A COMPACT S-BAND DIODE PHASE SHIFTER

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Abstract

The design and performance of a five-bit S-Band diode phase shifter is described. This thick-film microstrip device uses series coupled diodes for the small bits and constant phase-frequency switched line bits for the three large bits.

Introduction

This paper describes the design of a miniature five-bit diode microstrip phase shifter, which has been optimized for low cost batch processing while maintaining a high degree of performance over a 12% bandwidth. This phase shifter is incorporated in a solid state transmit-receive antenna element module which is under development at Hughes Ground Systems.

The module requirements for this phase shifter are as follows:

Center Frequency	3.3 GHz
Bandwidth	12%
Average Loss	1.75 dB
Number of Bits	5
Phase Shift Accuracy	$\pm 3^{\circ}$
VSWR	1.5 maximum
Size	1" x 2"
Average Power	15 watts

Design

A schematic diagram of the phase shifter is shown in Figure 1. The 180, 90, and 45 degree bits are frequency compensated switched line circuits, and the 22.5 and 11.25 degree bits are series coupled loaded line circuits. Hybrid coupled sections were considered for the three large bits. The specified bandwidth required the use of either three branch hybrids or coupled line hybrids. These were discarded because of the large physical size of the three branch hybrid and the tight fabrication tolerances of the coupled line unit.

The 11.25 and 22.5 degree phase bits use series coupled loaded line circuits. These circuits use switched loading reactances spaced a quarter wavelength along a transmission line (Figure 2). Adjacent loading reactances are normally equal and are switched into a capacitive or an inductive state. Impedance-matched transmission for both stages is maintained by correctly choosing the impedance level of the transmission line section between diodes.

Shunt coupled loaded line circuits have been treated extensively in the literature.[1,2] Very little attention has been given the series loaded circuit configuration mainly because of the difficulty in adjusting the amount of series loading in order to realize different bit sizes with similar diodes. This problem is particularly difficult in micromin circuits where small capacitance PIN diode chips are used. These PIN chip diodes have a reactance which is typically 10 to 20 times the impedance of a 50 ohm line at S-Band, hence will normally give a large mismatch loss when reverse biased. In order to prevent this large mismatch, each series mounted diode is shunted by a short length of high impedance transmission line as shown in Figure 3. A capacitor is in series with each shunt line in order to prevent shorting out the diode bias. If the short length of transmission line around each diode is represented by a π equivalent circuit,[3] the electrical equivalent circuit of a single diode switch can be drawn as shown in Figure 4. When the diode is changed from forward to reverse bias, the reactance of the series element in the π network changes from a low inductive value to a high inductive value respectively. In the special case when the capacitive reactance of the diode is much greater than the series inductive component, the equivalent circuit reduces to that of a short piece of high impedance transmission line. Also of interest is the forward biased case where the diode series inductance is zero. The equivalent circuit of the forward biased switch reduces to just 2 capacitors (B) in shunt across the line, or a shunt loaded line circuit.

Computer calculations have been run on the series coupled loaded line circuit. These calculations have shown that if the interconnecting transmission line between identical switches is reduced from the nominal quarter wavelength by about 20%, matched transmission in both states can be realized over an octave bandwidth for a 22.5 degree phase bit.

Figure 5 shows the results of a series of experimental circuits where the length of the transmission line around the diodes was changed in a uniform manner in a series of discrete steps. The experiment shows that fairly precise control of the nominal phase shift can be obtained by simply adjusting the length of the transmission line around the diode. The curves also show a phase-frequency slope which is proportional to frequency.

The most difficult parameter to achieve in the design of this phase shifter was a flat phase-frequency characteristics over the 12% bandwidth using switched line phase bits. Schiffman[4] sections can be used, but these require long delay lines on the order of at least two wavelengths for a 180° bit as well as 4 dB coupler sections in the reference paths. Tight couplers are difficult to realize on thick film micromin microstrip circuits. A flat phase-frequency characteristic was achieved by compensating the reference path in the switched line bits with shorted quarter wavelength loading stubs. This loading allows the phase slope versus frequency characteristic for each reference path to be equal to the phase slope of the delay path; thus, the net phase difference over the frequency band is constant. The normalized characteristic admittance (y_o) of a stub required to give flat phase phase is related to the midband phase shift $\Delta\psi$ by:

$$y_o = \frac{2}{\pi} \cdot \Delta\psi$$

Thus, for a 180° phase bit, the normalized characteristic admittance of one stub must be 2 in order to give flat phase shift. Likewise, the admittance of a stub must be 1 for a 90° bit.

A photograph of the completed phase shifter is shown in Figure 6. The phase shifter is fabricated on a .025" thick 99.5% alumina substrate and measures 1 inch by 2 inches. Thick film gold conductors and thick film blocking and bypass capacitors are used throughout. Electro-Science Lab's No. 8831 gold is used for conductors, and the capacitor dielectric is ESL No. 4310. The bias bypass capacitors function in a manner similar to that of a feedthrough capacitor; that is, the quarter wavelength bias leads pass over the bottom plate of the capacitors which are wrapped around the substrate edge to make contact with the ground plane. This method minimizes series inductance and provides an rf ground for the bias leads.

