A PRECISION ANALOG DUPLEXING PHASE SHIFTER

C. R. Boyd* and G. Klein**

*Microwave Applications Group, Chatsworth, California
**Westinghouse Electric Corp., Baltimore, Maryland

Introduction

Ferrite phase shifters have long been employed in high power, analog control applications. However, the control characteristics of most of these structures have left much to be desired. The suppressed-rotation (Reggia-Spencer) type unit is a typical example; although it is simple to build, this geometry suffers from excessive temperature drift and frequency dispersion. Also, the phase shift vs. coil current characteristic depends intimately on the magnetization curve of the particular piece of ferrite used, and large hysteresis effects are generally experienced, further complicating the problem of accurate control. Finally, the mechanical configuration of a rod suspended in a waveguide makes removal of large amounts of dissipated rf energy difficult at best.

This paper describes an analog ferrite phase shifter that provides unlimited phase shift with uniformly low hysteresis and a dispersionless phase shift vs. frequency characteristic. The phase shift angle has a simple mathematical relationship to the driving current values, and is essentially independent of the shape of the magnetization curve of the ferrite material or its variation with temperature. The amount of ferrite material needed for phase shifting is only enough to provide 180 degrees of differential phase shift, and consequently the insertion loss is lower than conventional approaches. An additional 90° nonreciprocal differential phase shift section allows a duplexing function to be incorporated in the unit. Finally, the geometry is very convenient for liquid cooling, permitting operation at high average power levels.

Phase Shifter Approach

The ferrite phase shifter configuration to be described is a magnetically variable version of the Fox-type phase shifter.(1) This phase shifter consists essentially of a transducer from rectangular to circular waveguide, followed by a linear-to-circular polarizer, a rotatable half-wave plate, a circular-to-linear polarizer, and a transducer from circular waveguide back to rectangular. The phase shift angle is proportional to twice the mechanical angle of rotation of the half-wave plate, and is in principle independent of frequency.

A low-power X-band magnetically variable version of this phase shifter was described in 1971.(2) This phase shifter used a pair of dielectric quarter-wave plates with a ferrite half-wave plate. The ferrite half-wave plate was magnetized with a transverse quadrupole-field pattern that was provided by a multipole yoke. This yoke was wound with two sets of interlaced coils so that smooth rotation of the pattern could be achieved.

The high power phase shifter that is the topic of this paper differs from the design previously described in a number of important respects. As indicated in the block diagram of Figure 1, a non-reciprocal ferrite quarter-wave plate was substituted for one of the dielectric polarizers. This change causes the received energy to be coupled to the input waveguide with a linear polarization orthogonal to the transmitted wave. An orthogonal mode junction fitted to the phaser input then allows the function of a circulator to be accomplished with almost negligible increase in the overall loss of the unit. From a "black box" viewpoint, the combination of phase shifter and orthogonal mode junction performs the functions shown in Figure 2.

The key element in this phase shifter is the yoke that provides the rotatable transverse quadrupole field. The two interlaced windings on this yoke are designated as the "sine" and "cosine" windings, because of the field patterns generated by their respective excitations. Consider the usual cylindrical co-ordinate definitions of Figure 3. In this case the radius of the ferrite rod is given by the dimension R_o, and the orientation around the circumference of the rod by the angle ϕ. Ideally, the sine winding is arranged to produce a radial magnetic field B_s around the rod circumference that has the dependence

$$B_s = B_{so} \sin 2\phi \qquad (1)$$

Similarly, the cosine winding should produce a field B_c with the characteristic

$$B_c = B_{co} \cos 2\phi \qquad (2)$$

Neglecting saturation effects, the total field will be the superposition of the two,

$$B = B_s + B_c = B_{so} \sin 2\phi + B_{co} \cos 2\phi \qquad (3)$$

Now define an electrical angle θ and let the magnitudes B_{so} and B_{co} be varied as $B_o \sin\theta$ and $B_o \cos\theta$, respectively. The resultant field will be

$$B = B_o \ (\sin\theta \sin 2\phi + \cos\theta \cos 2\phi) \qquad (4)$$

$$= B_o \cos(2\phi - \theta)$$

It is seen that the quadrupole excitation is rotated through a mechanical angle $\phi_o = \theta_o/2$ when an angle θ_o is introduced. Since the r-f phase shift angle is proportional to twice the mechanical rotation, it follows that a change of θ_o degrees in electrical excitation will also produce θ_o degrees of r-f phase shift.

