A LUMPED ELEMENT DIODE PHASE SHIFTER

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Abstract

A digital phase shifter utilizing three PIN diodes in a tee configuration is described. The operation is explained in terms of low and high pass filter characteristics. Design expressions for phase change, insertion loss and VSWR as a function of element values are given. Frequency characteristics for 45, 90 and 180 degree units are shown in graphical form.

Introduction

Most diode type digital phase shifters utilize lengths of transmission line as an integral part of the design. Included in this category are the switched line, hybrid coupled and loaded line phase shifters.[1] More recently, some phase shifters have used lumped element techniques to realize digital phase change.[2,3] This paper describes a lumped element type that employs three diodes in a tee structure. A complete circuit description of the unit is given in Figure-1. In one state (Diodes D_1 forward biased, Diode D_2 reverse biased), the circuit behaves like a constant K low pass filter while in its alternate state it approximates a constant K high pass filter. The circuit parameters are chosen so that the cutoff frequency of the low pass filter (f_A) is greater than the cutoff frequency of the high-pass filter (f_B). Hence the network exhibits low loss in the frequency band between f_B and f_A. Since the network produces phase delay in the low pass state and phase advance in the high pass state, low loss digital phase change is obtained between f_B and f_A.

The original version of this device made in 1967 did not contain capacitors C_1 and C_2. The unit gave 180 degrees of phase change at 1400 mc in an insertion length of about 1 inch. However, the loss was in excess of 2 db. In this version, the capacitors provide the required reactance while the diodes merely act as ON-OFF switches. In addition to the obvious size advantage, this configuration is easily biased with a single source injected through an rf choke at point P and dc returns at the input and output ports.

Circuit Analysis

In this analysis, it is assumed that the equivalent circuit for a forward biased diode is a resistance R_f (R_{f1} for diodes D_1 and R_{f2} for diode D_2). In the reverse (or zero) bias state, the equivalent circuit is a resistance R_r in series with a junction capacitance C_j (R_{r1} and C_{j1} for diodes D_1 and R_{r2} and C_{j2} for diode D_2). It is assumed that any parasitic inductance due to diode packaging may be lumped in with inductances L_1 and L_2.

By replacing D_1 and D_2 with their appropriate equivalent circuits, the network for the two bias states can be approximated by those shown in Figure-2. State A is defined as the bias condition in which diodes D_1 are forward biased and diode D_2 is reverse biased. In bias State B, D_2 is forward biased while diodes D_1 are reverse biased.

Phase Change

In order to determine the phase change and VSWR versus frequency, the following assumptions are made:

1. The diodes are lossless (R_{f1}, R_{f2}, R_{r1} and $R_{r2} = 0$).
2. The diode impedance in the reverse bias state is infinite (ωC_{j1} and $\omega C_{j2} = 0$).

With these assumptions, the equivalent circuit for State A reduces to a constant K low pass filter with series inductors of value L_1 and a shunt capacitor of value C_2. In state B, the network can be made to approximate a constant K high pass filter by proper choice of C_1 and L_2. The equivalent series capacitance C_e and shunt inductance L_e in state B are given by

$$C_e = \frac{C_1}{1 - \omega^2 L_1 C_1} \qquad \text{and} \qquad L_e = \frac{L_2}{1 - \omega^2 L_2 C_2}$$

when $\omega^2 L_1 C_1$ and $\omega^2 L_2 C_2 < 1$. From constant K filter theory, the expressions for impedance level (K) and cutoff frequency in the two bias states are

$$K_A = \sqrt{\frac{2L_1}{C_2}} \qquad \text{and} \qquad K_B = \sqrt{\frac{L_e}{2C_e}}$$

$$f_A = \frac{1}{2\pi}\sqrt{\frac{2}{L_1 C_2}} \qquad \text{and} \qquad f_B = \frac{1}{2\pi}\sqrt{\frac{1}{2L_e C_e}}$$

If the phase shifter is placed in a transmission system of characteristic impedance Z_o, then K_A and K_B should be close to Z_o. One such compromise which leads to low VSWR between f_A and f_B is

$$K_A = \sqrt{2}\, Z_o \qquad \text{and} \qquad K_B = Z_o/\sqrt{2}$$

Similarly, the center frequency (f_o) of the unit must be somewhere between f_B and f_A. A reasonable choice is to define f_o as the geometric mean of f_A and f_B. That is

$$f_o \equiv \sqrt{f_A f_B} \tag{1}$$

Manipulation of the above expressions leads to the following relationships among the circuit elements.

$$C_2 = \frac{L_1}{Z_o^2} \quad ; \quad L_2 = \frac{1}{2\omega_o^2 C_2} \quad ; \quad C_1 = \frac{1}{2\omega_o^2 L_1} \tag{2}$$

If we define

$$X_o \equiv \frac{\omega_o L_1}{Z_o} \quad ,$$

then the midband phase change ($\Delta\phi_o$) between states A and B is given by

$$\Delta\phi_o \equiv \phi_A - \phi_B = 2 \arctan \left[\frac{X_o}{2} \left(\frac{3 - X_o^2}{1 - X_o^2} \right) \right] \quad (3)$$

Values of X for common values of digital phase shift are given in the following table.

