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A Low Cost P-I-N Diode Phase Shifter for Airborne Phased-Array Antennas

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***Abstract*—This paper presents a description of a p-i-n diode phase shifter that was designed for low cost production for use in *X*-band phased-array systems. The phase shifter is designed to make maximum use of photoetched circuit components and low cost materials, and is well suited for assembly on a fully automated assembly line. The salient features of this phase shifter are a printed-circuit transmission structure and inexpensive RF connectors that are integrated into the circuit package. The microwave performance characteristics are generally superior to those of equivalent devices; a useful band width of 40 percent with an average insertion loss of 1.6 dB has been demonstrated with 3-bit units.**

INTRODUCTION

THE primary deterent to the use of phased arrays in airborne radars has been their cost. In particular, the several thousand phase shifters and driver circuits needed in a typical airborne *X*-band radar represent a significant fraction of the total phased-array cost. A phase shifter that is simple and suitable for automated production, and that offers significant reduction in both the cost and weight of phased arrays is described in this paper.

In airborne phased-array applications p-i-n diode phase shifters possess important advantages over ferrite devices; among these are light weight, temperature insensitivity, repeatable insertion phase characteristics, simple driver requirements, and high switching speed. The p-i-n diode phase shifters have a further important advantage in that production techniques can borrow heavily from integrated circuit production technology with its present high degree of automation. For the mass production of phase shifters it has been established through cost analysis that the lowest unit cost is achieved through manufacture with automated production lines, with testing limited to the unit level only.

Many important radar system applications require the use of a linearly polarized antenna. The phase shifter described in this paper, because of its simplicity, low cost, and light weight, has been developed for such an antenna requirement. The phase-shifter design can also be extended to a version that provides circular or variable polarization.

Although it is recognized that the driver and the array logic circuits that are an essential part of any practical array system will figure significantly in the total antenna cost, the problem of producing these circuits is not considered in this paper. In airborne phased arrays, the comparatively simple driver requirements of p-i-n diode phase shifters permit the drivers to be grouped together behind the array as integrated circuits. Because of the resultant simplification of the interconnections, this configuration is more cost effective than one in which individual drivers are placed at each phase shifter. Consequently, in the phase-shifter design described here, the drivers do not form a part of the phase-shifter package.

PHASE-SHIFTER CONSTRUCTION

In common with most *X*-band p-i-n diode phase shifters, this unit consists of several cascaded digital phase-shifting stages. Each stage provides one phase bit of control; the number of stages then determines the fineness of phase control possible. In typical phased-array applications

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3 or 4 bits (corresponding to a smallest phase bit of 45° or 22.5°) are adequate to satisfy the radiation pattern requirements.

The schematic diagram for a 3-bit phase shifter is shown in Fig. 1. The phase-shift sections that provide the individual phase bits each utilize a hybrid-coupled design. Each such section consists of a microwave hybrid junction with two of its four ports terminated in identical reflective p-i-n diode phase shifters. When the two diodes are switched in parallel by changing the bias from a forward to a reverse condition, the phase of the transmission through the two remaining ports of the hybrid changes by an amount equal to that provided by the reflective phase shifters. Bias blocks between the cascaded stages and bias chokes permit independent biasing of the various stages.

Both the superior microwave performance and the ready manufacturability of this phase shifter result from the particular transmission line utilized, a typical cross section of which is illustrated in Fig. 2. The transmission line consists of two parallel photoetched copper conductors sandwiched between three punched layers of dielectric and enclosed in a rectangular trough that forms the outer conductor of the line. Within various portions of the circuit either or both of the two conductor layers may exist. The microwave energy propagates in various transmission line modes, including coaxial, stripline, and both even and odd modes of a shielded asymmetrical two-conductor line. The three dielectric layers are glass-reinforced Teflon such as Rogers Duroid 5870. The outer conductor is a copper or aluminum case and cover which, in mass production, can be formed by impact extrusion. Details of the assembly can be seen in Fig. 3 which shows a disassembled 3-bit unit with SMA connectors and a machined case.

