Shared Aperture Technology Development

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The demand for increasingly sophisticated sensor and communications systems aboard military platforms has grown while space and weight constraints have become more stringent. These opposing factors have created a strong desire to reduce the number of associated antenna systems by combining the functions of several systems into a single antenna. Shared aperture antennas are a new class of phased array antennas that combine the functionality of several antennas into one aperture using wideband multiple beam technology. Applications for shared apertures include radar, communications, and electronic warfare. This article describes an experimental shared aperture antenna under development at the Applied Physics Laboratory. The antenna incorporates key shared aperture technologies, including wideband dual-polarized tapered notch radiating elements and dual-channel monolithic microwave integrated circuit receive modules.

INTRODUCTION

The proliferation of advanced sensor and communications systems aboard military platforms (ships, aircraft, land vehicles, etc.) has led to an increasingly large number of associated antenna systems. A Navy Aegis cruiser, for example, has over 100 antennas, and the number is expected to increase as new systems are added. Many of these are aperture-type antennas, including large mechanically steered reflector ("dish") antennas or phased array antennas in which the antenna beam is electronically steered. Increasing numbers of sophisticated antennas are also envisioned for airborne platforms as the integration of additional advanced systems is contemplated. Since space, weight, and antenna siting for optimal coverage are at a premium on these platforms, it is desirable to reduce the number of antennas by consolidating the functionality of several systems into a single shared aperture antenna. Shared apertures with active phased array technology would also benefit future ship topside concepts as well as air platforms that necessitate increasing use of flush-mounted or conformal antennas. The implementation of such apertures may potentially reduce platform costs by prorating expenses over all functions using them. However, significant technological advancement is needed, and system-level trade-offs must be investigated to determine if potential cost savings can be realized while maintaining required system capabilities.

Combining the functionality of several antennas into one shared aperture presents several technical challenges. An aperture can be shared between systems in various ways. One way is to simply time-multiplex the use of the aperture. Radar operation, for example, includes periodic, scheduled transmissions and receptions; therefore, when the radar is not transmitting or receiving, the aperture could be used for other functions, time permitting. This approach is already seen in modern multifunctional radars in which a common aperture performs several functions (e.g., search, track, illumination, weapon control). For weapon system applications, time multiplexing alone offers limited benefits since modern weapon system timelines are generally full, and the weapon system demands on these timelines are ever-increasing. Time multiplexing may be useful for tactical communications systems, but system analysis and trade-offs are required.

Another straightforward approach is to segment a larger aperture into subapertures, each performing a specific function. This technique, although not providing the full potential benefits often envisioned for a shared aperture, would nonetheless have some advantages, particularly if some of the subapertures could also be time-multiplexed between functions.

The most dramatic implementation of a shared aperture would be to use a single common aperture to perform multiple functions *simultaneously*. This can be achieved with an aperture that provides multiple, independently controlled beams. The approach, although potentially the most advantageous, is also the most challenging since significant issues arise relating to isolation and control of intermodulation products between signals from the systems that are operating simultaneously.

The introduction of shared apertures can be expected to be evolutionary in nature. Given the available enabling technology, shared apertures are most likely to be implemented using a combination of the approaches already noted (time multiplexing; aperture segmentation; and independent, simultaneous beams) to optimize the aperture suite for the various systems and platform types. For time multiplexing and multiple simultaneous beam approaches, the shared aperture will have to be operational over wide, instantaneous bandwidths and multiple polarizations. These requirements challenge the state of the art in radiating element technology, monolithic microwave integrated circuit (MMIC) transmit/receive module technology, and array design. The use of multiple, simultaneous beams places unique demands on the array architecture in terms of the required number of channels in the transmit/receive modules and the complexity of the beamforming networks. The requirements for isolation between channels and control of intermodulation products make demands on the state of the art in filters/diplexers and amplifier linearity.

This article describes efforts at APL to develop an experimental set of antenna hardware with which to investigate the technology, risks, and potential system trade-offs associated with shared aperture antennas. In 1994, APL developed two critical components for a shared aperture antenna: a wideband dual-polarized radiating element and a wideband dual-channel receive module. In 1995, work began on a 64-element multibeam receive array using these components. The focus of current efforts is to complete development of the receive array, demonstrate the functionality of the shared aperture array, and explore system-level issues and risks associated with shared apertures.

ARRAY CONCEPT

The Laboratory has developed a shared aperture array concept that provides sufficient functionality to demonstrate key shared aperture technologies while minimizing the size and complexity of the array to control costs. Three fundamental technologies are addressed in the concept: (1) wideband dual-polarized radiating element technology, (2) wideband MMIC dual-channel module technology, and (3) wideband multiple simultaneous beam array technology.

The following array requirements were derived to support the demonstration goals: a 7- to 10-GHz operating band, receive operating mode, left- or right-hand circular polarization, two independently steered beams, –5 dB/K gain-to-noise temperature (G/T), and a 50° maximum scan angle. Since the G/T requirement drives the antenna size, the G/T was chosen to provide sufficient capability for potential experiments while maintaining an affordable antenna size. The –5 dB/K G/T ratio is also sufficient to support high data rate communications over a simulated (land-based) satellite communications link or (under optimal conditions) low data rate communications over a satellite-to-Earth link.

