DIGITAL PHASE SHIFTER ELEMENTS FOR A K_u-BAND PHASED ARRAY RADAR*

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Abstract

A three-bit phased array element has been designed using PIN diode phase shifters and a printed circuit dipole for coupling the energy from the waveguide feed and radiating into free space. The element, including the coupling loss of the dipoles, has 3.2 dB insertion loss (average) with an rms loss variation of 0.5 dB, over the 16.0 to 16.5 dB frequency band. Data from 250 units is analyzed for the performance in the array.

Introduction

Phased array antennas often specify the nature of the elemental design by considerations of range, radiated power, size, weight, and cost. For ground-based systems where weight and size are of secondary importance, and where an active element approach is not impractical, microwave integrated circuit phase shifters are usually not chosen. However, in an airborne environment where weight and cost of the radiation elements are prime design criteria, the microstrip phase shifter often has the technical advantage.(1) For these considerations, an integrated dipole, PIN diode phase shifter was chosen for use in the HOWLS** demonstration phased array radar.

In microstrip circuitry, the physical size of the element sets a lower bound on the loss of the element. The elements were 2.3 inches in length and at K_u band the measured loss of this length of 50-ohm line and two dipole transitions was 1.0 dB. Hence, minimizing the loss of the element lies heavily in the choice of the phase shifter design and the use of low loss diodes. The diodes used were diffused junction planar PIN diodes and the phase shifter was basically a loaded line design for the 90° and 45° bits and a ring hybrid 180° device. Because of the small size of the elements

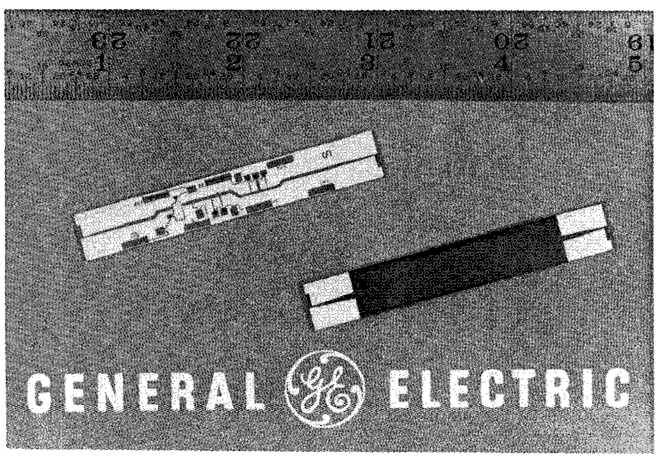

Figure 1. K_u-Band Phase Shifter Element

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**HOWLS - Hostile Weapons Locator System

(0.350 in. x 2.3 in.) and the need to obtain very uniform line definition, 14 elements were fabricated on a single 4 in. x 4 in. substrate and separated with a numerically controlled CO_2 laser scriber as previously described in Reference 1.

Element Design

The phased array element is shown in Figure 1 and, as previously mentioned, functions between a waveguide feed system and the radiating aperture. The dipoles at each end are the only connectors required and were empirically matched to K_u-band waveguide on one end, and to free space as a dipole radiator in an array environment on the other. The waveguide to microstrip transition became the standard transition because of its excellent match at these frequencies and the reproducibility of the transition. Typical return loss data for a loaded 50-ohm line on 25-mil alumina inserted approximately 0.155 in. into standard K_u-band waveguide is given in Figure 2.

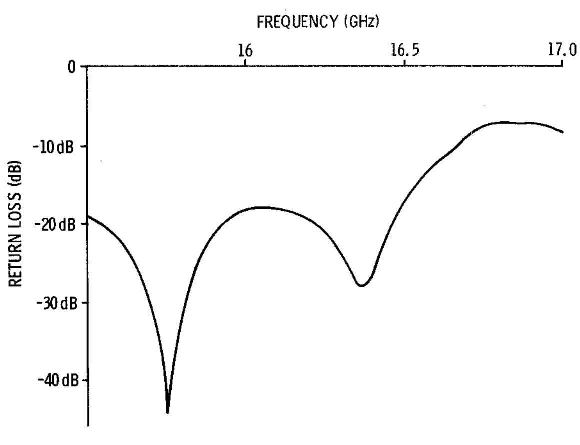

Figure 2. Return Loss for Microstrip Dipole - Waveguide Transition

The diodes used were internally developed silicon PIN diodes which were double diffused planar devices using a high resistivity (approximately 5000 ohm-cm) wafer as starting material. Typical junction capacitances of 0.06 to 0.08 pF and series bulk resistances of 2.0 to 2.7 ohms were measured on sample diodes from four wafers used in the production of 250 such elements. The lead inductance of one-mil gold wire

