Design Considerations For Rotary-Field Ferrite Phase Shifters

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Key factors influencing the design of a rotary-field ferrite phase shifter are the required r-f performance, the desired control characteristic and the switching time. These factors are examined as a function of the saturation magnetization of the ferrite and the number of turns on the drive yoke. A performance table is presented giving the characteristics of these phase shifters in the 2-20 GHz range.

I. Introduction

A phase shifter is a device which provides variable insertion phase in a microwave signal path without altering the physical path length. Most phase shifters are two-port devices characterized by low insertion loss and low VSWR. Ferrite phase shifters have been realized in both reciprocal and nonreciprocal configurations and may also be characterized as latching or nonlatching depending upon whether continuous holding current must be supplied to sustain the magnetic bias field. The rotary-field phase shifter is a reciprocal nonlatching device.

The rotary-field phase shifter offers several advantages when compared with latching ferrite phase shifters which typically depend upon variations in permeability to effect a phase change by modifying the propagation constant. First, the rotary-field device is a true phase shifter exhibiting a modulo-360 phase characteristic as opposed to a variable line length device. Second, the rotary-field device uses a constant magnitude bias field which is rotated in space to obtain phase shift. This results in extremely low changes in insertion loss as the phase shift is varied since the characteristic impedance of the ferrite section is not changed when the bias field is adjusted. Third, the control characteristics of the device are determined by the application of currents to two orthogonal windings on the yoke. Phase accuracy is determined by the ratio of the control currents as contrasted with the establishing of a given flux level for latching phase shifters. This control characteristic also minimizes the effect of the shape of the magnetization curve and its variation with temperature.

The rotary-field phase shifter is the electronic equivalent of the rotary van phase shifter described by Fox [1]. A photograph of an S-band unit is shown in Fig. 1. Linearly polarized r-f energy propagating in the input and output rectangular waveguides is converted to circular polarization in a ferrite half-wave plate by the combination of a waveguide transition and a reciprocal quarter-wave plate. The half-wave plate is a nonreciprocal differential phase shift section whose angular orientation is controlled by the external magnetic bias field. The r-f signal receives differential phase shift of twice the relative rotation of the half-wave plate and is reconverted to the TE_{10} rectangular waveguide mode by another reciprocal quarter-wave plate and waveguide transition. Resistive film to absorb any cross-polarized energy is generally incorporated into the waveguide transitions. Since the half-wave plate need provide only 180 degrees of differential phase shift, minimum length of ferrite is utilized.

The device is not reciprocal in the strictest sense because signals propagating through the rotary-field phase shifter in opposite directions exhibit a fixed differential phase shift of 180 degrees. However, the phase changes imparted to signals traveling in opposite directions through the device are the same, and if the units are used in an antenna array, switching between transmit and receive is not required.

II. RF Design Considerations

Physically, the rotary-field phase shifter consists of a composite ferrite/dielectric rod which has been coated with thin metal layer to form a circular waveguide, a drive yoke which provides the rotatable magnetic field and a housing which generally incorporates the input and output waveguides. Cooling fins, as shown in the photograph of Fig. 1, can be machined in the housing to provide for increased power dissipation.

Since minimum r-f signal loss is almost always required in phase shifter design, the rod diameter is made as large as possible to minimize this loss. The upper frequency limit is determined by the onset of the TE_{21} circular waveguide mode. The rule of thumb for maximum rod diameter may be written

