BROADBAND DIODE PHASE SHIFTERS

by
Robert V. Garver
Harry Diamond Labs.
Washington, D. C.

Abstract

Design figures are presented for four types of diode phase shifters. Comparison is made of their bandwidths, and it is shown that most of them can work over an octave bandwidth. The fourth type of phase shifter is new using lumped element high-pass and low-pass circuits.

Introduction

Three types of phase shifters are well known: switched line, reflection, and loaded line. Although many versions of these phase shifters have been designed, none of the designs have fully exploited the bandwidth possibilities of these circuits. Most designs to date have had about 10% maximum bandwidth. But most of the circuits have the potential of providing octave bandwidths. A new fourth type of phase shifter using lumped element high-pass and low-pass circuits has the potential of being smaller than the other types and providing slightly better bandwidth than some of them. The four types of phase shifters with their design equations are shown in figure 1.

The specification of bandwidth depends on the system requirements. Broadband phase shifters for phased array radars require constant time delay elements while broadband phase shifters for serrodyne modulators or phase comparison networks should have constant phase shift. The switched line and reflection types of phase shifters are most suitable for constant time delay while all four types can be made into constant phase shift devices.

Switched Line Phase Shifter

The switched line phase shifter is inherently a constant time delay device. It is made into a constant phase device by using a Schiffman coupled line in one path[1]. Bandwidth is limited by phase error spikes and insertion loss spikes introduced by the switching diodes. This error is correctly calculated[2] using the method of symmetrical circuit excitation. The errors for a 90° differential path length are shown as figure 2, for various values of ℓ. Calculations made for the errors in a wide range of differential path lengths indicate that large errors are caused by the off path when it is $\lambda/2$ long as corrected for by the capacitance of the off diodes. (Their capacitance makes them equivalent to a short section of open circuit terminated line.) No error occurs for 180° phase shift and with modest diode isolation (20 dB) very little error is present from $0°<2\pi\ell/\lambda<80°$ for all phase shifts equal to or less than 90°.

Reflection Phase Shifters

The reflection type phase shifter may be made either with a circulator or 3 dB coupler. Phase errors are introduced by the finite isolation of the circulator or coupler and the diode. A phase accuracy of $\pm 2°$ requires that intervening mismatches must have a VSWR less than 1.02[3], which corresponds to a circulator isolation of greater than 40 dB, (assuming a perfect diode is used). To make a wideband constant time delay phase shifter, it is necessary to have a very good circulator or 3 dB coupler and a very good diode in front of the switched line section. These requirements are very difficult to meet, making the reflection type phase shifter difficult to use for precision broad band phase shifting. Some degree of component matching can be used to improve the accuracy from the device when the mechanism of finite circulator isolation can be closely defined. To make a wideband constant phase shift device lumped circuit diode parameters may be selected using the values given in figure 3. More than octave bandwidths can be achieved for all phase shifts.

Loaded Line Phase Shifters

ABCD Matrices give the phase delay of a loaded line phase shifter as

$$\phi = \tan^{-1}\left(\frac{B_N + (1-B_N^2/2)\tan\theta}{1 - B_N\tan\theta}\right)$$

in which two identical normalized shunting susceptances B_N are separated by $\theta=2\pi\ell/\lambda$. This equation was used to generate the solid curves given in figure 4. The dashed curves give the bounds the susceptance pairs cannot exceed, to keep VSWR low. Shunt stubs and shunt lumped element diodes give admittance curves approximately perpendicular to the phase curves. Widest bandwidth occurs around $\ell/\lambda= .25$. Figure 5 shows the bandwidth possible with lumped element diodes for B . The curves stop when the VSWR becomes higher than 1.46. Approximately the same bandwidth is possible with shunt stubs. For 45° .38 = Y_{OS}/Y_O; 22.5°, .178; and 11.25°, .082 in which Y_{OS} is the characteristic admittance of the shunting stub and Y_O is the characteristic admittance of themain transmission line. Octave bandwidth is available for 11.25° and almost octave bandwidth is possible for 22.5°.