Blocking capacitors are incorporated in the frequency compensating stubs of the three larger bits. These capacitors are required to prevent shorting out the DC bias in the reference paths.

There are four diodes in each of the three larger bits, and two diodes in each of the two smaller bits for a total of sixteen diodes in the complete phase shifter. The diodes, Hewlett Packard Associate's No. 5082-0012, have a reverse bias capacitance of less than .1 pf at 50 volts. DC breakdown voltage is 200 volts.

Figure 7 shows the DC bias circuitry for the phase shifter. In the 45, 90, and 180 degree bits, the diodes in each path are biased in series, with the DC polarity of the delay path diodes being opposite to that of the reference path diodes. This arrangement allows for the minimum number of bias return leads and necessitates the use of only 1 bias control lead per bit. Phase switching is accomplished by simply changing the polarity of the control voltage. The bias requirement is therefore approximately ±1.5 volts at 50 mA. The two diodes in each of the two smaller bits are in DC parallel and operate at a level of 0 volts and +.75 volts at 50 mA.

Performance

The measured performance of the completed phase shifter is shown in Figures 8 and 9. The input VSWR for all 32 phase steps is less than 1.5 over the frequency range of 3.1 to 3.5 GHz. Average insertion loss is 1.75 dB with the maximum loss being less than 2 dB over the same frequency range. Phase shift accuracy of any step is within a few degrees of nominal over the entire band.

References

1. White, J. F., "High Power, PIN Diode Controlled Microwave Transmission Phase Shifters," IEEE Trans., Vol. MTT-13, pp.233-242, March 1965.

2. Opp. F. L. and W. F. Hoffman, "Design of Digital Loaded Line Phase Shift Networks for Microwave Thin Film Applications," IEEE Trans on MTT, Vol. MTT-16, pp. 462-463, July 1968.

3. Matthaei, Young, Jones, "Microwave Filters, Impedance-Matching Networks and Coupling Structures, "McGraw-Hill, 1964, pp. 361.

4. Schiffman, B. M., "A New Class of Broadband Microwave 90-degree Phase Shifters," IRE Trans. on MTT, April 1958, Vol. MTT-6, No. 2, pp. 232-237.

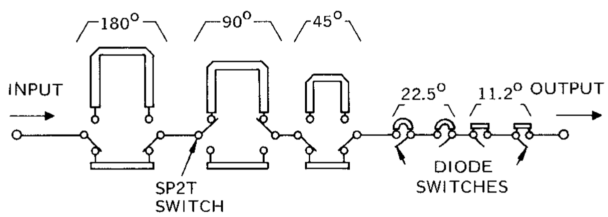


Figure 1. Schematic Diagram of 5-Bit Micromin Diode Phase Shifter

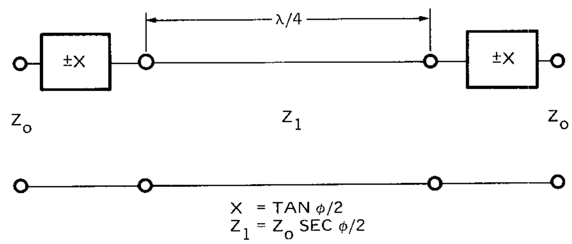


Figure 2. Series Coupled Loaded Line Phase Bit

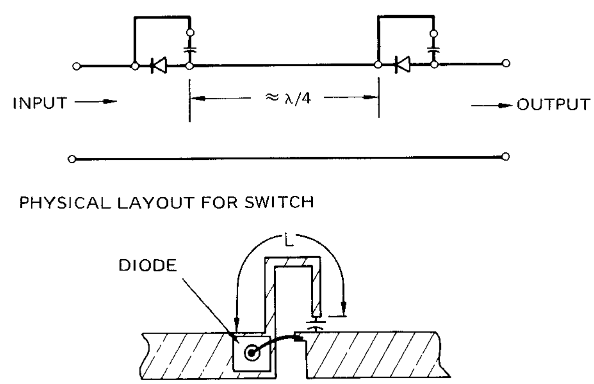
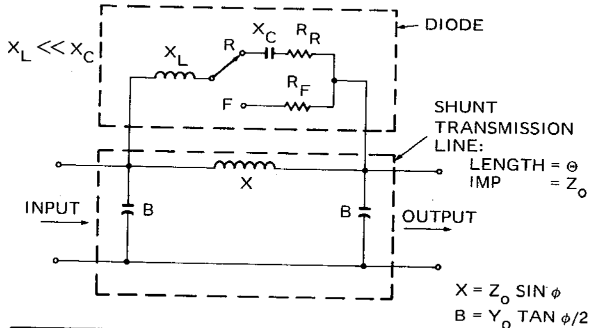


Figure 3. Electrical Equivalent Circuit for 11.25° and 22.5° Phase Bits



TOTAL REACTANCE OF SERIES COMPONENT OF Π NETWORK	
REVERSE BIAS	FORWARD BIAS
$X_T = \frac{X \cdot X_C}{X_C - X}$	$XT = \frac{X_L \cdot X}{X_L + X}$
IF = $X_C >> X$	IF = $X_L \longrightarrow 0$
THEN $X_T = X$	THEN $X_T \longrightarrow 0$