In practice, it is not possible to generate an ideally smooth bias field distribution from a finite number of driving points. For example, an eight-pole yoke is a simple and obvious approach for producing interlaced quadrupole-field patterns. However, the field distribution does not rotate smoothly with such a small number of poles, and rather large deviations of r-f phase shift from excitation angle are experienced for this arrangement. A larger number of poles will give a more stable field distribution, i.e. one that rotates more smoothly as the coil currents are varied. Examination of the error patterns measured on experimental units indicates that the major irreducible contribution to phase control eventually arises from a residual dipole-field component of transverse magnetization. An important design consideration is that the ferrite is continuously operated above the knee of the hysteresis loop, independent of the phase shift angle. Thus the particular shape of the magnetization curve is unimportant, and the amount of phase shift hysteresis is not a function of the command angle. Another interesting feature is that the phase shift angle can be advanced or retarded continuously. Therefore a small frequency offset is possible with high efficiency and at high rf power level.

Experimental Results

An S-band phase shifter of the type described above has been built and tested. The essential design features and test results are as follows:

1. Phase Shifter Geometry - The phase shifter housing was arranged to incorporate liquid cooling so that high average power levels could be accomodated. A sketch of the mechanical configuration is shown in Figure 4.

2. Ferrite Half-Wave Plate - The ferrite half-wave plate was made using an yttrium-iron garnet material with gadolinium and holmium doping. As predicted by elementary theory, the differential phase shift between principal axes exhibited a monotonically decreasing frequency dispersion approximately inversely proportional to frequency. Peak power threshhold at the 0.02 dB insertion loss increase point was measured at about 80 KW.

3. Dielectric Quarter-Wave Plate - A ceramic dielectric quarter-wave plate design was used, based on the well-known broadband dielectric slab approach. Differential phase shift was 90 ± 2 degrees over the design frequency band.

4. Ferrite Quarter-Wave Plate - The same type ferrite material was used in the nonreciprocal quarter-wave plate. Magnetic bias was provided by permanent magnets placed around the rod.

5. Insertion Loss - Figure 5 shows a recorder trace of insertion loss vs. frequency. In this trace, the phase shifter was scanned over all phase states as frequency was slowly swept. It is evident that low values of insertion loss and insertion loss modulation are obtained.

6. Impedance Match - The phase shifter uses ceramic dielectric transformers to standard WR-229 waveguide. Figure 6 shows a trace of return loss vs. frequency. Again, the phase shifter was scanned over all phase states during the frequency sweep.

7. Isolation - Power coupled to the receiver from the transmitter was typically 25 dB down over all phase angles when the radiator port was terminated in a matched load.

8. Phase Accuracy - Figure 7 shows a swept trace of phase angle deviation from command value as a function of the command angle. It is evident that the rf angle follows very closely the command angle for unidirectional phase changes, and also that the hysteresis associated with reversal of the direction of phase change is limited to a few degrees.

9. Phase Shift vs. Frequency Dependence - None observed.

10. RF Power Levels - The basic design was tested with heavily doped garnet materials up to power levels on the order of 200 KW peak without failure. Also, an average power level of 3000 watts was successfully accomodated with less heavily doped material. The unit finally developed was a compromise between high peak power and high average power, and handled levels of 80 KW peak and 2000 watts average.

Conclusions

The phase shifter described here has performance characteristics far superior to other known approaches for achieving a low loss, highly accurate, high power, duplexing analog microwave phase shifter.

References

1. A. G. Fox, "An Adjustable Waveguide Phase Changer," Proc. I.R.E., Vol, 35, pp. 1489-1498, December 1947.

2. C. R. Boyd, Jr., "An Accurate Analog Ferrite Phase Shifter," 1971 G-MTT International Symposium Digest, pp. 104-105; May 1971.