Lumped Element High-Low Pass Phase Shifter

When the switches put the circuit in the low-pass state phase is delayed and when in the high-pass state it is advanced. ABCD Matrices give the phase delay through the T Section as

$$\phi = \tan^{-1}\left(\frac{B_N + 2X_N - X_N^2 B_N}{2(1 - B_N X_N)}\right)$$

in which X_N is the normalized series reactance of each series element and B_N, the normalized shunt susceptance of the shunt element. Note that when both B_N and X_N change sign, has the same magnitude but opposite sign. The phase for a wide range of reactances is shown by the solid curves in figure 6. The curves are for the low pass circuit. As frequency is increased a given set of circuit elements will have their combined impedances prescribe movement on the graph toward the upper left corner. The complimentary high pass circuit will cause movement toward the lower right corner. Both circuits tend to stay matched and lost phase in one state tends to be made up for by increased phase in the other state. The frequency dependance of these phase shifters is shown in figure 7. Note that octave bandwidth is available for $\Delta\phi=45°$ and almost an octave is available for $\Delta\phi=90°$.

Conclusions

All four types of phase shifters can give octave bandwidth for low values of phase shift. The phase shifter circuit least likely to give wide bandwidth is the loaded line type. The type next most difficult to work with is the reflection type because of the strict requirements on intervening mismatches to prevent phase errors. The switched line phase shifter is most satisfactory for constant time delay phase shifting but the region $90°<2\pi\ell/\lambda<180°$ must be avoided in either length. Thus if the phase shifter were to be used in a phased array of much length and large sweep angle then many 90° max. bits would have to be used for the longer time delay paths. When the switched line phase shifter is used with Schiffman constant phase delay lines the long lengths of the lines constrain the constant phase shift bandwidth to about 1/2 octave. The new lumped element high-low pass phase shifter gives very good constant phase shift for $\Delta\phi\leq 90°$. A practical octave bandwidth constant phase shift phase shifter would use the new type phase shifters for all but the 180° bit which could be a reflection device made using a very carefully matched quarter wavelength 3 dB coupler and a pair of diodes.

References

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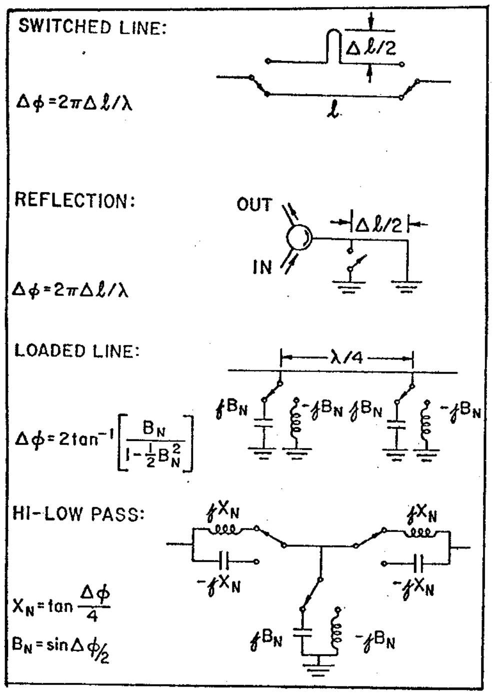
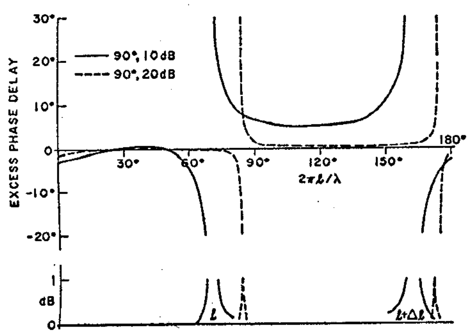
2. Wilkinson, E.J., L.I. Parad, and W.R. Connerney, "An X-Band Electronically Steerable Phased Array," pp. 43-48, Microwave Journal, February 1964.