The array is intended for receive-only operation. It is assumed that in an operational system, a separate array would provide the transmit function. The use of separate arrays allows isolation between transmit and receive signals, which is necessary for a full-duplex communications system in which signals closely spaced in frequency are being transmitted and received simultaneously. In a conventional reflector-based system, such isolation is typically provided by a diplexer and filter. Similar diplexing/filtering is difficult to implement in a phased array, since each element in the array would require a separate diplexer and filter. Typical diplexers and filters are too large to meet the size constraints imposed by the interelement spacing in the array. Improvements in the state of the art of filter/diplexer technology are necessary to support full duplex, multibeam operation in a single aperture.

To support demonstration of two simultaneous communications links, the array has two independently steerable beams. In an operational system, these beams would typically be able to operate with independent polarizations. For simplicity, the demonstration array requires operation with only a single polarization (left- or right-hand circular). Although the radiating element is being developed with dual polarization capability, the complexity of the remainder of the array was simplified by requiring the processing of only one polarization.

Based on the G/T requirement, the antenna was sized for 64 elements arranged in an 8 row × 8 column grid with a triangular element lattice. Spacing between elements was determined based on scan coverage requirements. For a typical shipboard application designed for hemispheric coverage with four array faces, the array must be able to scan on the order of ±45° in azimuth and –10 to +90° in elevation. To avoid grating lobes in the radiation pattern (spurious lobes caused by the periodicity associated with the element grid), the maximum element spacing allowable to meet this coverage over the 7- to 10-GHz band was determined to be 0.6 × 0.45 in., assuming the array is tilted back 15° from the vertical.

Figure 1 is a block diagram of the demonstration antenna concept. Signals incident on the array are first received by the dual linearly polarized radiating elements. The elements output horizontally and vertically polarized components of the incident signal, which are combined with a 90° phase shift using a quadrature hybrid network to produce a circularly polarized signal. That signal enters the receive module, where it is first low-noise amplified and then split into two channels. Each channel represents an independently steerable beam. A phase shifter in each channel is used to electronically steer each beam. Finally, two combiner networks are used to combine the outputs from all of the receive modules to form a collimated beam for each channel.

WIDEBAND DUAL-POLARIZED RADIATING ELEMENT

Radiating Element Design

The array bandwidth and dual polarization requirements precluded the use of many common types of phased array radiating elements (e.g., open-ended waveguides, microstrip patches, printed dipoles, etc.). These elements are typically limited to bandwidths on the order of 30% or less. For many shared aperture applications, bandwidths of 50% or more are required. Therefore, we chose a type of ultra-wideband radiating element known as a tapered notch or Vivaldi antenna.[1] The element consists of a section of slotline that is narrow at one end and opens in a V-shaped flare at the other (Fig. 2). The antenna, which is usually fabricated using printed circuit processing techniques on a copper-clad dielectric substrate (e.g., Duroid), is excited by a microstrip line printed on one side of the substrate. The V-shaped flare printed on the other side acts as an impedance transformation network between free space and the microstrip feed line. Radiation from the antenna occurs when the slotline impedance is matched to the impedance of free space. The narrower region supports radiation at high frequencies, whereas the broader region supports radiation at low frequencies.

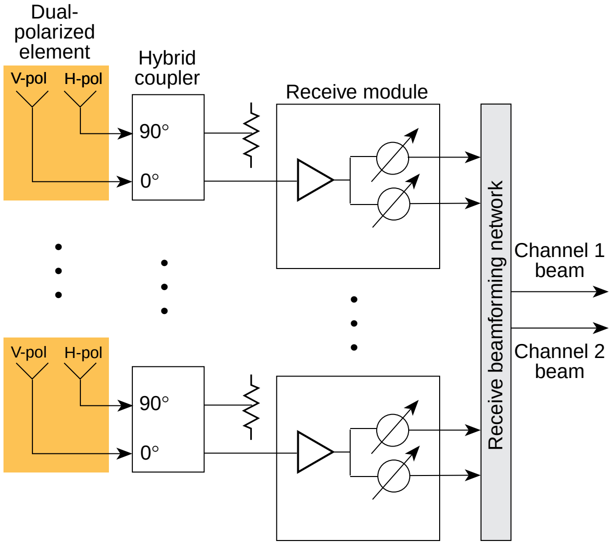

Figure 1. Receive array block diagram (V-pol and H-pol = vertical and horizontal polarization, respectively).

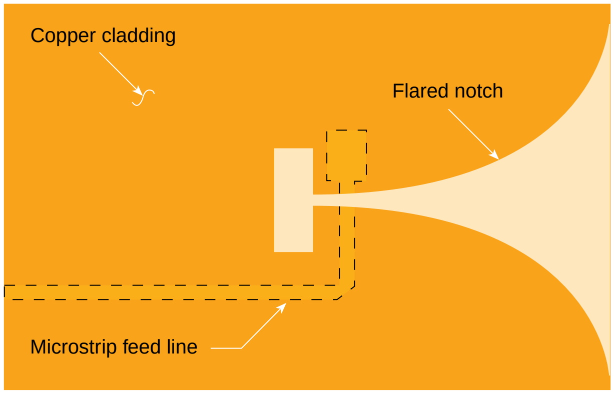

Figure 2. Vivaldi tapered notch radiating element geometry.

Design of the tapered notch element involves the solution of two matching problems, one associated with the microstrip or stripline-to-slotline feed transition and the other associated with the notch-to-free space transition. Because of the complex three-dimensional structures involved, rigorous analysis of the tapered notch has not been reported in the literature. For our design, we achieved good results applying a combination of simple equivalent circuit models, finite-element modeling using commercial (Hewlett-Packard High-Frequency Structure Simulation) software, and empirical experimentation.

