INTEGRATED DIODE PHASE SHIFTERS AND PERFORMANCE IN A 502-ELEMENT X-BAND ARRAY

Mark E. Davis
General Electric Company, Aircraft Equipment Division, Utica, New York

Abstract

The results of fabricating 502 integrated 3-bit PIN diode phase shifters and dipole radiators will be discussed. These phase shifters consist of chip PIN diodes mounted on 25-mil alumina microstrip. A horizontally polarized dipole has been printed on the same structure, giving a complete phased array element. Considerations in the program were given for diode and circuit variations and their effects on phased array performance. A transmissive phased array has been fabricated with these elements and the performance will be discussed in terms of the phase shifter manufacturing tolerances.

Introduction

In a phased array system where high speed scanning, transmission reciprocity, and array weight are prime engineering concerns, PIN diode phase shifters are usually chosen. Considerable effort has been expended within the past ten years to arrive at the optimum design and the lowest cost of PIN diode phase shifters for phased arrays. Several competitive factors dictate a design in each system that best meets the overall requirements of the phased array. The factors that most contribute to the design of the phase shifter are the available space, coupling to the array radiator, location and complexity of the driver units, and finally loss. Minimizing loss while simultaneously optimizing the overall system design from both performance and cost effectiveness usually becomes the most challenging engineering consideration. The remainder of this paper will give the results of the design, manufacture, and test of a 502-element, 18-inch diameter X-band transmissive phased array, where all of the above considerations dictated a 3-bit PIN diode phase shifter fabricated on 25-mil alumina dielectric.

The radiating element in a phased array has historically paced phased array performance. Because of the need to optimize antenna directivity over a large scan volume, minimize mutual coupling effects on pattern gain, and maximize match with the transmitter - receiver circuitry, the radiator and its phase shifter have, in the past, been designed separately. This dictates a transition, therefore, from the phase shifter medium to the radiating element that simultaneously increases loss and cost while drastically reducing reliability. For these reasons, an integrated design of phase shifter and radiating elements was chosen as shown in Figure 1. Because the phased array is transmissive, two dipoles are included in the design.

Phase Shifter Element Design

Several classes of phase shifters are available to the microwave designer as outlined in White's recent review article (1). In alumina microstrip, the choice is restricted to loaded line, branch line hybrid coupled, and rat race hybrid coupled designs because of fabrication tolerance limitations. The loaded line design is restricted by theory to phase shift values less than 90 degrees and in practice to values 60 degrees and less at X-band frequencies. The particular diode used then becomes the driving factor in the architecture of the phase shifter design.

A silicon PIN diode was developed internally for applications at X and K_u band. This diode is a planar diffused device utilizing 2000 ohm-cm starting material. The I-region is approximately 3 mils thick and the diffused contact 2.5 mils in diameter. To enable computer aided phase shifter design, a number of the diodes are characterized in the microstrip environment used. All diodes are mounted as chips and 1.0-mil gold wire used for electrical contact to the transmission line. Previous experience with packaged diodes eliminates all consideration for their use at X-band frequencies and higher.

The diode characteristics are summarized in Table I. Using these characteristics, which were measured in the same medium as the phase shifter, the loaded line phase shifters were designed using standard computer aided microwave transmission line calculations. As can be seen from Figure 1, three identical 45-degree bits are integrated to give the 45-degree and 90-degree phase shift states. This was found to be broader in bandwidth, to present less insertion loss variation, and to be less diode assembly dependent than a hybrid coupler 90-degree design.

TABLE I. PIN DIODE MICROSTRIP CHARACTERISTICS AT 9.5 GHz

Junction Capacitance	0.09 pf (@ 10 V V_R)
Gap Stray Capacitance	0.02 pf
Lead Inductance	0.55 nH
Series Resistance	1.2 ohms (@ 10 mA I_f)
Reverse Breakdown	250 volts minimum
Chip Size	0.012 inch square
Contact Size	0.0025 inch diameter

The 180-degree phase shift state utilizes a coupling from microstrip to slot line and back to microstrip (2) to obtain an exact 180 degrees of phase shift over a broad (20%) bandwidth. By coupling microwave energy in two different directions through the ring structure, exactly opposite odd mode propagations are excited within the slot transmission line in the phase shifter ground plane. This mode excites fields in the balun transition that have an exact 180 degrees of phase shift between the two diode switch states.

Phase Shifter Element Performance

The phase shifter phase states are given in Figure 2 as measured on a microwave network analyzer. The data points given are average phase shift values for the 502 elements tested at each phase state and frequency. A mean variation of the relative phase shift was calculated but was significantly less than the 10-percent accuracy of the individual phase shift states. This is attributed to the fact that the diodes were from the same process run and had less than 5 percent variation in junction capacitance.