$\Delta\phi_o$	0	$11\frac{1}{4}^\circ$	$22\frac{1}{2}^\circ$	45°	90°	180°
X_o	0	0.07	0.14	0.26	0.53	1.00

Thus the design procedure for the phase shifter reduces to the following steps:

1. Determine X_o for the required midband phase change $\Delta\phi_o$ from the above table or Equation (3).
2. Calculate L_1 from $X_o = \frac{\omega_o L_1}{Z_o}$.
3. Calculate C_2, L_2 and C_1 from the appropriate expressions in Equation (2).

The frequency sensitivity of the phase shifter for 45°, 90° and 180° units is shown graphically in Figure-3.

VSWR

In order to determine the VSWR of the phase shifter, an expression for the reflective loss (RL) is first derived from the ABCD matrix. The loss ratios for the two bias states are given by

$$RL_A = 1 + \frac{A^2}{4} - \frac{A^4}{2} + \frac{A^6}{4}$$

$$RL_B = 1 + \frac{B^2}{4} - \frac{B^4}{2} + \frac{B^6}{4}$$

where $A \equiv \left(f/f_o\right) X_o$ and $B \equiv \left(2\frac{f_o}{f} - \frac{f}{f_o}\right) X_o$

Calculations for reflective loss (converted to VSWR) are plotted in Figure-4 for 90 and 180 degree units. It is apparent from Figures 3 and 4 that reasonable performance (VSWR < 1.5 and phase change within $\pm$ 10 percent of nominal) can be achieved over a 20 percent bandwidth.

Dissipative Loss

It was indicated earlier that capacitors C_1 and C_2 provide the required capacitive reactances while the diodes merely act as ON-OFF switches. The diodes, in fact, perform an additional function! By separately controlling their junction capacitances, one can minimize the loss as well as equalize the insertion loss in the two bias states.

The equivalent series resistance and shunt conductance for the two bias states are given by the following expressions.

STATE-A: $R_A = R_{f1}$ and $G_A \simeq R_{r2}\omega^2 C_{j2}^2$

STATE-B: $R_B \simeq R_{r1}\left(\frac{C_{j1}}{C_1}\right)^2$ and $G_B = \frac{R_{f2}}{\omega^2 L_2^2}$

Approximate insertion loss (I.L.) expressions (in db) for 90 and 180 degree units are as follows:

$$I.L._A \text{ (db)} \simeq 8.7 \left(\frac{R_A}{Z_o} + \frac{G_A}{Y_o}\right)$$

$$I.L._B \text{ (db)} \simeq 8.7 \left(\frac{R_B}{Z_o} + \frac{G_B}{Y_o}\right)$$

Phase Shifter Design

To illustrate the design procedure and performance characteristics of the phase shifter, calculations for a 3 gc, 90 degree unit in a 50 ohm system are described.

For $\Delta\phi_o$ = 90° , X_o = 0.53

Thus $\omega_o L_1$ = 26.5 ohms or L_1 = 1.40 nh.

From Equation (2)

C_2 = 0.56 pf , L_2 = 2.45 nh , C_1 = 1.00 pf

The PIN diodes chosen for this design are

Series Diodes (D_1):
C_{j1} = 0.20 pf, R_{f1} = 1.5 ohms, R_{r1} = 6 ohms

Shunt Diode (D_2):
C_{j2} = 0.20 pf, R_{f2} = 1.5 ohms, R_{r2} = 6 ohms

With these diodes the midband insertion loss (I.L.) in the two bias states are

$$I.L._A = 0.3 \text{ db} \quad \text{and} \quad I.L._B = 0.3 \text{ db} .$$

Figures 3 and 4 show that the VSWR of this unit should be less than 1.50 over a 40 percent band. The phase shift is within ten percent of the nominal value over a 20 percent band. Experimental results will be presented at the symposium.

Acknowledgement

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References

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3. Onno, P. and Plitkins, A., 1971 GMTT International Microwave Symposium Digest, May 1971, pp. 22-23.