The bandwidth of the radiator is limited primarily by the bandwidth of the microstrip-to-slotline transition (the notch transition is inherently wideband). Conventional microstrip-to-slotline transitions are fundamentally bandwidth-limited, since they typically use quarter-wavelength stubs and other frequency-dependent tuning mechanisms. To overcome this limitation, our design incorporates a unique "double-Y" microstrip-to-slotline transition (Fig. 3), previously developed for mixer applications.[2] The double-Y transition has no inherent bandwidth limitations other than parasitic inductances

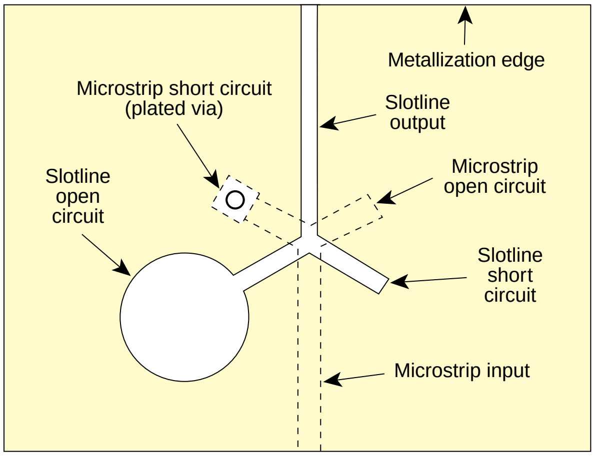

Figure 3. Double-Y microstrip-to-slotline transition used for radiating element feed network.

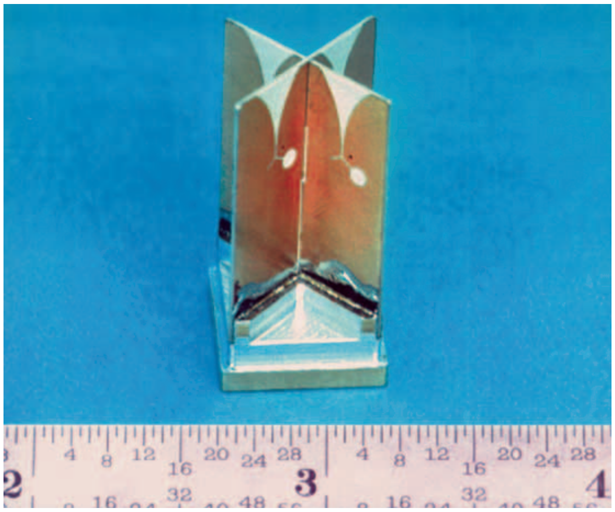

Figure 4. Dual-polarized tapered notch radiating element.

and capacitances. It is also extremely compact, which is important since the overall size of the element must be kept small to achieve the required interelement spacings in the array.

The basic tapered notch is a linearly polarized radiator. For our application, the requirement for dual circular polarization was achieved by combining two orthogonal tapered notches, which provide horizontal and vertical linear polarization. To obtain right- and left-hand circular polarization, the horizontal and vertical polarizations are combined with a 90° phase offset in a quadrature hybrid circuit. The dual-polarized element was implemented in a configuration in which each polarization element comprises two smaller notches, with the substrates crossed between notches. This approach creates a common phase center between polarizations while simplifying the problem of crossing the feed circuitry. Figure 4 shows the assembled dual-polarized element.

Radiator Performance

The prototype radiator achieved an impedance bandwidth of more than 2:1. The input return loss, shown in Fig. 5a, was less than –10 dB from 7 to 14 GHz. Over most of the band, the return loss was less than –15 dB. The radiator element pattern is shown in Fig. 5b. The broad, smooth response is desirable for uniform scan performance in the array. We verified element performance in an array environment using a waveguide simulator that contains a section of metal waveguide sized to replicate the element spacing in the array. When the element is tested inside the waveguide, the imaging effect of the metal walls of the waveguide simulates the environment seen by the element in an infinite array. In this manner, mutual coupling between elements and other array effects can be simulated without the expense of constructing a full-scale array.

