# A WAVEGUIDE SWITCHED-SUSCEPTANCE (DIODE-PATCH) PHASE SHIFTER

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## ABSTRACT

A new digital PIN-diode phase shifter that operates in double-ridge waveguide is described. The phase shifter consists of several split conductive patches etched on a dielectric strip which is inserted in the longitudinal direction in the waveguide. The upper and lower half of each split patch are electrically connected by a diode that is switched between forward and reverse bias to shift the phase in the waveguide. An optimization design approach and experimental test results are presented.

## INTRODUCTION

PIN-diode phase shifters are often used in phased-array systems where high-speed scanning, low weight, and transmission reciprocity are prime concerns. Considerable effort has been expended in the past 20 years to design high performance, low cost PIN-diode phase shifters. Several excellent sources discuss the various types of diode phase shifters (1), (2).

Of particular interest here are the RADANT phase scanning approach (3) and the loaded line phase shifter approach (4). The RADANT system requires considerable space because it consists of a feed antenna, such as a horn or a fixed beam array, and a pair of diode grids located in front of the feed antenna. Loaded line phase shifters use two stubs placed a quarter wavelength apart. Each stub has a $+jB$ susceptance for one bias condition and a $-jB$ susceptance for the other bias condition. This type of phase shifter is usually realized in microstrip or stripline which requires a transition from microstrip to waveguide if the phased-array system uses an open ended waveguide or waveguide-fed radiating element. Generally, the loss increases as a result of mismatch reflections at this transition.

The phase shifter described in this paper is highly desirable because it operates inside the array waveguides, thus eliminating the requirement for a feed antenna and allowing for a system more compact than the RADANT system. This approach is also preferable because it eliminates the need for special transitions from microstrip or stripline to waveguide. Furthermore, it can be designed to work in a waveguide having the same cross section as the radiating element waveguide.

## DESCRIPTION OF PHASE SHIFTER

The diode patch phase shifter consists of several split conductive patches symmetrically located on both sides of a dielectric strip, such as copper-clad duroid, which is inserted in a broadwall slot that is centered in the longitudinal direction in double-ridge waveguide. The upper and lower halves of each conductive patch are electrically connected together by a PIN-diode that is switched between forward and reverse bias to change the susceptance of the patch and therefore shift the phase through the waveguide. The resulting phase shift through the entire phase shift section is determined by the difference in transmission phase between the two cases when all the diodes are forward biased or reverse biased. The total amount of phase shift is determined by the forward and reverse bias diode characteristics and by the right combination of the number of patches and the area sizes of the individual patches. The VSWR is determined by the spacings between the patches. A compromise between insertion loss and VSWR must be made when choosing the number of patches for a particular phase shifter because a small number of patches results in low loss while a large number patches results in low VSWR over a wide frequency range.

A long phase shifter strip having the same diode-patch pattern repeated at the appropriate waveguide element spacing down its entire length can be fabricated so that it can be inserted into a slot cut in a column of waveguides stacked upon each other. DC bias paths etched on the strip provide the means to switch the diodes to supply each waveguide element in the column with the same phase delay. Several columns can be aligned and set with the required phase progression between columns to provide one-dimensional scanning. A small choke coil and a double-stub filter attached at the interface between the patches and DC bias path help reduce RF coupling to the bias path. The filters lie in the section between waveguides so they will not interfere with the fields traveling through the waveguides. A diode-patch phase shifter for three stacked waveguides is shown in Figure 1; a side view is shown in Figure 2; a view looking down a single waveguide is shown in Figure 3.