The multiple-mode transmission-line configuration makes it possible to use photoetched circuit components for all the basic building blocks necessary in the phase shifters with the exception of the p-i-n diode; the need for separate discrete components such as chip capacitors is eliminated. Thus the quadrature hybrids are fabricated as quarterwave overlap or proximity couplers; the bias blocks are bandpass filters formed from overlapping quarterwave sections of line; and the bias chokes are double-stub stripline chokes.

The broad-band constant-phase p-i-n diode reflective phase shifter is the basic phase-shifting element. It consists of a passivated p-i-n diode chip mounted on a cylindrical pedestal, an open-circuited shunt stub, and a quarterwave transformer. All diodes are interchangeable regardless of bit size and are ribbon stitched to the stripline circuitry. Typical diode parameters are 225-V reverse breakdown voltage, 0.1-pF junction capacitance, 200-ns minority carrier lifetime, 1.4-Ω forward resistance, and 1.0-Ω reverse resistance. The n-i-p (rather than p-i-n) diodes have been used almost exclusively for convenience in driver design. The performance results presented in this paper were obtained using levels of 20-V reverse bias and 25 mA per diode forward bias. Both diodes of any bit are driven in parallel.

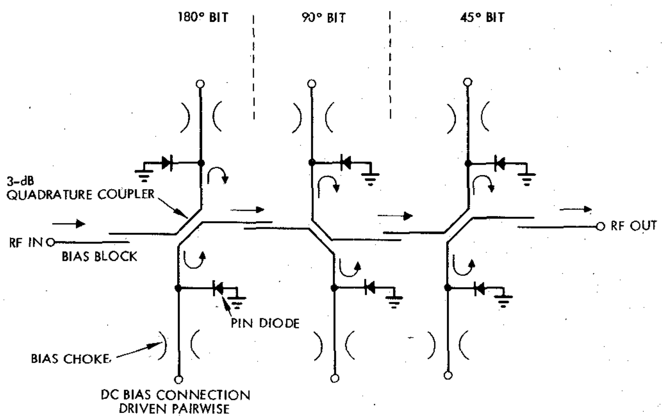

Fig. 1. A 3-bit phase-shifter schematic diagram.

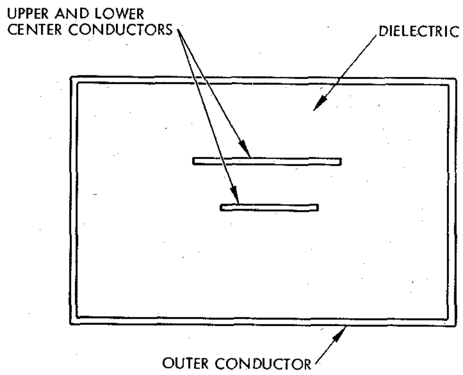

Fig 2. Transmission-line cross section.