The insertion phase of each phase shifter, however, did vary from element to element, as summarized in Figure 3. In this figure, the data points represent the average insertion phase of the phase shifter in each state when compared to an element of equal length with two dipoles, but with only a 50-ohm microstrip transmission line. A spread in the data representing the root-mean-squared insertion phase variation is given by the solid lines with calculated values given at select frequencies. This rms variation is due to etch process variation, variation in the gold wire bond lengths, and other material variations. The significance of the data is that the amount of phased array gain that would be lost, if individual element insertion phase is not compensated, is directly proportional to the rms phase variation.

As mentioned above, the dipole radiator has equal importance in the phased array design as the phase shifter. A dipole was chosen for several reasons. First, it lends itself to reproducible construction through the microwave integrated circuitry, and does not require microwave connectors for transitions. Also, it is possible to design an array element pattern for a particular scan volume empirically and fully include material coupling effects in the design. In this manner, the array directivity versus scan angle is simply a constant product of the array element pattern in the scan direction and the full aperture broadside directivity pattern (3). The array element pattern shown in Figure 4 was obtained by measuring the scattering parameters of a dipole in a smaller array (90 elements) where the neighboring elements were all terminated in their source impedance. By optimizing spacing and dipole dimensions, an array element pattern that approximates the ideal dipole $\cos\theta$ pattern within 0.5 dB over a ±60-degree scan volume in both the E-plane and H-plane is obtained.

Phased array element loss data was also taken on each element. The average insertion loss of the phase shifter, referenced to the 50-ohm microstrip element, was 1.9 dB with approximately 0.7 dB of loss variation about this value, over the eight phase shifter states. The element loss, however, must include the loss of this reference element to account for the line length in microstrip. The total average loss experienced was 3.1 dB over all 502 elements.

Figure 5 shows the completed phased array. Radiation pattern measurements were taken over a ±45-degree scan volume in azimuth and elevation. Peak sidelobe levels of 20 dB were determined by a space-fed amplitude taper on the array. A total array gain of 25.5. dBi was measured compared to an ideal directivity of 31 dBi. The additional loss is due to the nonuniform distribution of the space feed, phase error losses, and array coupling losses on the inner face of the lens. The total array, including monopulse horn, drivers, and mechanical structure, weighed less than 52 pounds.

Summary

An X-band phased array has been designed and fabricated using integrated 3-bit PIN diode phase shifters. It was demonstrated that reproducible phase shifters can be fabricated in volume in a manner compatible with a cost effective, lightweight array design. Phase accuracies and insertion phase match are sufficient to allow a simple phased array design without complicated phase error corrections, but with sacrifice of 1 dB of array gain. The element loss is higher than ferrite or stripline phasors because of higher conductor loss in alumina microstrip; however, the element weight is only 0.24 ounce (including array row block structure, flex cable interconnect, and microstrip element).

References

1. J.F. White, "Diode Phase Shifters for Array Antennas," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-22, No. 6, June 1974.
2. P.P. Britt, Antenna Element Including Means for Providing Zero-Error 180-degree Phase Shift, U.S. Patent No. 3803621, issued Apr. 9, 1974.
3. A.A. Oliner and R.G. Malich, Microwave Scanning Antennas, R.E. Hanson, ed., Chap. 3, Academic Press, New York, 1966.

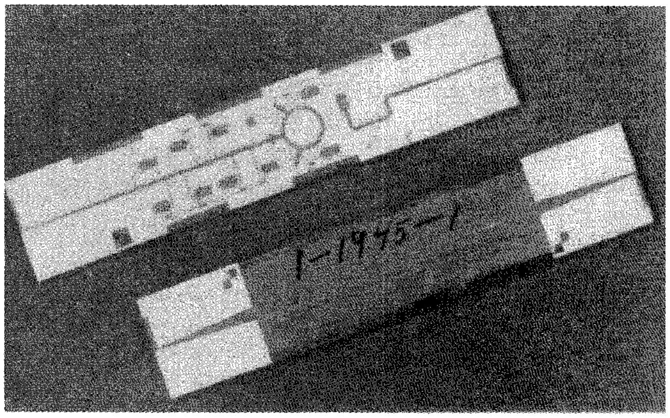

Figure 1. Integrated PIN Diode Phase Shifter and Radiating Dipoles

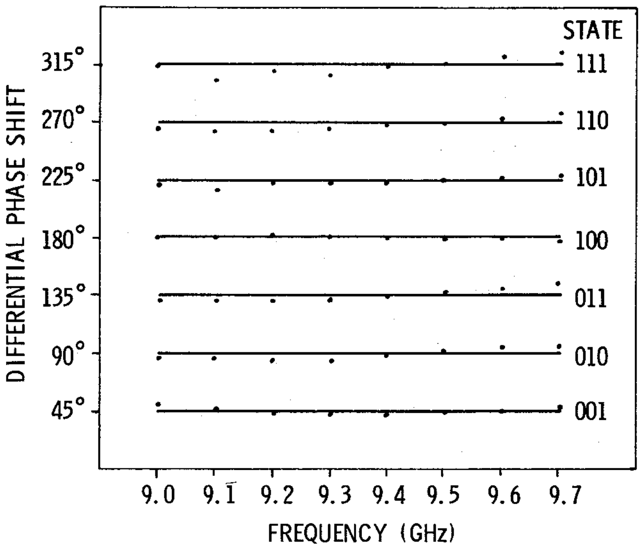

Figure 2. Average Phase Shifter State Variation with Frequency (502-Element Production)