## COMPUTER DESIGN PROGRAM

To design the phase shifters, a computer program was developed that calculates the phase shifter performance and applies a least-squares minimizing routine to optimize the variables in the



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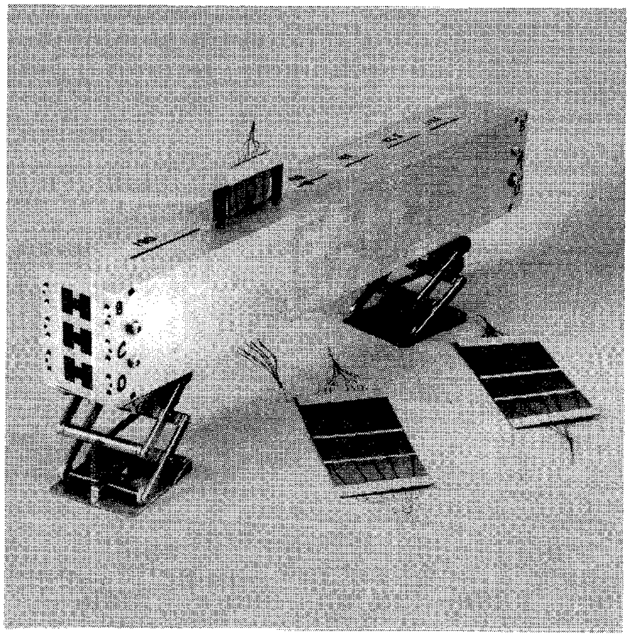

**Figure 1. Patch Diode Phase Shifter in Three High Fixture**

design. The program uses a phase shifter equivalent circuit and a database of measured characteristics of individual diode-patch elements. The program generates the phase shifter dimensions (patch size and separations) that yield the desired VSWR and phase shift response. These dimensions are then used to fabricate the phase shifter strips.

The equivalent circuit shown in Figure 4 was used to evaluate the phase shifter performance. The performance can be calculated by cascading the wave-amplitude transmission matrices (T-matrices) of the different circuit elements to come up with the overall phase shifter T-matrix. Table 1 lists the T-matrices of the circuit elements. The interfaces between the empty waveguide (no dielectric card is placed in this region) and the edges of the dielectric card are modeled as ideal transformers with ratio, n, calculated as the ratio of the propagation constants of the loaded and unloaded waveguide. The separations between patches are modeled as lossless transmission lines and the diode patches as differential susceptances.

To form the database, a diode and a dielectric constant and thickness were first chosen. A set of fifteen different-sized individual patches was fabricated and each patch was characterized in both its forward and reverse bias state. Each piece used a 0.015 inch gap between its upper and lower patches and incorporated the coils and filters. The scattering parameters (S-parameters) of each piece inserted in a waveguide slot were measured at a minimum of three different positions in the slot to remove measurement and system errors. The T-parameters of the entire set for both bias states were calculated from the measured S-parameters and used to create the database.

The computer design program begins by reading the desired phase shifter performance (VSWR with the diodes forward biased,