$$D_{max} = \frac{3.0}{f_h} \text{ inches}$$

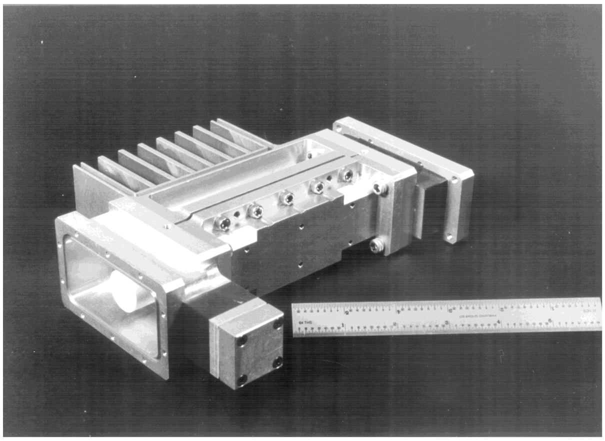

Fig. 1 Photograph of S-band phase shifter

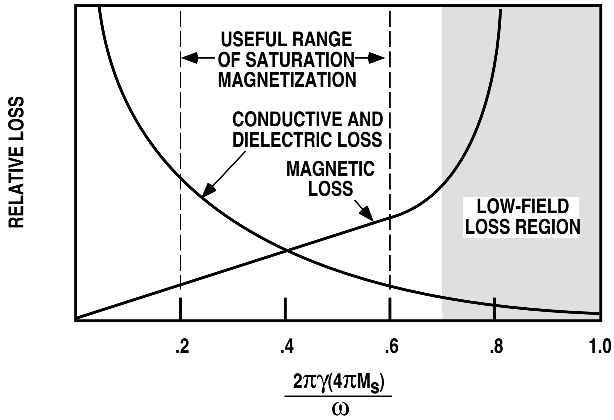

Fig. 2 Loss components as a function of normalized saturation magnetization

where f_h is the highest operating frequency in GHz. This rod diameter will support the TM_{01} circular waveguide mode, but this mode is weakly coupled to the dominant TE_{11} mode and any energy in the TM_{01} mode is absorbed by the resistive film.

The ferrite material is the other parameter which significantly affects r-f performance. Yttrium-iron garnet is used almost exclusively in these phase shifters because of the extremely low dielectric loss tangent and good power handling capability of garnets. The saturation magnetization in garnet may be easily controlled by aluminum substitution. Also, temperature compensation may be achieved by substituting gadolinium for some of the yttrium.

The amount of phase shift from a differential phase shift section is directly proportional to the saturation magnetization of the ferrite [2]. Hence, the length of the ferrite half-wave plate required to yield 180 degree phase shift at a given frequency is inversely proportional to the saturation magnetization. This means that the conductive loss and the dielectric loss which are directly proportional to length will vary inversely as the saturation magnetization. The magnetic loss on the other hand varies directly as the saturation magnetization since the magnetic loss tangent is proportional to the square of the saturation magnetization. The sum of these three loss will vary with the saturation magnetization exhibiting a fairly broad minimum, as shown in Fig. 2., which implies that the saturation magnetization may be selected on a basis other than insertion loss. Other prime considerations are length (i.e., size and weight), instantaneous r-f bandwidth and r-f peak power capability.

The peak power capability of the phase shifter is limited by the onset of sharply increased insertion loss once a critical r-f magnetic field intensity level is reached. For the garnet materials used for these phase shifters, the critical r-f power level is inversely proportional to the saturation magnetization [3].

The instantaneous r-f bandwidth of the device depends upon the performance of the waveguide transition, the reciprocal quarter-wave plate and the nonreciprocal half-wave plate. Return losses of the order of 20 dB are achievable for a two-section quarter-wave transformer operating over a 10 percent bandwidth when matching from air-filled rectangular waveguide to ferrite-filled circular waveguide. This bandwidth may be extended to 15 percent by allowing the return loss to increase. Larger bandwidths would necessitate using a three-section (or more) quarter-wave transformer. The reciprocal quarter-wave plate may be designed to operate over a large bandwidth [4] and seldom is a cause of bandwidth limitation. Within the bandwidth determined by the waveguide transition, the ferrite half-wave plate will limit the instantaneous r-f bandwidth. This limitation is caused by the differential phase between orthogonal axis not being exactly 180 degrees. All the circularly polarized r-f energy incident on the plate is not converted to the opposite sense of circular polarization. The r-f energy which remains copolarized is absorbed by the resistive film after it is reconverted to linear polarization. Thus, phase errors are converted to amplitude errors which is one of the reasons for the excellent phase accuracy of the device. Theoretical curves are given in Fig. 3 showing the insertion loss versus frequency for various values of the saturation magnetization over a twenty percent frequency bandwidth. A typical plot of insertion loss and return loss is given in Fig. 4 for an X-band device. The curves were generated by continuously scanning the phase shift angle while slowly sweeping across the frequency band.