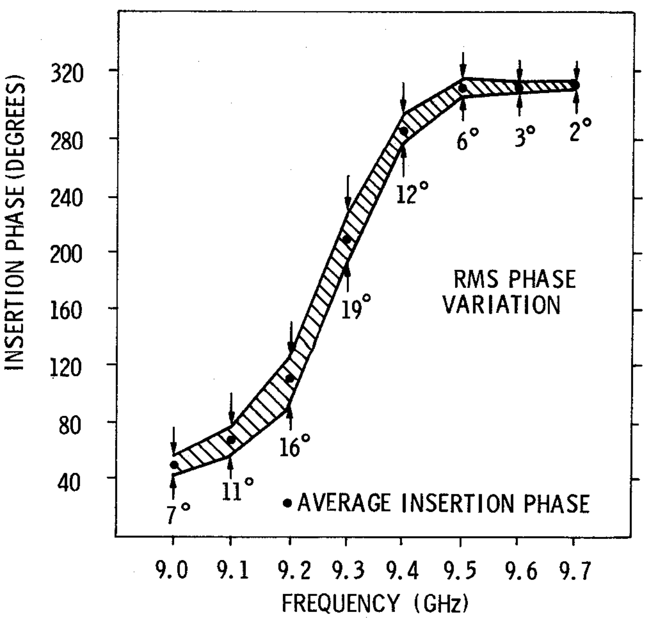

Figure 3. Insertion Phase Average and rms Variation over 502 Elements

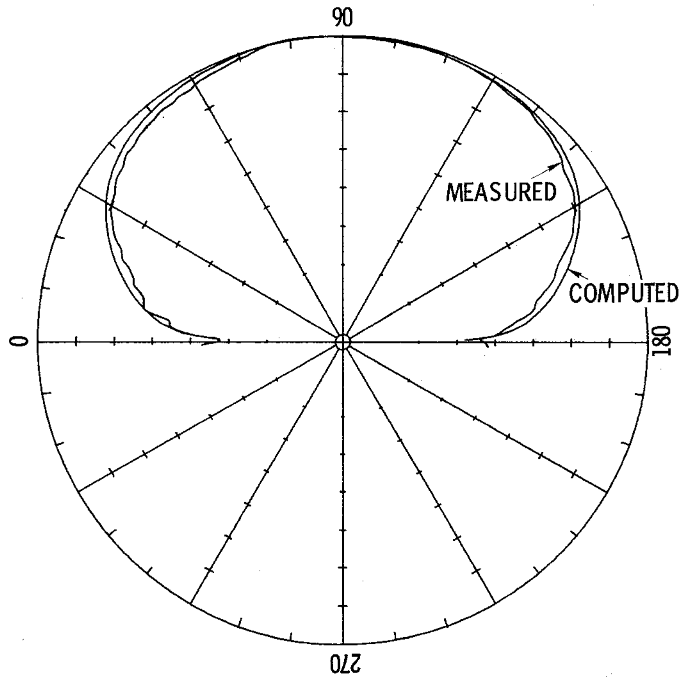

Figure 4. Array Element Pattern of Dipole Compared to Theoretical cos Θ Directivity

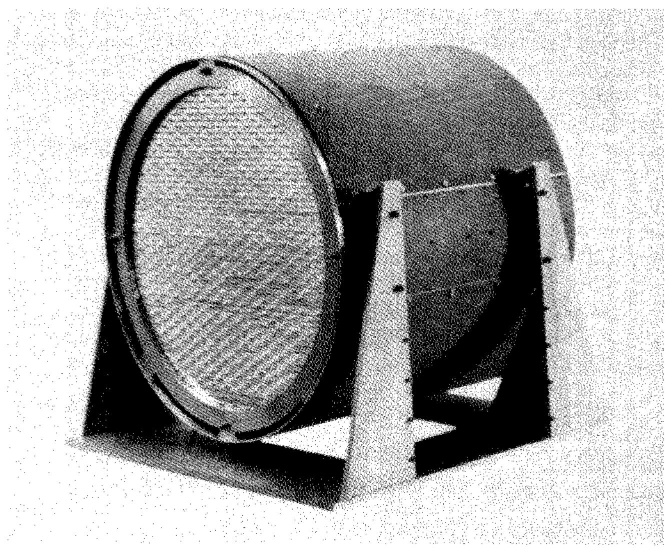

Figure 5. Completed 502-Element X-Band Phased Array