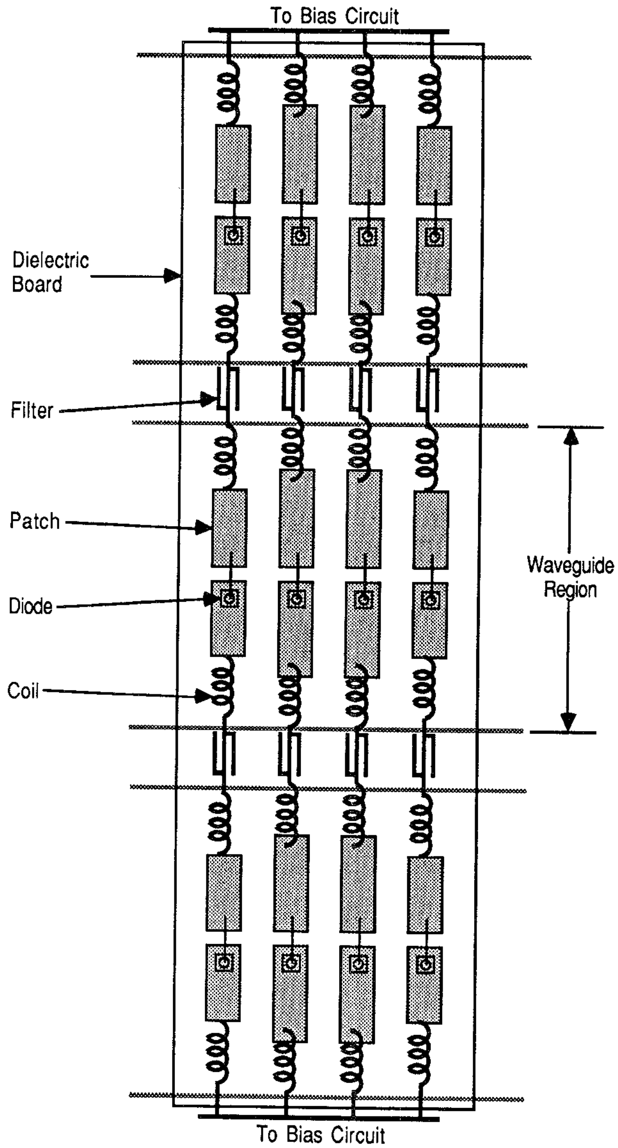


**Figure 2. Phase Shifter Side View**

VSWR with the diodes reverse biased, the differential phase shift, and frequency weights) and the initial, or "seed," phase shifter dimensions required to start the optimization. Program control is then transferred to the optimization routine, which is from IMSL, a special FORTRAN library package (5). This routine minimizes the sum of squares of M functions for N variables using a finite difference Levenburg-Marquardt algorithm. Once the optimization subroutine is invoked it calculates the actual performance of the "seed" design after cascading the T-matrices for each patch, separation between patches, and the trailing and leading edge transformers. One T-matrix is calculated for the forward bias state and another for the reverse bias state for each patch and frequency. The T-matrix of a particular patch size is calculated by interpolating the values over the range of the measured patch sizes used to create the database. After all the matrices are cascaded,

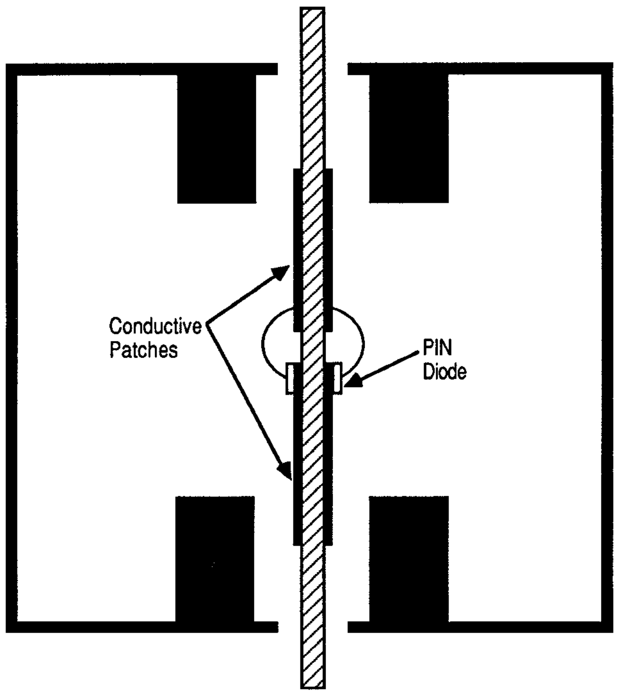


**Figure 3. Phase Shifter View Looking Through Waveguide**

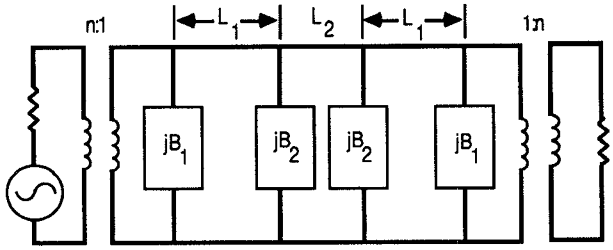


**Figure 4. Phase Shifter Equivalent Circuit**

the program calculates the difference between the actual performance of the seed design and the desired performance read by the program in the beginning. The algorithm then adjusts the dimensions of the seed design in a manner that will minimize the difference between the actual and the desired performance. The optimization routine repeats the design adjustment and actual performance computation of each change as many as several hundred times as required to converge on the desired design. Convergence is determined by any combination of three possible criteria. Those criteria, and the values read by the program that affect the criteria, are discussed in the IMSL documentation. When the optimization is completed, the program computes the actual performance a final time and prints it to an output dataset.