Figure 4. Electrical Equivalent Circuit of Series Coupled Switch

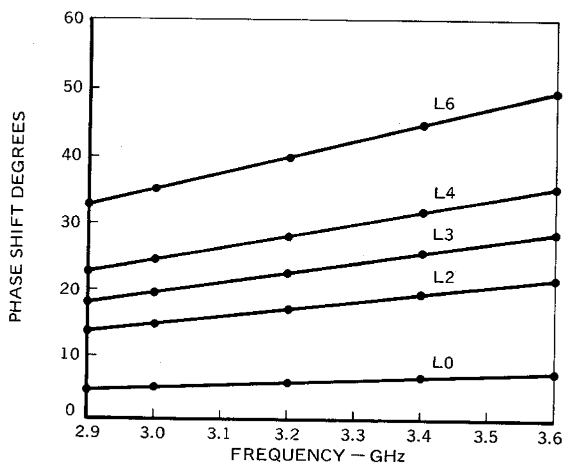


Figure 5. Measured Phase Shift for Small Bit Design

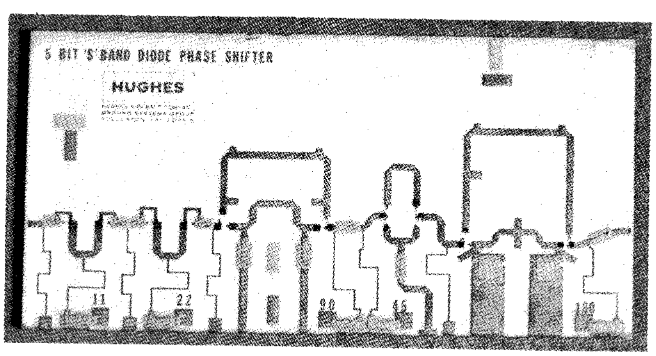


Figure 6. Photo of a Five-Bit S-Band Diode Phase Shifter. The Phase Shifter is Fabricated on a 1 by 2 inch Alumina Substrate

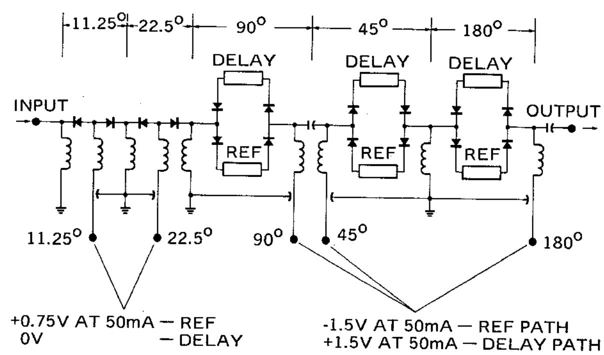


Figure 7. Bias Circuit for 5-Bit Phase Shifter

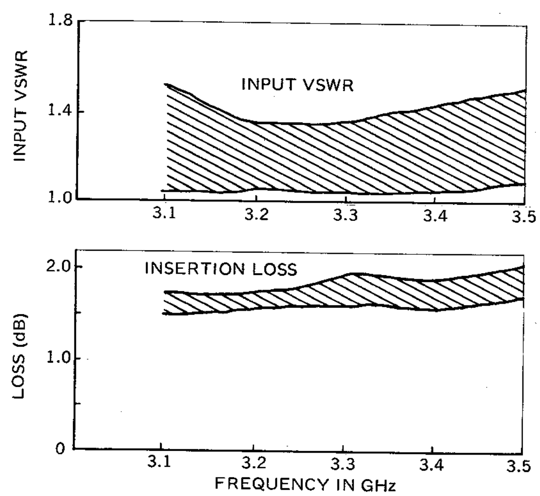


Figure 8. Measured Performance of all 32 Steps for 5-Bit Micromin Phase Shifter

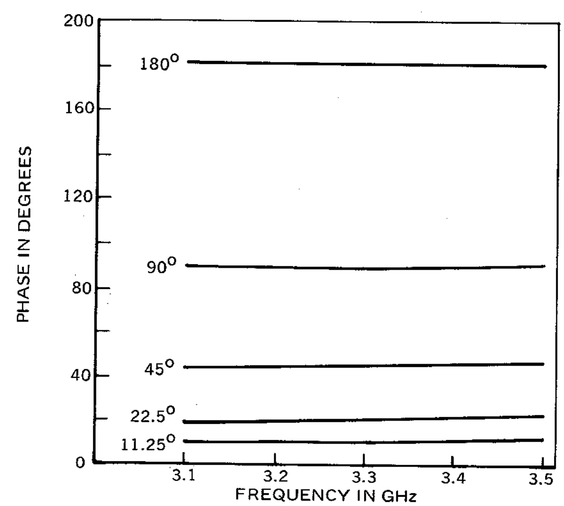


Figure 9. Measured Phase Shift for 5-Bit Micromin Phase Shifter