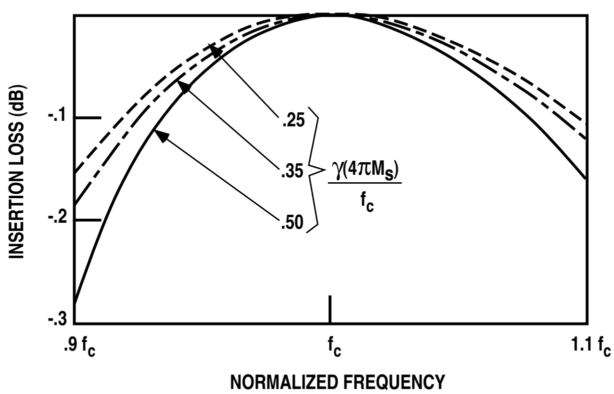

Fig. 3 Insertion loss vs. frequency for various saturation magnetization

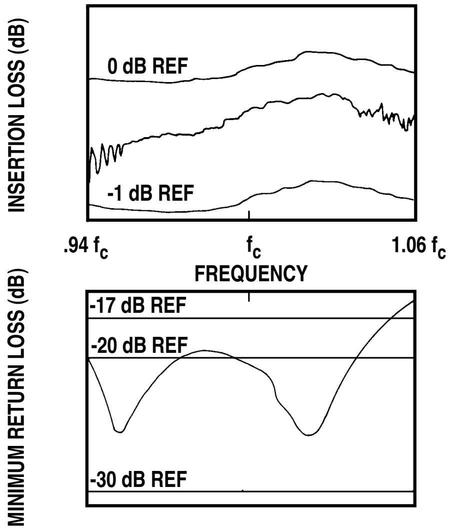

Fig. 4 Insertion loss and return loss for X-band phase shifter

It should be noted that this loss may be removed at any given frequency by changing the bias current to the unit and readjusting the half-wave plate to provide exactly 180 degrees of phase shift at that frequency. For systems operating over instantaneous bandwidths less than that determined by the matching structure, this compensation technique is often used.

III. Electrical Design Considerations

The ferrite half-wave plate uses a quadrupole field geometry [5] which must be rotated to effect phase shift. This is accomplished by fitting a ferromagnetic yoke over the half-wave plate portion of the ferrite/dielectric rod waveguide. The yoke has a number of slots in which are wound two sets of interlaced coils each of which generates a four-pole field. The two windings are referred to as the "sine" and "cosine" windings because of the patterns generated by the exciting currents. Applying a current $I_m \sin\theta$ to one winding and $I_m \cos\theta$ to the other winding results in the four-pole bias field being oriented at angle $\theta/2$ which yields a phase shift of twice the relative rotation of this angle from a prescribed reference.

The number of turns on the yoke is the design parameter which determines phase accuracy, switching time, control power and phase shifter diameter. The yoke must provide a field pattern which rotates smoothly as the coil currents are varied. Certain combinations of number of slots and number turns tend to minimize the error in the angular variation of the magnetomotive force. The table shown below illustrates this for a particular slot configuration:

NUMBER OF TURNS	58	73	89	127
MAXIMUM MMF ERROR	1.50	1.40	1.15	1.01

Experimentally, it has been verified that the phase accuracy tends to improve as the number of turns is increased although not in the same ratio as the improvement in the MMF error. Phase shifters constructed with the number of turns shown above have had RMS phase errors ranging from 1.5 degrees for the least number of turns to about 0.8 degrees for the greatest number of turns. Typically phase deviations from command state are shown in Fig. 5 when the phase shifter is controlled by monotonically increasing the phase (rotating the bias field in one direction) and then monotonically decreasing the phase (rotating the bias field in the other direction).

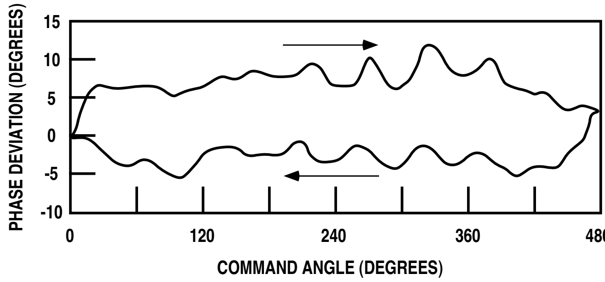

Fig. 5 Phase deviation from command state

If the phase states are to be accessed in a random fashion, the hysteresis effects shown in Fig. 5 have to be eliminated. This is done by applying a "back-up" angle to the phase shifter before applying the final phase command. In effect the back-up angle ensures that the final bias field is always approached from the same direction, thus closely approximating the conditions under which the curves of Fig. 5 were taken. However, if the back-up angle is not applied for a sufficient length of time, the phase accuracy will be less than the intrinsic phase accuracy of the device as shown in Fig. 6 for an X-band phase shifter.

The control power necessary to provide the magnetic bias field is inversely proportional to the number of turns in the control winding. This implies that a large number of turns are desirable in order to minimize this power requirement. The circuit time constant, on the other hand, is directly proportional to the number of turns, which would imply that the number of turns be held to a minimum since

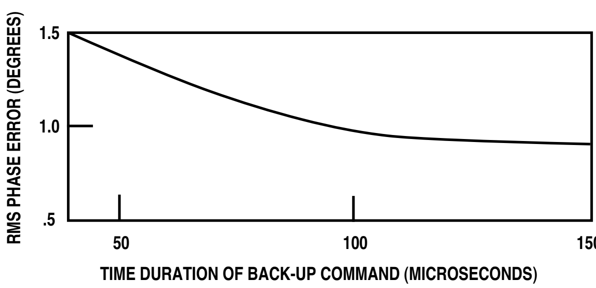

Fig. 6 Effect of backup angle duration on phase accuracy

small switching times are generally desirable. If there are no constraints on the phase shifter diameter, the number of turns is generally determined by the control power specification. If the switching time cannot be achieved with the specified control voltage, a high voltage “boost” supply can be used during the switching cycle, which increases the voltage per turn and results in faster switching. This method increases the complexity, and consequently, the cost of the driver.