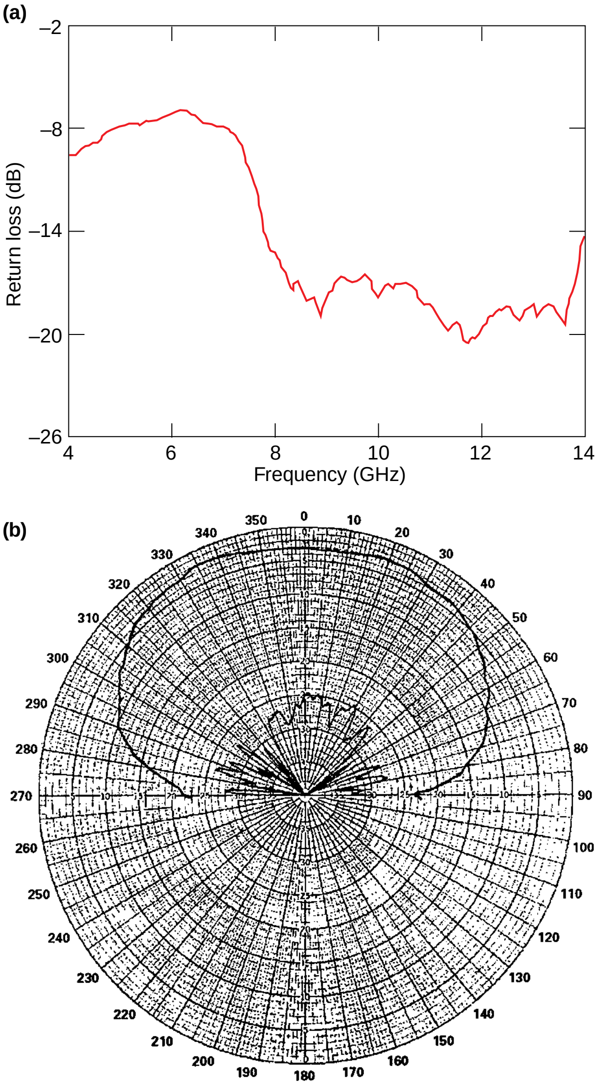

Figure 5. Wideband, dual-polarized radiating element performance: (a) return loss, (b) radiation pattern at 7.5 GHz.

WIDEBAND DUAL-CHANNEL RECEIVE MODULE

The prototype dual-channel receive module was designed, fabricated, and tested at APL within a period of 6 months.[3] The module features a single low-temperature cofired ceramic (LTCC) substrate to establish all direct current (DC), control, and microwave interconnections; gallium arsenide MMICs for all microwave functions; and silicon integrated circuits for all control functions in a compact housing that meets the phased array integration requirements. The Laboratory's Technical Services Department has manufactured the receive modules to support the 64-element receive array. Modules exhibit a noise figure of 3.5 dB, a gain of 23 dB, a root-mean-square (rms) amplitude error of 0.5 dB, and a rms phase error of 7° from 7 to 10 GHz.

Module Operation

Figure 6 is a block diagram of the dual-channel receive module. The received microwave signals first enter a low-noise amplifier (LNA), which sets the module's noise figure. To minimize development costs, limiter and circulator functions were excluded (the shared aperture technology demonstration and experimentation objectives did not require them). Following the LNA are two 5-bit digital phase shifters that are fed from a 3-dB power divider. The phase shifters are independently controlled to electronically steer the two separate antenna beams. A shift register and clock pulse provide independent control signals for each bit of the digital phase shifters by converting an input serial data stream into parallel data lines. An inverter chip converts these signals into complements of the parallel signals necessary for the phase shifters. Integrated power transistors control the LNA bias.

Packaging Design

The need for tight element spacing results in a module width requirement of 1.06 in. The array slat design dictates that the DC supply and controller interfaces be on the side of the module opposite the antenna elements. The microwave outputs are also on this side to provide a simple connection to the two microwave beamformers. To keep the module width to 1.06 in., the 20 command signals of the phase shifters are fed into the module in a serial data stream, thus minimizing the number of control lines into the module and allowing a small connector for the DC supply and controller. The MMICs and control integrated circuits therefore require only seven DC supply and control inputs into the module, for which APL used a custom eight-pin DC connector with 0.018-in.-dia. pins on 0.050-in. centers. The additional pin provides flexibility for future increased functionality or redesign. All microwave connections are made with blind-mate connectors.

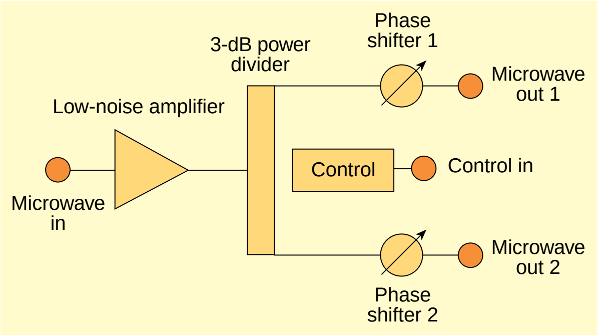

Figure 6. Dual-channel receive module block diagram.

The housing design also must be able to suppress undesired resonances within the specified bandwidth that can be created in the 1.06-in.-wide cavity. One way to reduce cavity resonance is with a septum from the base of the housing that is connected with a silver-loaded elastomer to the housing lid. However, this configuration would preclude the use of a single substrate, which is necessary to minimize the assembly complexity. Another technique to suppress the resonance is to load the cavity with ferrite material to lower the cavity Q (quality) factor. Our design implements this technique with a 0.025-in.-thick ferrite material attached to the housing lid.

Substrate and Interconnection Design

The restriction in module width also creates a design challenge, i.e., how to interconnect the four microwave components and four digital functions. The design cannot use single-layer substrate technology because of the module width limitation and interconnect density. The LTCC medium was chosen because it provides adequate microwave performance at X band as well as a way to make interconnections in overlapping planes within a multilayered structure.

To simplify the module assembly, our design uses a single LTCC substrate for all interconnections. The substrate incorporates a 3-dB Wilkinson power divider.[4,5] The Technical Services Department fabricated the LTCC substrate using Dupont's 901 gold tape system, which features 0.004-in.-thick postfired layers and a 5.2 dielectric constant. The LTCC contains three-layer-high microstrip microwave transmission lines; the microwave ground plane is buried within the LTCC. Seven additional layers provide mechanical strength as well as DC supply and control interconnections. The microstrip ground plane is affixed to the LTCC's bottom layer through quarter-wavelength–spaced vias (laser-drilled holes in the ceramic) placed in the vertical planes containing the outlines of the top layer microstrip. Additional vias at microstrip transition areas suppress undesired electromagnetic propagation modes.