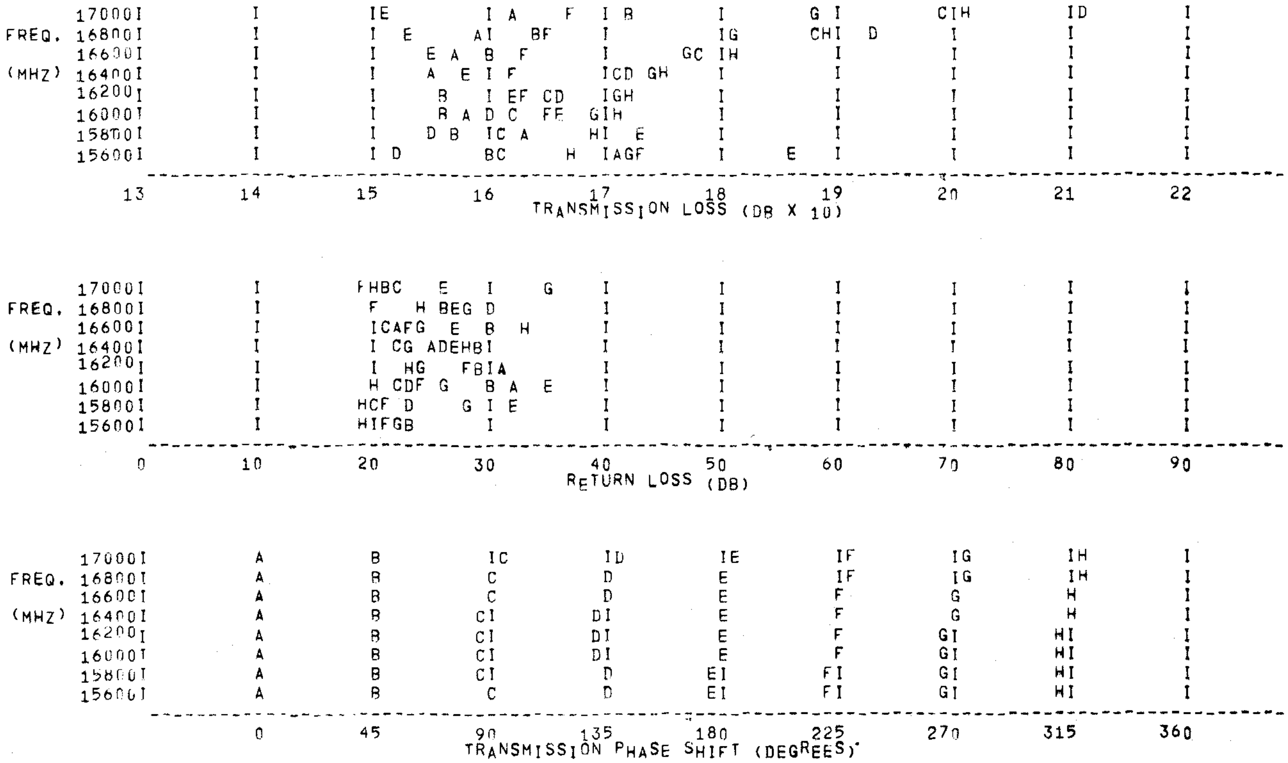

Figure 3. Simulated Performance of a 3-bit PIN Diode Phase Shifter (without dipole contribution)

used in the circuit was 0.5 nanohenry. All data was taken on the devices by measurement of the series insertion loss of four diodes in both bias states and computer reduction of the data from the known circuit loss and isolation characteristics without the diodes. This approach has shown excellent reproducibility in allowing computer aided phase shifter design as described next.