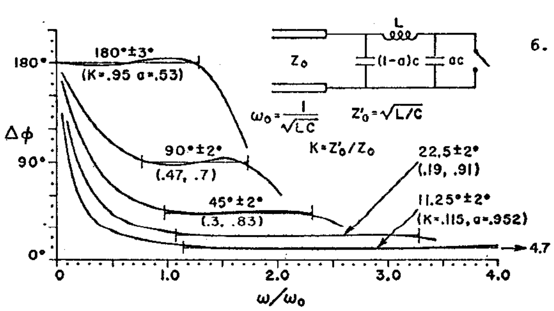
3. R. Garver, D. Bergfried, S. Raff, B. Weinschel, "Errors in S_{11} Measurements Due to Residual SWR of the Measuring Equipment," paper III-4 this symposium digest.



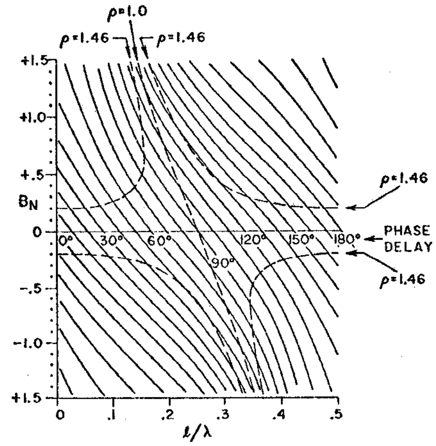
1. Circuits and désign equations for diode phase shifters.



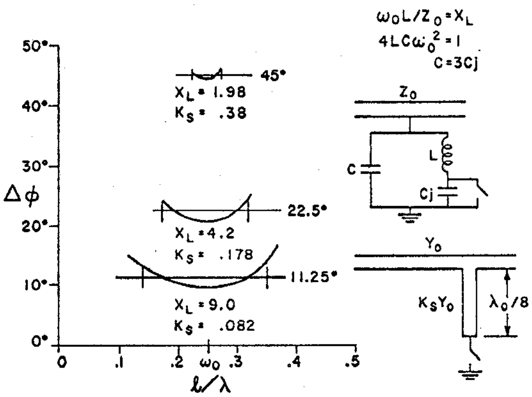
2. Errors for $\Delta\phi = 90°$ switched line phase shifter.



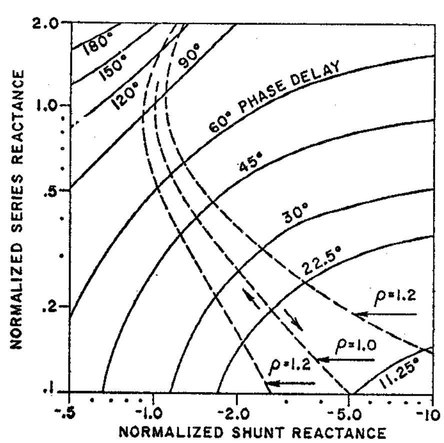
3. Phase shift and design parameters for constant phase shift reflection type phase shifter.



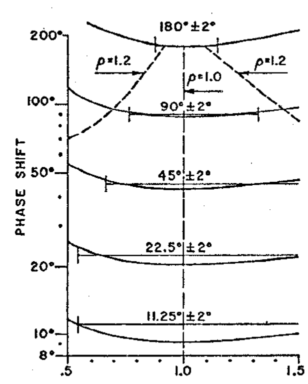
4. Phase delay for a loaded line phase shifter.



5. Frequency dependence of loaded line phase shifters.



6. Phase delay for a lumped element T section.



7. Frequency dependence of High-Low pass lumped element T section phase shifter.