Alumina thin-film substrates (0.010 in. thick) transition from the blind-mate microwave pins to the LTCC microstrip lines. Thin-film substrates minimize packaging tolerance problems with the single-piece LTCC substrate, allow quick optimization of the microwave transitions, and eliminate possible microwave pin damage if rework requires LTCC substrate replacement. The thin-film substrates are mounted on 0.030-in. molybdenum carriers to minimize the vertical distance to the LTCC and to permit a planar (lower-cost) housing floor. A 0.010 × 0.001 in. gold ribbon connects the microwave pins and thin-film substrates. In bench testing, the microwave pin–alumina–LTCC transitions exhibit an 18-dB return loss at 10.5 GHz.

MMIC Design and Selection

To minimize engineering costs, APL sought commercially available MMICs for this module. Both pseudomorphic high electron mobility transistor (PHEMT)- and metal-semiconductor field effect transistor (MESFET)-based LNAs are available. Although MESFET LNAs generate a higher noise figure than PHEMTs, they are less expensive. We selected M/A Com's MESFET-based MAAM71200, which typically provides a 2.3-dB noise figure, a +7-dBm-input third-order intercept (TOI), and 17 dB of gain from 7.5 to 12 GHz.[6] Since the module requires a 3.5-dB noise figure with a minimum of 20 dB of gain, the design uses two of these MMICs in series in each module.

Digital MESFET-based phase shifters are preferable to analog approaches because they can use simple control signals. To provide low-error 4-bit performance, 5-bit phase shifters were chosen. The 5th bit compensates for errors in the larger 4 bits. The Westinghouse WPHS2580 digital phase shifter meets these requirements, providing 4° rms phase errors and 0.5-dB rms amplitude errors.[7] This MMIC also yields a +40-dBm input TOI, so it will not limit system dynamic range.

Module Manufacture and Performance

Figure 7 is a photograph of the receive module. Each module contains 106 wire bonds. These 0.001-in. bonds connect the MMICs and digital integrated circuits. Each module requires about 6 h of manual assembly and test time. Packaging materials, control integrated circuits, and MMICs cost about $950 per module.

Figure 8 shows the rms phase error performance and rms gain error of the completed units. The typical module noise figure across the bandwidth is 3.5 dB. Of

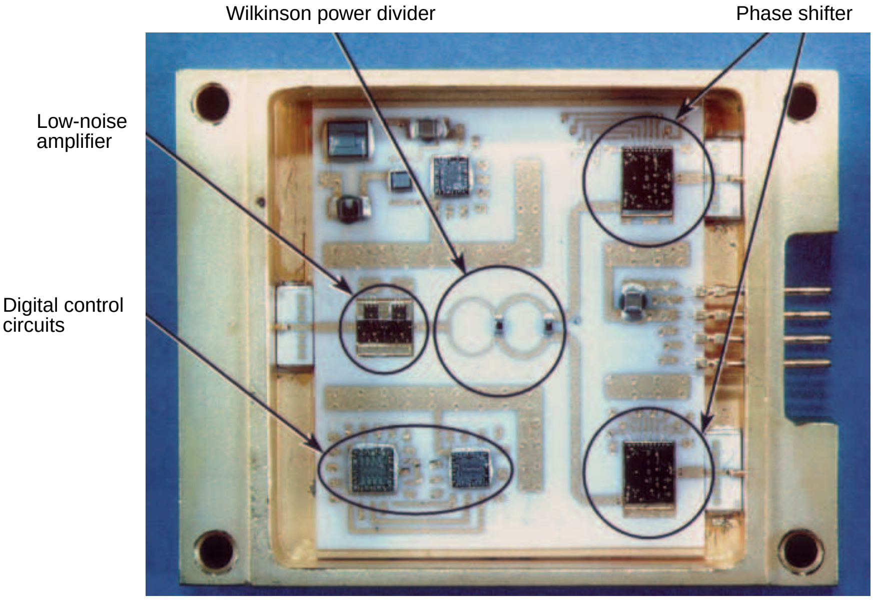

Figure 7. Wideband, dual-channel receive module.

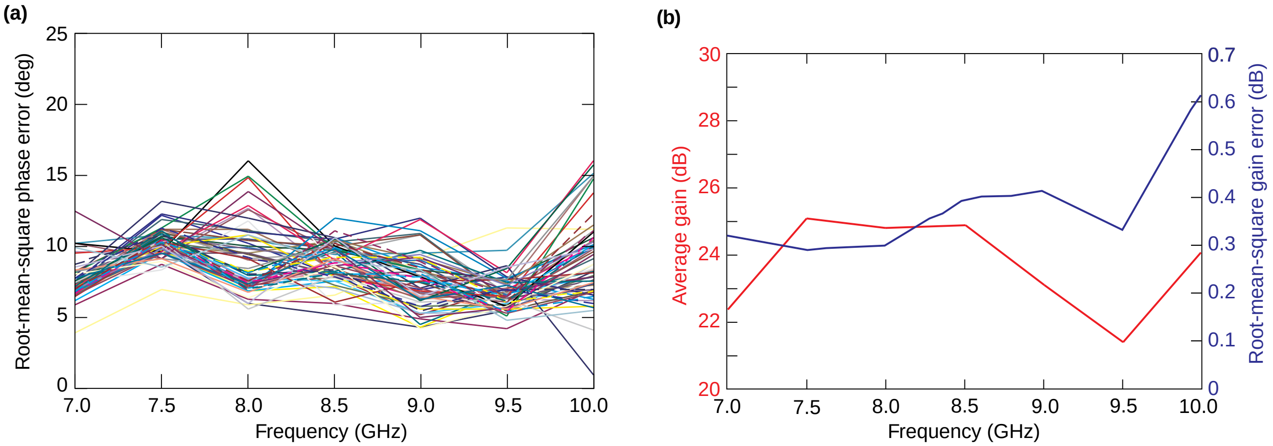

Figure 8. Receive module performance: (a) rms phase error, (b) rms gain error.

the first 38 modules produced, 80% met the specifications on the first pass.