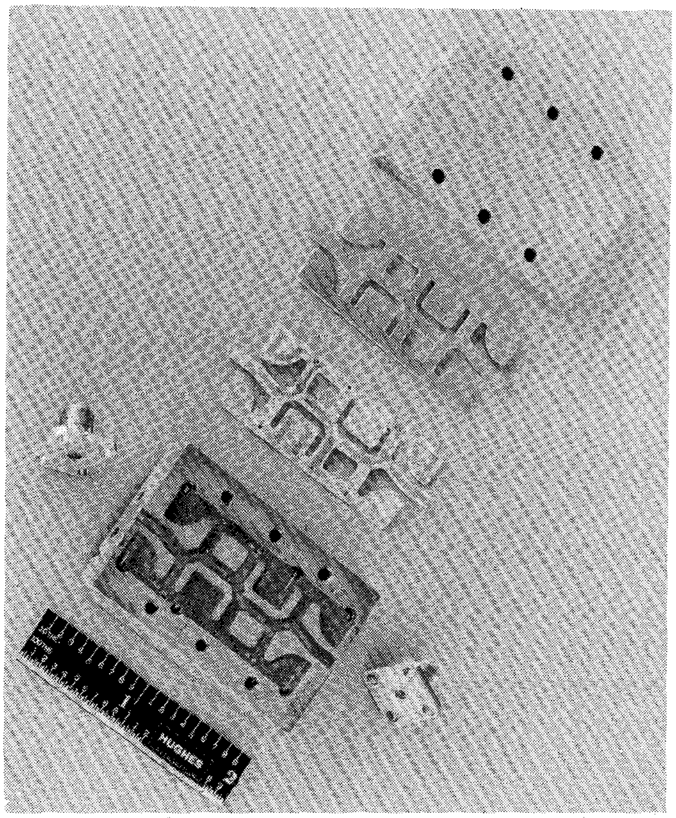

Fig. 3. A 3-bit phase shifter with SMA connectors.

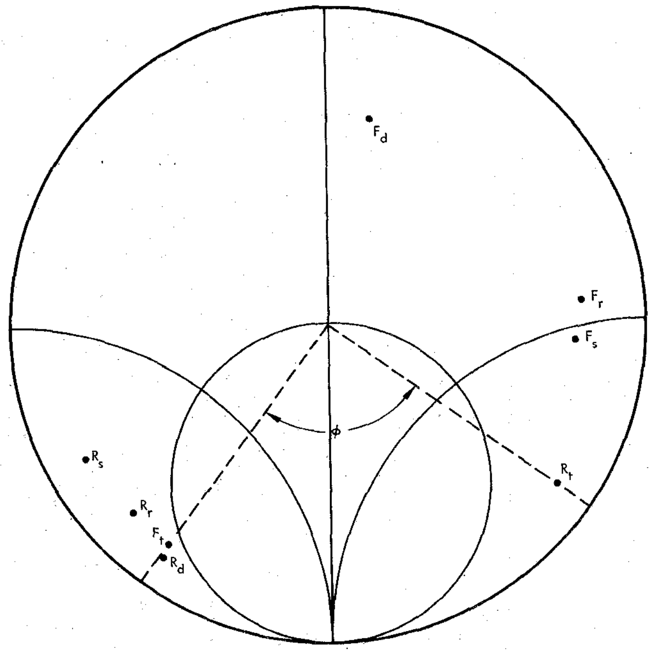

Fig. 4. Smith chart of bit size adjustment.

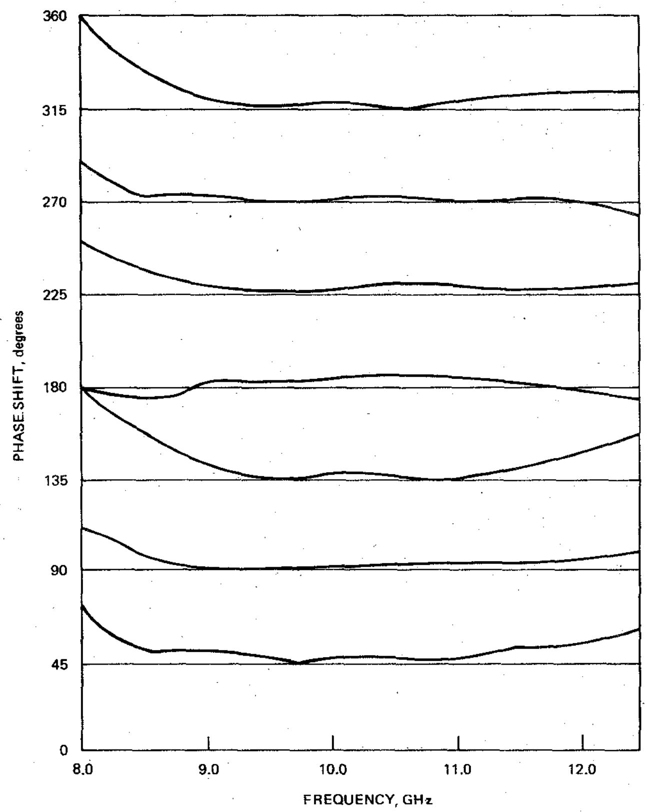

Fig. 5. Measured phase characteristics of 3-bit phase shifter.