Each individual phase shifter bit and the integrated structure was designed using a computer program for microstrip microwave integrated circuits developed by one of the authors (AW). The analysis is a straightforward calculation of the two-port ABCD matrices for each circuit element using empirically measured phase velocities as a function of line impedance and frequency, following Getsinger.[2] The simulated results for the three-bit phase shifter are shown in Figure 3. The design was reasonably straightforward once the effects of the junctions at this frequency band were determined and these were compensated in the analysis program as simple line length alterations. In addition, there was a transformation effect at the shunt susceptance T-junction boundary, as treated by Easter.[3] This manifested itself simply as a translation of the phase shift magnitude in the design pass band, however, and was compensated for in the development.

Results

Measured phase shift, insertion loss, and return loss for a typical element are given in Figure 4. Here the element is coupled into two waveguide sections. The data was taken in the Hewlett Packard K_u-band waveguide adaptor to the 8410 Network Analyzer. Zero loss reference is at the waveguide flanges so that the dipole transitions are included in the loss, as is their effect on the return loss.

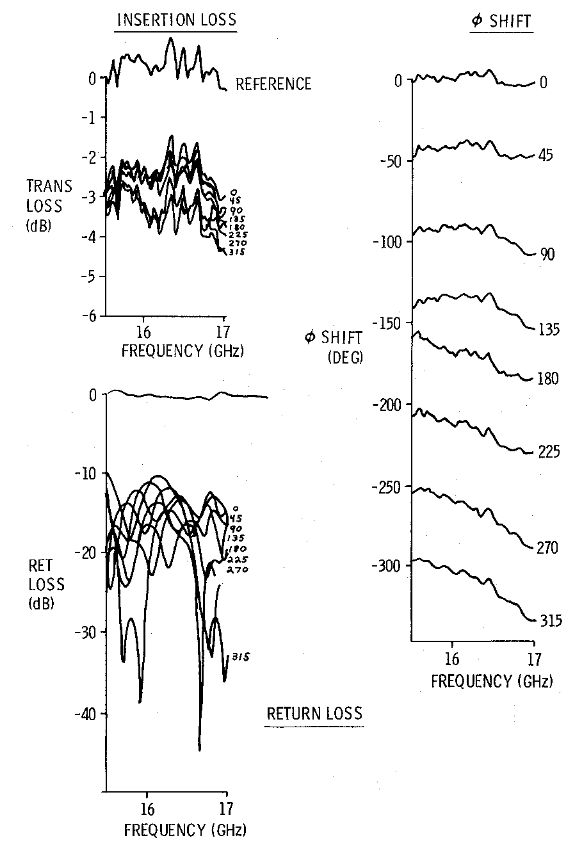

Figure 4. Measured Performance on a K_u-Band Phase Shifter Element

Over 250 elements were fabricated using the chip and wire bond fabrication techniques. Each element was measured at six frequencies in the 16.0 to 16.5 GHz frequency band on an automated network analyzer in a manner similar to that just described. In addition, the insertion phase of each element was recorded to determine the variation of electrical length of each element due to physical and electrical variances. The maximum insertion loss was 4.5 dB for any state of phase shift with the average at 3.2 dB. The standard deviation of the loss was 0.5 dB. Phase error was exceptional with only a 4.4° standard deviation about the mean value of -1.4° over all states and frequencies. The insertion phase at midband exhibited a peak 10° variation and 6° standard deviation.

It has thus been demonstrated that PIN diode phase shifters can be fabricated in reasonable quantities at high K_u band using standard microwave integrated circuits techniques. In fact, the performance of the elements is satisfactory for phased array operation without costly manual adjustments to the circuitry to compensate for process and device variations. The loss of the devices is characteristically high due to the microstrip alumina conductor and dielectric loss. However, the light weight (0.3 oz) and low cost element design will find its use in many systems applications.

References

1. Mark E. Davis, "Integrated Diode Phase Shifters for an X-Band Phased Array Antenna," IEEE Transactions on Microwave Theory and Techniques, MTT-23, Dec. 1975, p 1080.
2. W.S. Getsinger, "Microstrip Dispersion Model," IEEE Transactions on Microwave Theory and Techniques, MTT-21, Jan. 1973, p 34.
3. B. Easter, "The Equivalent Circuit of Some Microstrip Discontinuities," IEEE Transactions on Microwave Theory and Techniques, MTT-23, Aug. 1975, p 655.

Acknowledgements

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