WIDEBAND DUAL-BEAM RECEIVE ARRAY DESIGN

We have completed the design of an 8 × 8 element wideband dual-beam technology demonstration array. Final array integration and testing is planned for June 1996. Figure 9 illustrates the major microwave components of the array and the general packaging complexity. Behind each dual-polarized radiating element is a quadrature hybrid coupler and a dual-channel receive module. The beamforming network consists of a pair of custom eight-way power dividers per row, one for each channel. Another pair of eight-way power dividers is used for combining all eight columns, again one for each channel. Not shown in the figure are the module interface cards (MICs) that control the eight receive modules in each row and a signal distribution card that routes control signals and power to the eight MICs from an external computer and power supplies.

An X-band array designed for wide-angle scan imposes tight spacing between the radiating elements (on the order of 0.5 in.). To meet these packaging constraints, we chose a card cage concept and used microminiature blind-mate connectors for all microwave interconnects. The radiating elements are mounted on a faceplate that forms a microwave backplane. The microwave and digital components are mounted on slats that plug directly into the faceplate to complete the microwave connections between the hybrid couplers and the radiating elements. A precision cabinet is then used to hold the slats and faceplates together. The signal distribution card forms a digital backplane that allows for the direct connection of the MICs. The result of this packaging concept is a very compact cabinet that is only 13.4 (width) × 6.75 (height) × 10 in. (length) and weighs under 10 lb.

The faceplate serves the dual purpose of forming both the radiating aperture and microwave groundplane. The radiating aperture consists of the 8 × 8 element array surrounded on all sides by two additional rows and columns of identical elements that are terminated into a matched load. These additional elements prevent edge effects that can degrade the antenna pattern in an array of this size. As shown in Fig. 10, 64 active radiating elements and 56 passive radiating

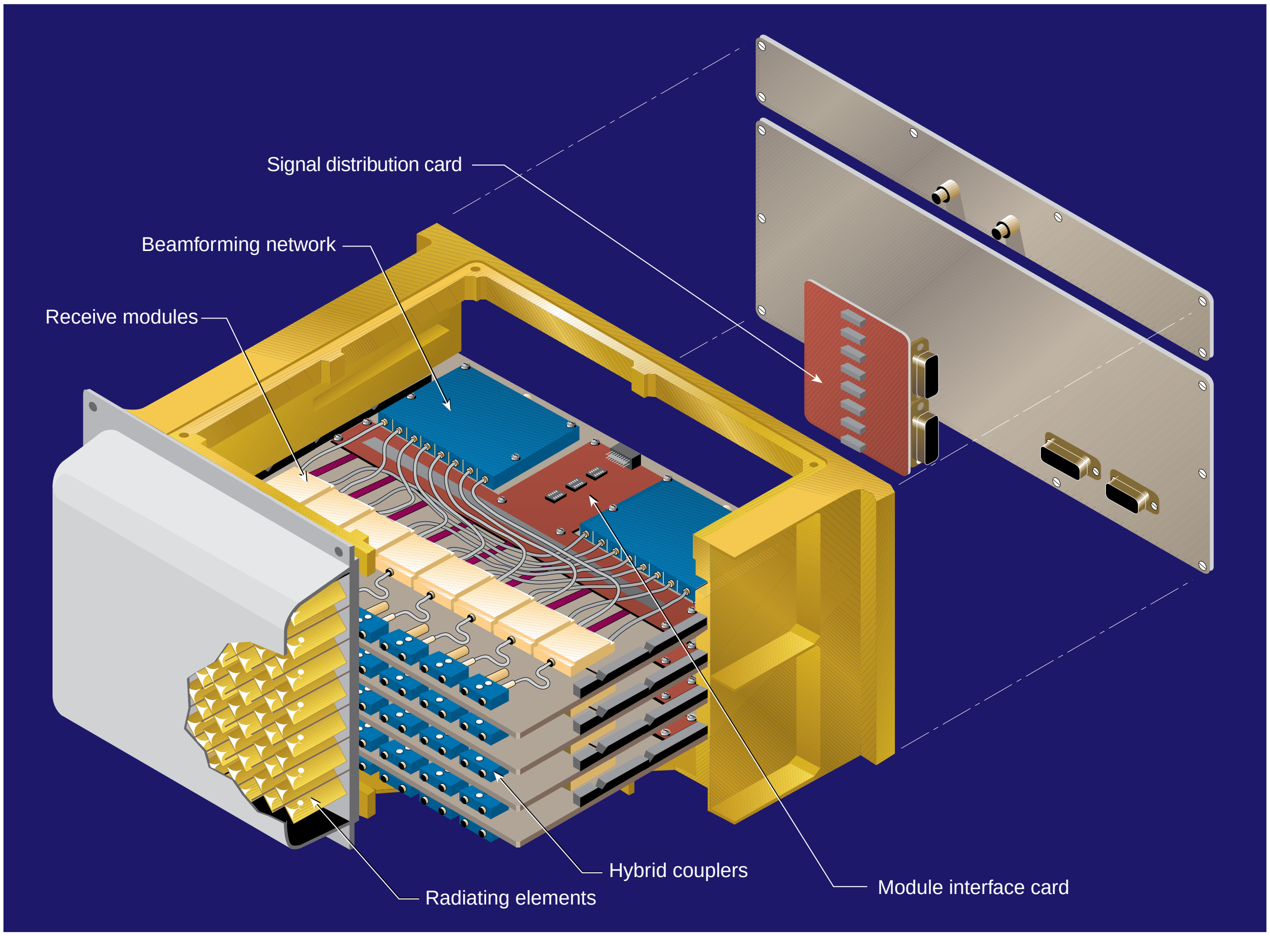

Figure 9. Dual-beam receive array packaging concept.