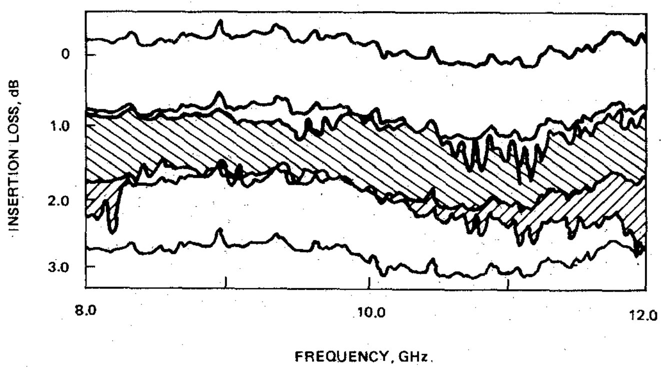

Fig. 6. Measured insertion loss characteristics of 3-bit phase shifter.

Fig. 4 is a somewhat simplified Smith chart impedance plot which helps explain the function of the diode-activated reflective portions of the phase shifter. For the sake of clarity, the diode losses have been considerably exaggerated on this chart.

The impedance of the diode alone in the forward bias condition is indicated by point F_d in Fig. 4, and the reverse bias impedance by point R_d. As is evident from the plot, the diode losses are significantly greater in the forward bias case. When the diode is bonded to the circuitry, the ribbon used to make the connection adds a series inductance which moves the forward bias impedance to point F_r and the reverse bias impedance to point R_r. The stub-line section can then be considered to introduce a shunt capacitance across the diode mounting assembly. Adding this capacitance shifts the impedance points F_r and R_r to F_s and R_s, respectively. The net effect of these changes tends to balance the diode losses in the forward and reverse states. Finally, the quarterwave transformer transforms the impedance in the two bias states to points F_t and R_t. Thus the angle ϕ is the phase shift provided when the diode is switched between the forward and reverse bias states. The parameters of the transformer, the stub, and the ribbon-mounting configuration are adjusted to provide an optimum combination of phase-shift differential loss and bandwidth.

PERFORMANCE

Well over a hundred 3-bit phase shifters of the basic type shown in Fig. 3 have been fabricated and tested. The measured phase and insertion loss characteristics of a typical unit are given in the curves of Figs. 5 and 6. The input VSWR of this unit was less than 1.5 to 1 over the frequency range covered in these curves.

Fig. 5 shows the differential phase shift measured from 8.0 to 12.5 GHz. The useful bandwidth, allowing a maximum phase error in any phase state of $\pm 22\frac{1}{2}°$ or half the least significant bit, is 40 percent. For a maximum permissible error of $\pm$ 10°, the bandwidth is about 30 percent. Fig. 6 gives the total insertion loss, including mismatch, for the same unit. The cross-hatched area is the envelope for all eight states. In phased-array applications using large numbers of phase shifters, the parameter of concern is the average insertion loss. As may be seen, between 8.5 and 10 GHz the average loss is about 1.6 dB and climbs to about 2 dB at 12 GHz. The 1.6-dB loss can be divided approximately as follows: diodes 0.7 dB, conductors 0.5 dB, dielectric 0.3 dB, and mismatch 0.1 dB.

The high degree of precision that can be obtained with

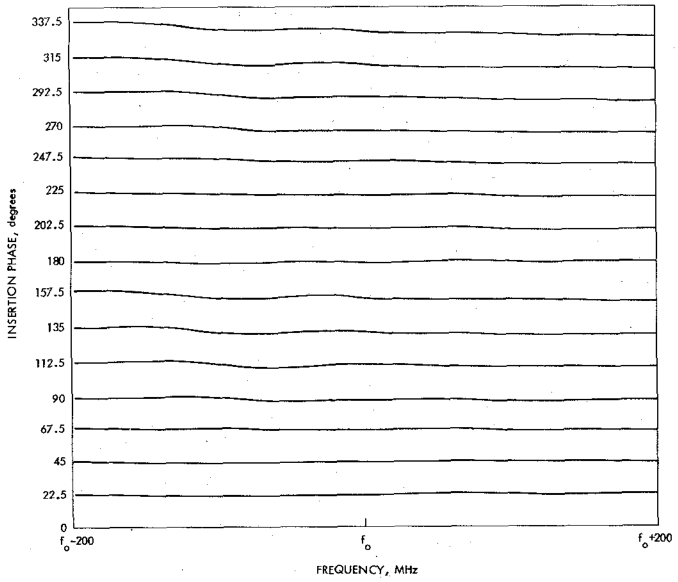

Fig. 7. Measured phase shift of hand-trimmed production flight hardware.

