIDIUM

IRIDIUM is a registered trademark of Iridium Inc., a subsidiary of Motorola, Phoenix, AZ. The main mission antenna (MMA) of the IRIDIUM global personal satellite communications systems consists of three fully active L-band phased-array panels like those shown in Fig. 16 [28]. Each phased-array panel provides 16 fixed simultaneous beams, for a total of 48 beams, with users on the ground communicating with the IRIDIUM network through the satellite whose beam covers the user. The MMA is capable of simultaneously radiating multiple carriers into multiple beams with high efficiency and linearity, as well as being lightweight and able to function in the thermal and radiation environment of space.

Each panel array consists of over 100 lightweight patch radiators each driven by a TRM. The beamformer is composed of eight 16×16 Butler matrices fed in turn by ten 8×8 orthogonal Butler matrices. A power divider then combines different beamlets as required to form the required 16 far-field beam patterns.

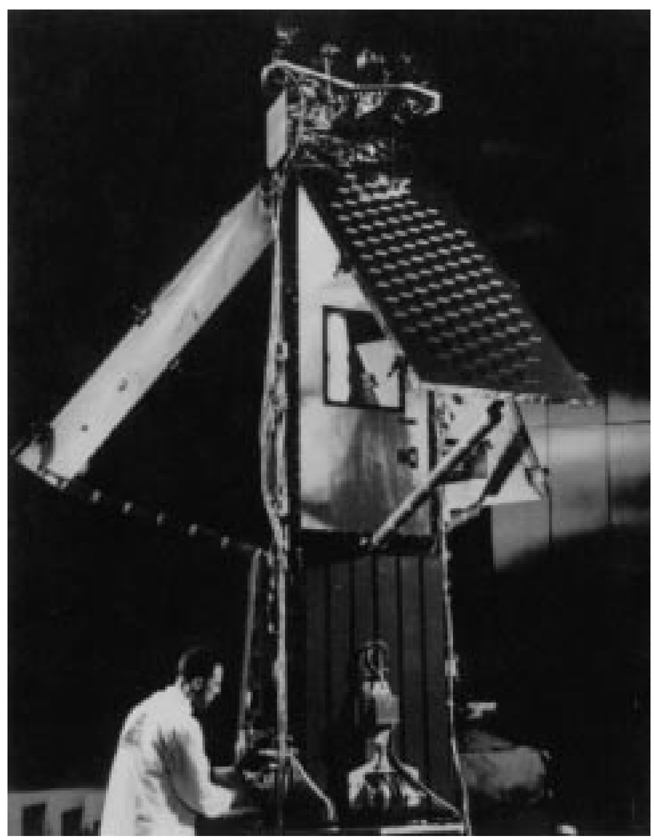

Fig. 16. IRIDIUM MMA consists of three panels each with 100 TRMs.

D. CTS Arrays

The continuous transverse stub (CTS) array developed by W. W. Milroy represents a new class of low-cost traveling-wave

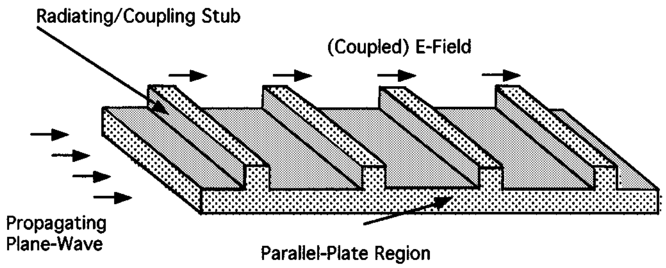

Fig. 17. Basic configuration of a (series) CTS array architecture.

low-profile planar array capable of 2-D electronic scanning with appropriate design implementations [29]–[32]. Fig. 17 presents an illustration of the canonical architecture of a typical CTS antenna. It is realized as an array of broad continuous transverse radiating stubs, finite in height, extending from the upper conductive plate of an open parallel-plate transmission line structure that is internally excited by a (generic) linear source. The transverse stubs efficiently couple energy from the parallel-plate feed structure and radiate it into free space as linearly polarized waves. The CTS elements are inherently low-Q (nonresonant) and compared to slot or patch radiators have significant advantages in bandwidth, polarization purity, wide scanning capability, and insensitivity to dimensional tolerances. The continuous geometry of the stub radiators allows for a dramatic reduction in part count: N continuous stubs replace M by N discrete radiators.

H-plane electronic scanning of a CTS array can be accomplished by altering the phase front of the traveling wave in the parallel-plate region of the array with a linear array of TRMs feeding the CTS array. Scanning in the E-plane is accomplished through controlled variation of the effective propagation constant within the parallel-plate region. Various methods demonstrated or being investigated to achieve this variation include controlled frequency variation (frequency scanning) and incorporation of nonlinear voltage-variable dielectric and periodic insertion of rows of varactor diodes between the parallel plates [33]–[35]. Combining the H- and E-plane scan techniques can provide 2-D electronic scanning.

The architecture of the CTS array is very compatible with extrusion manufacturing techniques for very low cost. This makes CTS arrays very attractive for low-cost millimeter-wave applications. Currently, a 38-GHz CTS array is in production for point-to-point communications [36].

E. Space-Based Applications

Due to the desire for 2-D electronic scanning, phased-array antennas are prime candidates for SBR applications [37], [38]. The main issues are the high cost and weight of current phased-array designs. More than one-half million radiators are envisioned for some SBR systems and a paradigm shift in antenna design and manufacturing techniques are required to meet the projected weight (2 kg/m^2) and cost goals for SBR. Significantly advanced methods for assembling millions of components into a single antenna must be developed, as well as approaches for reducing the total part count in large space-based arrays.