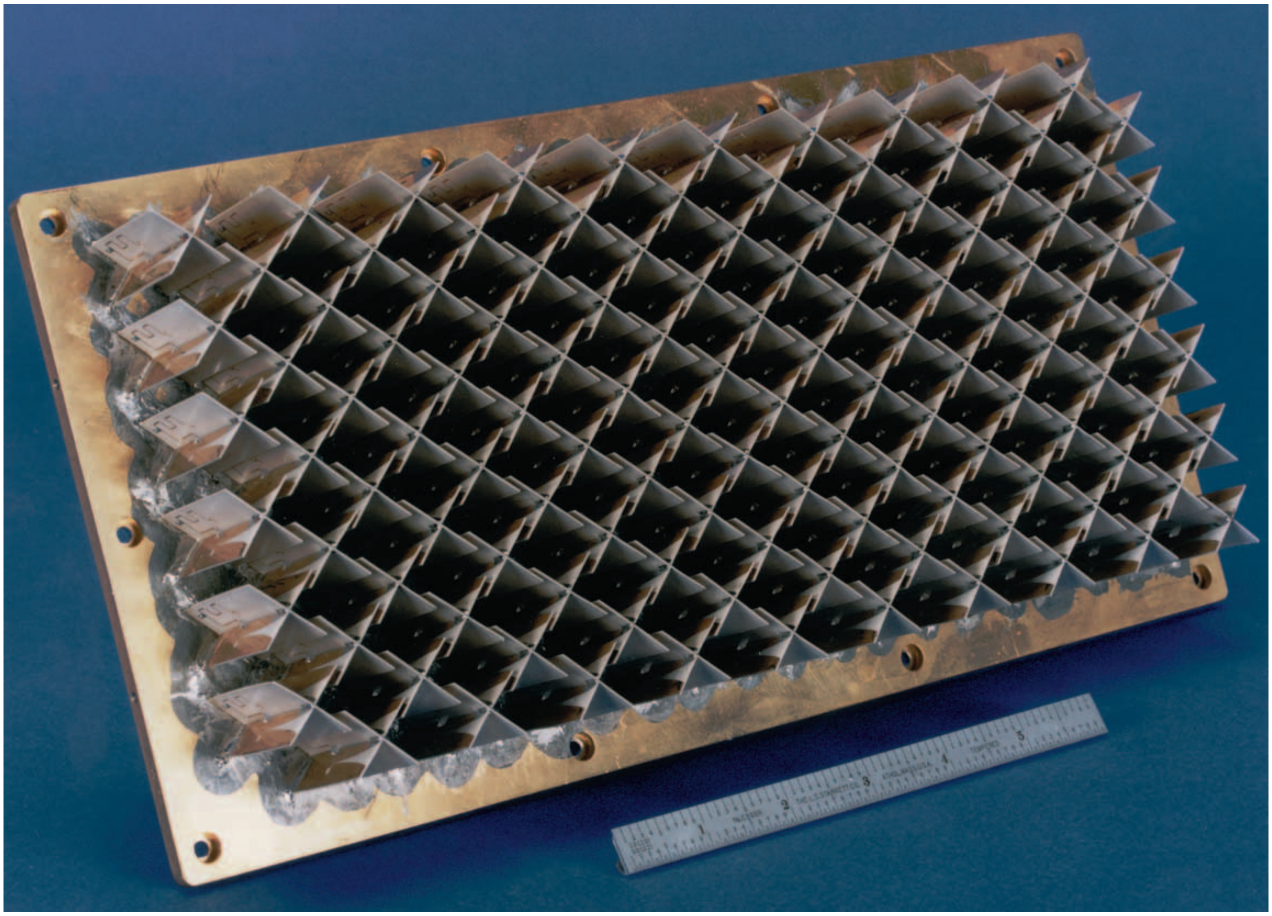

Figure 10. Dual-beam receive array faceplate.

elements are attached to the front of the plate. Each active radiating element is soldered onto a pair of custom microminiature blind-mate connectors. The 128 blind-mate connectors form a microwave backplane that allows the hybrid couplers on the array slats to plug directly into the faceplate. To alleviate the alignment tolerances required by blind-mate connectors, we added a "catcher's mitt" feature, which catches the connector on the hybrid coupler and guides it into the base of the connector. In addition, the faceplate contains pins that align the faceplate with the cabinet and align the individual slats to the faceplate.