this phase-shifter design is demonstrated in the curves of phase shift versus frequency shown in Fig. 7. The particular unit measured to obtain these data was a production model of a 4-bit phase shifter used in a signal processing application. Twenty-one such units have been built with nearly identical performance characteristics. Due to the fact that an additional power dividing network is incorporated directly into the circuit of this particular phase shifter, it is not possible to directly measure insertion loss or VSWR for the phase-shifting section alone. However, if the power divider insertion loss is subtracted from the overall insertion loss it is estimated that the average phase-shifter losses are approximately 1.7 dB.

The RF power handling capability of a p-i-n diode phase shifter is largely determined by the p-i-n diodes. The peak power limitation is determined principally by the diode voltage breakdown characteristic, and the average power the phase shifter can handle is limited by the thermal characteristics of the diode and the effectiveness of the heat sinking. The phase-shifter design shown in Fig. 3 has been tested with an input of 130-W peak at a 10-percent duty factor using 50-μs pulses. No special cooling was provided during the power tests. With diodes that are rated at 225 V, peak power failure occurs in the reverse bias state at nominal peak power levels of 130, 180, and >200 W for the 180°, 90°, and 45° bits, respectively. Experiments with diodes rated at 450 V show a substantial increase in the peak power breakdown level.

The excellent performance of this design in terms of loss and constant-phase bandwidth is attributable to the transmission-line structure, which permits broad-band microwave structures yet suppresses parasitic modes, to the diode mounting configuration and the use of chip diodes, and to the use of rolled-copper center conductors with resulting low skin resistivity.

INSTALLATION

The microwave design of the phase shifter is only one part of the problem of arriving at a practical device for phased-array systems. The choice of an installation technique that is compatible with a useful array configuration and at the same time is mechanically simple and lends itself to automated assembly procedure is an equally important aspect of the overall design. In particular, it is essential that the microwave connectors not add significantly to the cost or weight. A phase-shifter package meeting these requirements is shown in Fig. 8; this package is suitable for use in any phased array using open-ended waveguide sections as radiating elements.

The phase shifter shown in Fig. 8 is designed to slip directly into the length of guide that forms the array-radiating element. The two RF connectors are E-plane coupling probes, one located at each end of the case. The simple spring clip attached to the center of the case locks the phase shifter into the waveguide and, at the same time, provides RF short-circuit planes behind the coupling probes. The bias connections for the phase-shifter diodes are made at the center of the case and are brought out on a flexible cable through a hole in the waveguide. The spring clip ensures that no RF fields exist in this region.

A sketch showing the way in which the phase shifter would be installed in a typical array is presented in Fig. 9. The antenna is an array of reduced-height open-ended

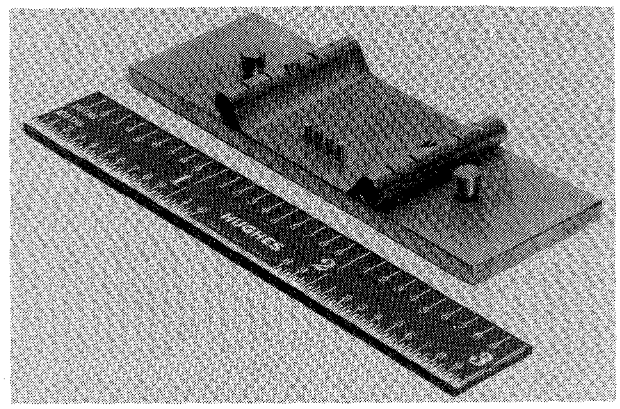

Fig. 8. Package suitable for array use.