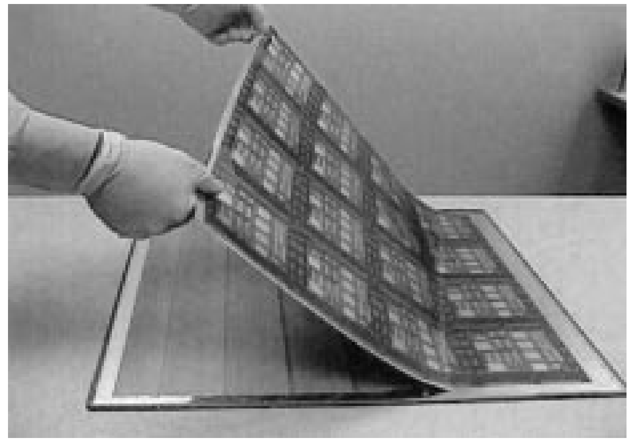

Fig. 18. Multilayer flexible substrate materials like these are being investigated for lightweight space applications.

The NASA Jet Propulsion Laboratory (JPL), Pasadena, CA, and the Air Force Research Laboratory (AFRL), Wright-Patterson AFB, OH, are developing lightweight structures for very large arrays. The NASA JPL recently demonstrated two different L-band microstrip patch-antenna prototypes. Each had multiple layers of stretched membranes that were supported by a space-inflatable planar frame structure. The AFRL is exploring concepts that integrate low-cost electronics directly onto inexpensive and flexible membrane substrates. In this "moduleless" approach, electronic components are integrated on flexible substrates at the subarray level. Signal and power distribution networks fabricated in multilayer flex circuits made of materials such as polyimide or liquid-crystal polymers in conjunction with flip-chip MMICs and dc control electronics are being considered. A photograph of a polyimide multilayer substrate is shown in Fig. 18.

F. Digital Beamforming

Perhaps, the ultimate goal for active arrays is a fully digital multifunction array with programmable functionality, as illustrated in Fig. 19. In this architecture, only the high power and LNAs at the aperture are analog circuits. Wide-bandgap (WBG) semiconductors are candidates for these high-power and linear amplifiers. All the amplitude and phase-shifting functions, as well as the beamforming are done digitally. Transmit waveforms are generated by direct digital synthesizers (DDS) and the received signals are captured with very high-speed analog-to-digital converters (ADCs). True time delay for steering very large arrays can also be implemented digitally. Obviously, this architecture requires very high-speed high-throughput data processing. It is envisioned that commercial of the shelf (COTS) processors will be able to satisfy this requirement.

G. Adaptive Arrays/Smart Antennas

A significant advantage of phased arrays is that it is possible to adapt the antenna pattern in real time to minimize the effects of interfering external or multipath signals or to improve the signal-to-noise ratio. This flexible capability is important for improved system performance for both radar and communication systems. Adaptive arrays also provide a means for in-

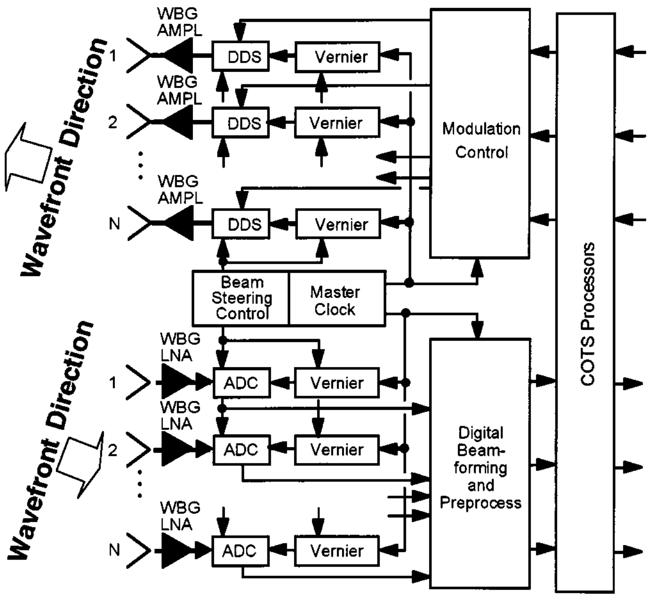

Fig. 19. Block diagram for a future digital multifunction active array with programmable functionality. WBG HPAs and LNAs are the only analog circuits at the aperture.

creasing the capacity of a mobile communication system. The pattern of an array can be changed by changing the phase and/or amplitude weighting on all or on selected elements of the array. In a sidelobe canceler, for example, only one or a small number of elements are used to detect the interfering signal in a sidelobe, process it, and combine it with the signal from the main array to cancel out the unwanted signal.

Analog or digital element weightings can be implemented. Analog methods tend to be complex and expensive. Digital techniques require high-speed ADC technology and place high demands on the throughput of the digital signal processor. For these reasons, hybrid techniques are also being investigated. In the distant future, when the technology is mature for full digital beamforming multifunction arrays, the adaptive capability of arrays will be natural fallout of the beamforming.

V. Summary/Conclusions

Initial realizations of phased arrays were passive arrays for radar applications. With the advent of MMIC technology and automated assembly of microwave components, development of active arrays is receiving significant attention for both radar and communication applications. As the cost decreases, utilization of active arrays in ground, airborne, and space applications will become widespread. Digital beamforming will tend to replace many analog designs as nanotechnology is developed.

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