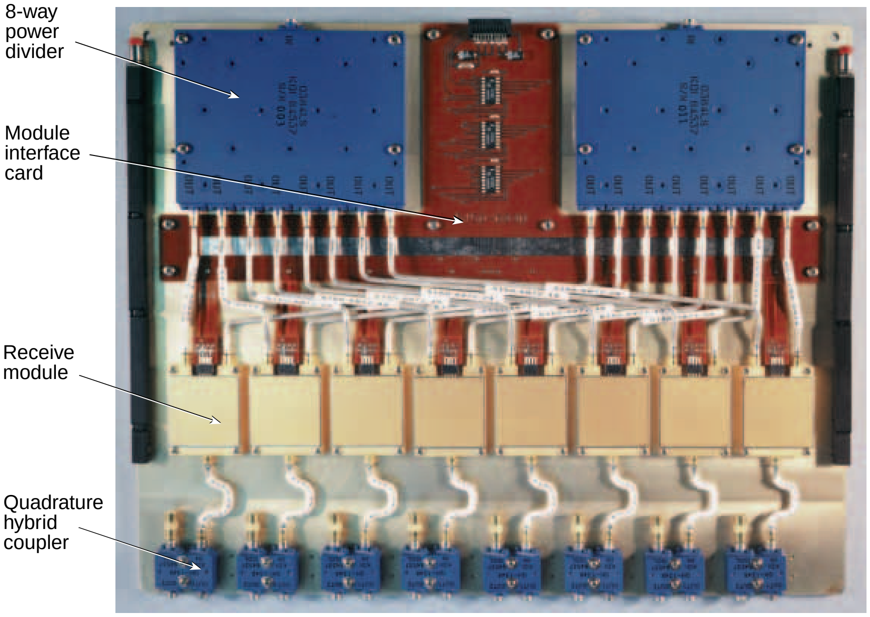

Figure 11. Dual-beam receive array slat.

The major subassembly of the array is the array slat (Fig. 11). Each side of the slat contains 8 quadrature hybrid couplers, 8 receive modules, 2 eight-way combiners, microwave interconnect cables, and a MIC. Custom eight-way combiners and hybrid couplers were designed that employ the blind-mate connector and

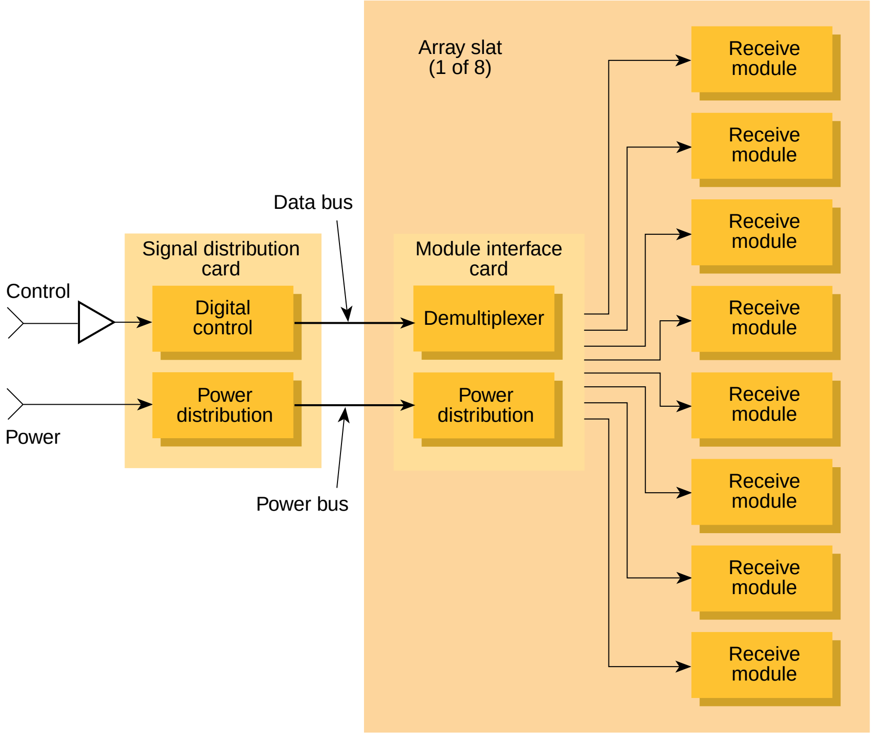

Figure 12. Receive array control block diagram.

meet the low profile required by the row spacing. The microwave components are interconnected using semirigid microwave cable. The cables were routed on a three-dimensional computer-aided design workstation to permit low-cost automated machine bending.

The MIC digital control board posed a significant challenge in packaging. To eliminate discrete wiring and reduce assembly time, we designed a rigid-flex printed wiring board. This T-shaped board fits into the narrow space between the pair of eight-way power dividers and underneath the microwave cables. The rigid part consists of four layers of polyimide substrate material; the flexible sections that connect to the receive modules are made up of a single layer of polyimide substrate material. This interconnect system resulted in a cost-effective design that is both compact and easy to assemble.

The function of the array controller is to distribute power and data to the receive modules. The array control concept is illustrated in Fig. 12. A computer calculates the phase shifter settings for all of the receive modules based on the position of the two independent beams. The data are then synchronously transmitted over a pair of differential lines to the receive array. The signal distribution card attaches addressing and control information to the data stream and transfers the data to the MIC, where the data are demultiplexed and fed to the receive modules. The entire array can be updated in less than 0.5 ms.

SUMMARY

Shared aperture antennas offer many potential advantages for future systems including reduced size and weight, easier integration and siting on platforms, and increased affordability when the cost is factored over multiple systems. However, the demanding antenna requirements challenge the state of the art in phased array technology. The simultaneous requirements for wide bandwidth, multiple polarizations, and multiple beams present a significant technical problem. The APL demonstration antenna, when completed, will provide a valuable tool for investigating the technological issues and risks associated with shared apertures.

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