In order to decide whether or not a phase shifter design should be fabricated, several parameters listed in the output dataset should be investigated; namely, whether or not the optimization converges and the final design dimensions are reasonable. In many cases convergence is not reached and the program should be run again using a modified "seed" design, while in other cases

**Table 1. TRANSMISSION MATRICES OF CIRCUIT ELEMENTS**

| Phase Shifter Component | Transmission Matrix |
|---|---|
| Length of Transmission Line | $\begin{bmatrix} e^{-j\beta l} & 0 \\ 0 & \frac{1}{e^{-j\beta l}} \end{bmatrix}$ |
| Diode-Patch Element, values calculated from database | $\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}$ |
| Leading Edge Transformer | $\begin{bmatrix} \frac{n^2+1}{2n} & \frac{n^2-1}{2n} \\ \frac{n^2-1}{2n} & \frac{n^2+1}{2n} \end{bmatrix}$ |
| Trailing Edge Transformer | $\begin{bmatrix} \frac{n^2+1}{2n} & -\left(\frac{n^2-1}{2n}\right) \\ -\left(\frac{n^2-1}{2n}\right) & \frac{n^2+1}{2n} \end{bmatrix}$ |
| $n = \sqrt{\frac{k_g}{k_{dg}}}$ | |
| $k_g$ = propagation constant of unloaded waveguide<br>$k_{dg}$ = propagation constant of dielectric strip loaded waveguide | |

convergence is not reached but acceptable performance is obtained. If the performance is acceptable then it is important to check that the overall width of the phase shifter is small enough to fit into the waveguide slot and that the spacings between adjacent patches are large enough so the fringing fields can be neglected as is assumed in the program. Once these items are checked it is safe to expect that a phase shifter fabricated with these dimensions will perform reasonably close to predicted values.

## RESULTS AND CONCLUSIONS

A four-patch 22.5° phase shifter and a five-patch 45.0° phase shifter were designed and fabricated using the computer design program. The measured VSWR and phase shift performance of the phase shifters are shown in Figures 5 through 8. Both phase shifters have less than 0.4 dB insertion loss and less than −40 dB interwaveguide coupling. The measured phases for both the phase shifters are slightly lower than their desired values; however, a design iteration using the same patch separations with slightly larger patches should increase the phase shifts. This type of design iteration is considered acceptable and is possibly due to the fact that line loss and transformer loss was not considered. To obtain designs with flatter phase shift responses over frequency will most likely require