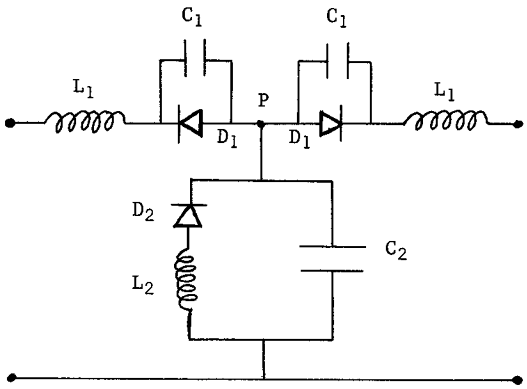


FIG. - 1 Tee Phase Shifter Circuit

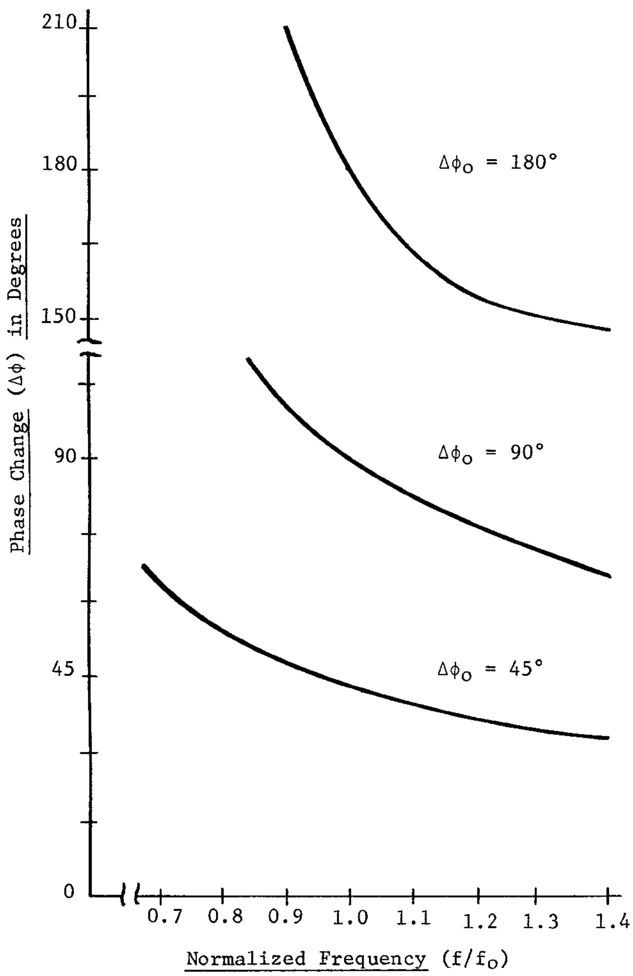
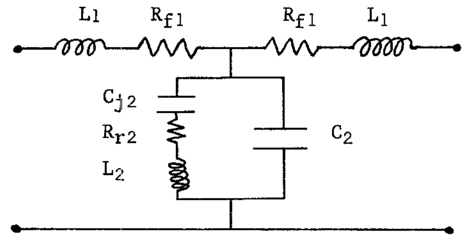
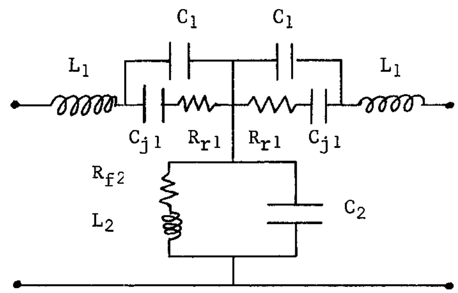


FIG. - 3 Phase shift as a function of frequency for 45, 90 and 180 degree units.

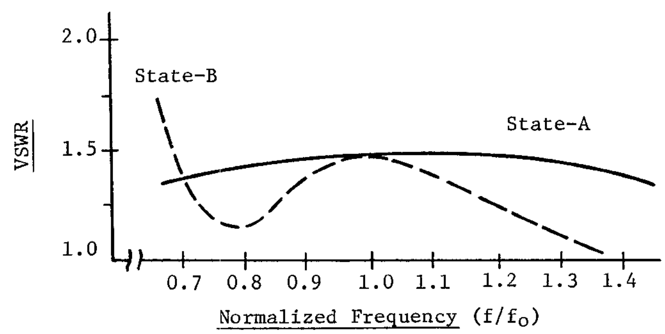


a) Bias State A

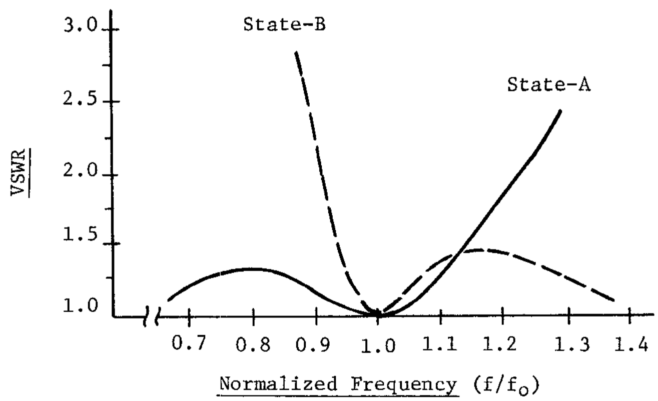


b) Bias State B

FIG. - 2 Equivalent circuits for the two bias states.



a) 90 Degree Unit ($\Delta\phi_o$ = 90°)



b) 180 Degree Unit ($\Delta\phi_o$ = 180°)

FIG. - 4 VSWR as a function of frequency for 90 and 180 degree units.