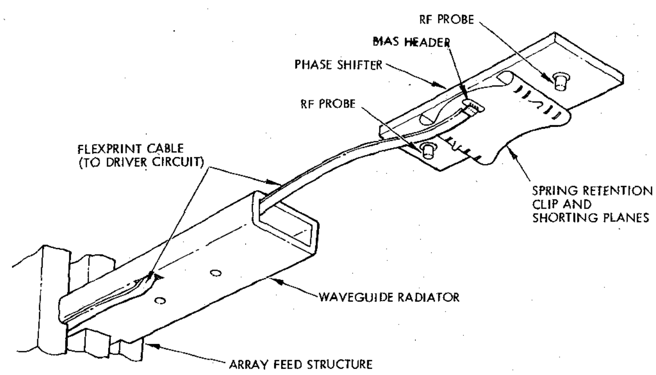

Fig. 9. Phase-shifter outline for phased-array usage, including mounting details.

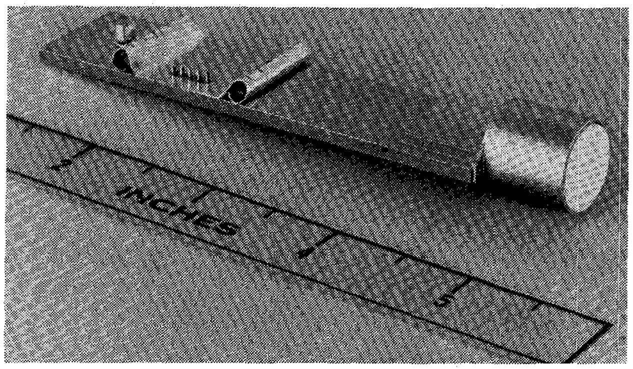

Fig. 10. Model of phase shifter/polarization selector/radiating element.

waveguides laid out in a triangular grid lattice. A phase shifter is inserted into each of the open-ended waveguides and is locked in placed by the spring clip. The RF probe at the rear end of the case couples microwave energy from the waveguide into the phase shifter. The probe at the forward end of the case couples the microwave from the phase shifter back into the guide section forming the horn radiator. The clip blocks RF leakage past the phase-shifter housing.

The same basic phase-shifter configuration can be extended to provide an array with dual or variable polarization capability. In this case the phase-shifter body is lengthened to allow room for a power divider and extra phase-shift sections. The additional circuitry is used to control the relative phasing and excitation of two orthogonally oriented output terminals in the radiating element. A model of a unit of such a design is shown in Fig. 10.

MANUFACTURING CONSIDERATIONS

The component parts for a complete phase shifter of the type shown in Fig. 8 consist of an impact-extruded case, a punched cover, a retaining spring, six diode chips, three hermetic feedthroughs (two probes and a bias header), and three punched dielectric layers. Two of the dielectric layers have conductor patterns photoetched on the top surfaces.

In the automatic assembly process the three hermetic feedthroughs and the retaining spring are attached to the case. The six diodes are then bonded to the pedestals, and the first two dielectric layers are inserted. Automatic ribbon-stitch bonders next make all interconnections between diodes, conductors, and feedthroughs. The top dielectric layer is then laid in place. The outer cover is welded on, after which the unit is ready for automatic electrical tests. The finished phase shifters are finally bulk leak tested using standard methods for semiconductor cases.

The resulting phase shifter is hermetically sealed, weighs about 1/3 of an ounce, and occupies about $2\frac{1}{2}$ in in the reduced-height waveguides forming the array aperture.

ACKNOWLEDGMENT

The development of the phase shifter described in this paper was the result of a joint effort of a team of engineers and technicians. The basic design approach was conceived by F. G. Terrio who directed and worked on the program from its inception through the reduction to practice of the idea. R. J. Stockton performed the detailed development of the diode reactance networks and chokes and subsequently directed the effort to make the device manufacturable. W. D. Sato was responsible for the detailed development of the coupler and bias blocks. F. D. Walton contributed many of the original manufacturability suggestions. D. J. Lewis provided support and advice on the problems associated with application to phased arrays and gave much useful assistance in the preparation of this paper.