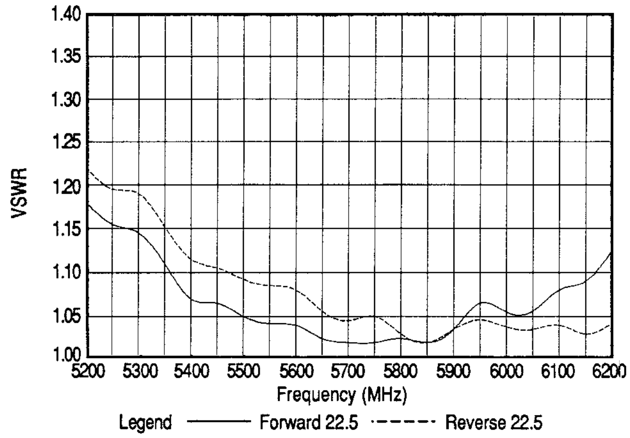


**Figure 5. 22.5° Bit, Measured VSWR as a Function of Frequency**

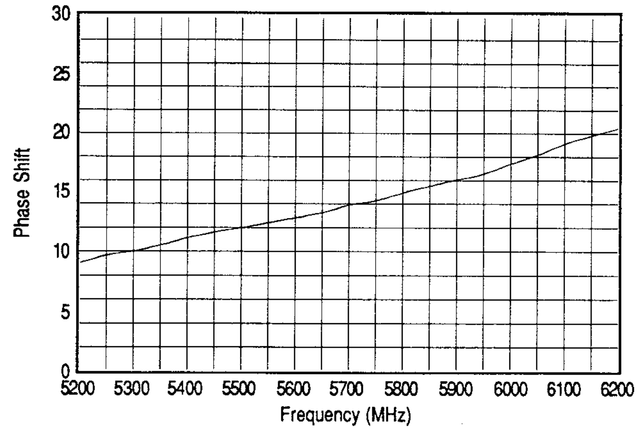


**Figure 6. 22.5° Bit, Measured Phase Shift as a Function of Frequency**

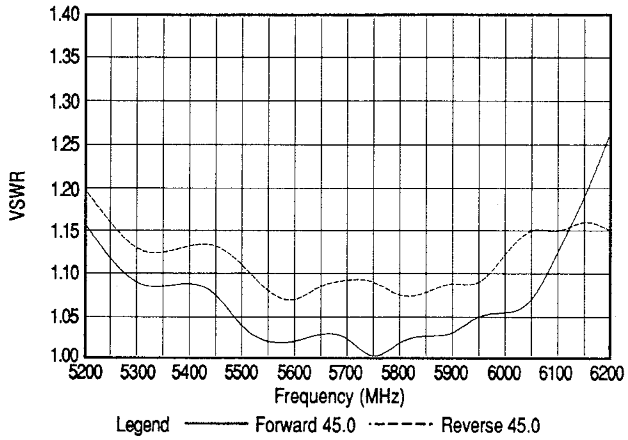


**Figure 7. 45° Bit, Measured VSWR as a Function of Frequency**

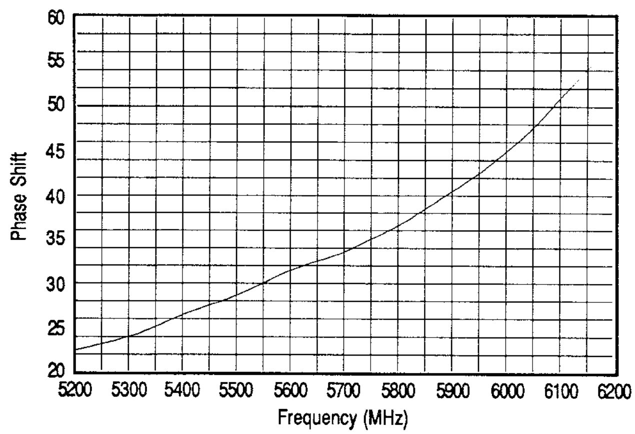


**Figure 8. 45° Bit, Measured Phase Shift as a Function of Frequency**

a more careful combination of the choice of diode and patch sizes used to comprise the characteristic database. The measured VSWR across the entire band, although higher than the desired VSWR (1.00 which is not expected), is very good. It is plotted over a larger bandwidth to show what happens just outside the band. The measurement fixture in which the phase shifters were measured has several waveguide transformer steps that were not calibrated out for these measurements and contribute some mismatch. The measured results confirm the design approach and indicate that the diode-patch phase shifters can be designed to have overall low VSWR and a prescribed phase shift.

## REFERENCES

(1) "Semiconductor Control," J.F. White, Artech House Inc., Dedham, Massachusetts, 1977.

(2) "Fundamental Limitations in RF Switching and Phase Shifting Using Semiconductor Diodes," M.E. Hines, PROC. IEEE, pp. 697–708: June 1964.

(3) "RADANT: New Method of Phase Scanning," C. Chekroun et al., Microwave Journal, pp. 45–53: February 1981.

(4) "Microwave Diode Control Devices," R.V. Garver, Artech House Inc., Dedham, Massachusetts, 1976.

(5) The IMSL Library, IMSL Inc., Houston, Texas, 1982.