If there are constraints on the phase shifter diameter, the number of turns will be dictated by the space available for wires in the slots of the yoke. For this case, the number of turns is maximized for the available space commensurate with selecting a winding pattern which achieves minimum error for the allowable number of turns. Figure 7 is a photograph of two different X-band phase shifters. The phase shifter on the right had no constraints on diameter while the one on the left was designed to be packaged side-by-side in a one-dimensional sscanning array application. The control power for the phase shifter on the right is 2.8 Watts (0.230 Amperes at 12 Volts) while the control power for the unit on the left is 4.8 Watts (0.4 Amperes at 12 Volts).

IV. Performance Characteristics

The performance characteristics of some rotary-field phase shifters are tabulated in Table 1. These are existing units which have been produced in more than prototype quantities. All of the units listed use either free convection cooling, forced air cooling or are attached to a cold-plate – – none incorporate liquid cooling.

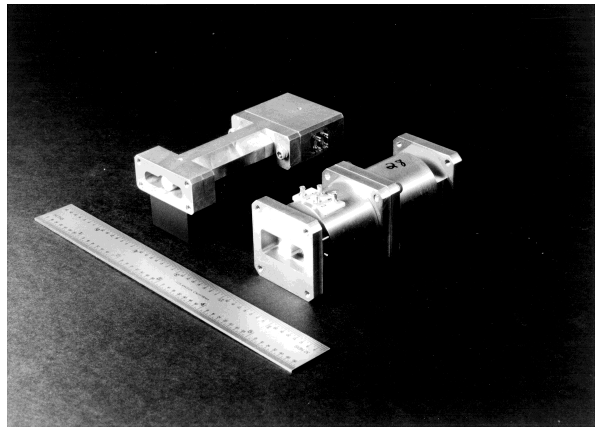

Fig. 7 Photograph of X-band phase shifter

V. Conclusions

The rotary-field ferrite phase shifter is a device well suited for application in single-axis electronic scanning arrays. Excellent phase accuracy and stability is achieved by employing two control windings on a drive yoke which are used to rotate the magnetic bias field. The device handles moderate to high power levels compatible with those experienced in single-axis scanning array and its weight is low enough to make it an attractive candidate for airborne, as well as ground-based arrays.

Table 1
Performance Characteristics
Rotary-Field Phase Shifter

PARAMETER	**FREQUENCY**			
	S-BAND	C-BAND	X-BAND	Ku-BAND
PERCENT BANDWIDTH	12.7	8.8	10.5	5.0
AVERAGE INSERTION LOSS (dB)	0.6	0.6	0.7	0.7
INSERTION LOSS MODULATION (dB)	0.3	0.3	0.3	0.3
MAXIMUM RETURN LOSS (dB)	-14.0	-15.6	-17.7	-17.0
PEAK RF POWER (KWATTS)	40	25	4	2
AVERAGE RF POWER (WATTS)	600	250	60	40
TYPICAL RMS PHASE ERROR (DEGREES)	1.0	1.0	1.0	1.0
SWITCHING TIME (μSECONDS)	300	250	200	200
SWITCHING TIME WITH BOOST (μSECONDS)	100	100	100	100
COIL CURRENT (MILLIAMPERES)	900	500	230	160
COIL RESISTANCE (OHMS)	1.0	3.0	9.5	14.0
SIZE (INCHES)	2.0 x 6.6 x 8.0	2.0 x 3.0 x 4.8	1.25 x 1.25 x 3.2	1.0 x 1.25 x 2.0
WEIGHT (OUNCES)	62	30	6	4
OPERATING TEMPERATURE RANGE (DEGREES CELSIUS)	0 TO 50	-20 TO 50	-40 TO 70	-40 TO 90

The insertion loss of the rotary-field phase shifter is relatively constant over a wide range of saturation magnetization of the garnet used for the differential half-wave plate. This allows a trade-off between half-wave plate length and peak r-f power capability, both of which decrease with increasing saturation magnetization. Another trade-off to be made is phase shifter outer diameter and control power to the drive yoke. As the diameter increases, the number of turns may be increased, lowering the control power.

VI. Acknowledgments

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VII. References

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