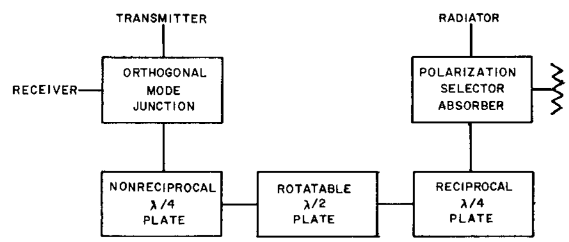

Figure 1 - Phase Shifter Equivalent Network

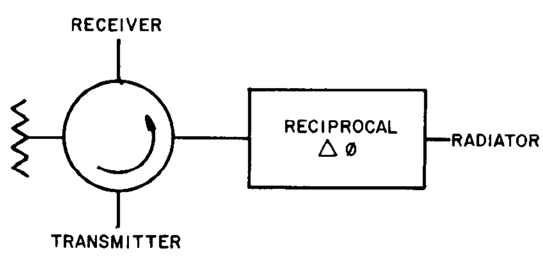

Figure 2 - Functional Equivalent Block Diagram

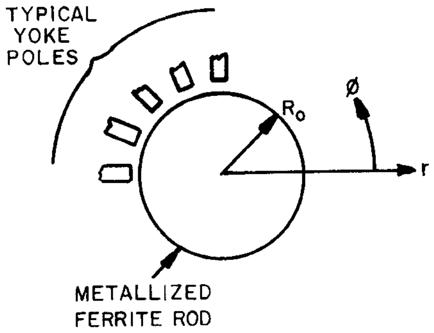

Figure 3 - Cylindrical Co-ordinate Definitions

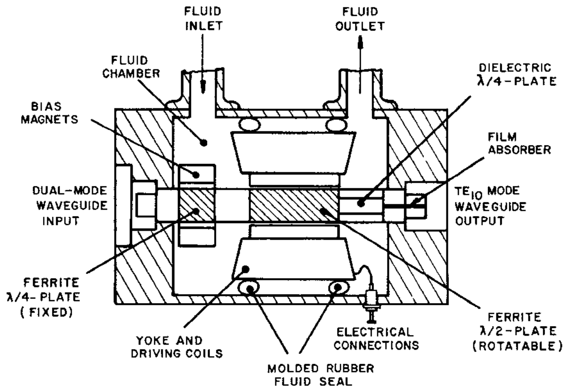

Figure 4 - Phase Shifter Mechanical Configuration

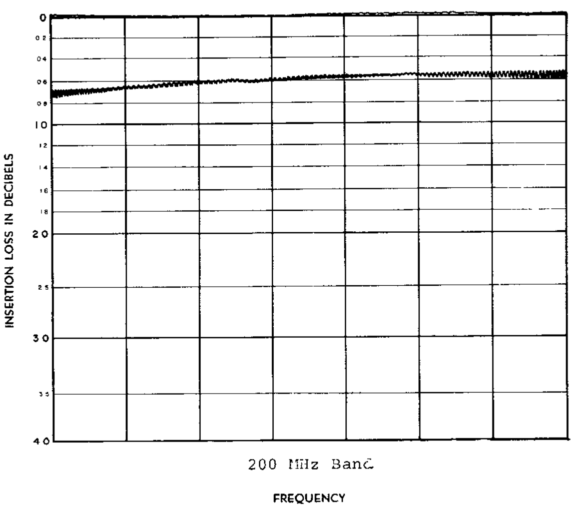

Figure 5 - Insertion Loss vs. Frequency Characteristics

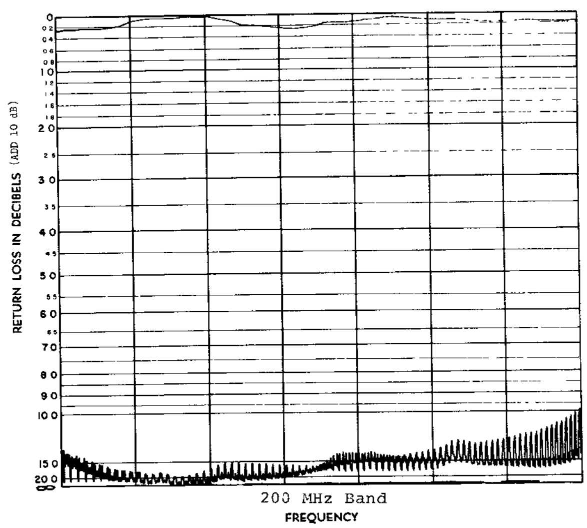

Figure 6 - Return Loss vs. Frequency Characteristics

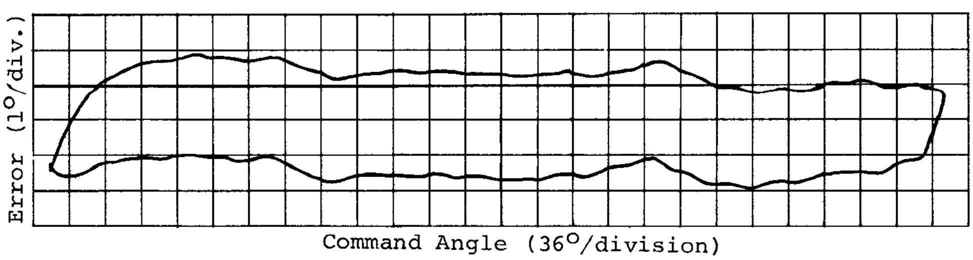

Figure 5 - Deviation of Phase Angle from Command Angle Value