

Microwave And Millimeter-Wave Ferrite Phase Shifters

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Three ferrite phase shifters — the twin toroid, the dual-mode and the rotary-field — which have found widespread application at microwave frequencies are discussed. Performance characteristics of the devices are detailed. The useful frequency range of the devices, determined by available values of the saturation magnetization of the ferrite, is described.

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 are classed as either reciprocal or nonreciprocal, depending upon whether the variable differential phase shift through the device is a function of the direction of propagation. Further, ferrite phase shifters may be latching or non-latching, depending upon whether continuous holding current must be supplied to sustain the magnetic bias field. Phase shifters may be used in a variety of ways in microwave systems, but their application in electronic scanning antennas is the single most important factor influencing their development.

Three types of ferrite phase shifters are generally encountered in microwave circuits and systems. The twin toroid is a latching, nonreciprocal device; the dual-mode is a latching, reciprocal device and the rotary-field is a non-latching reciprocal device. All are constructed from ferrite materials which have a square hysteresis loop. The latching phase shifters use either a closed magnetic circuit or a magnetic circuit with very small air gaps. The relative permeability of the ferrite is controlled by adjusting the flux level existing in the closed magnetic circuit. These phase shifters effect a phase change by modifying the propagation constant of the transmission line which contains the ferrite. The rotary-field phase shifter on the other hand is a true phase shifter, as opposed to a variable line length device, since it realizes phase shift by rotating a fixed amplitude magnetic bias field. This results in a modulo-360 phase control characteristic as well as inher-

ently low phase error since the phase shift is controlled by the angular orientation of the bias field rather than the magnitude of the bias field. The angular orientation may be controlled easily and accurately by controlling the current into a pair of orthogonal windings [1].

Two factors influencing the frequencies for which physical realization of these phase shifters is practical are the device geometry and the saturation magnetization of the ferrite used to construct the device. Figure 1 shows the frequency variation of the various components contributing

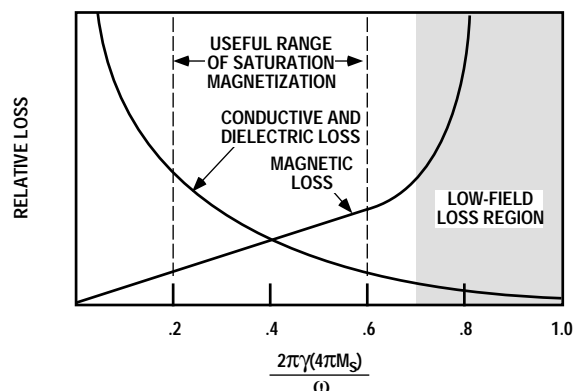


Fig. 1 Loss components as a function of normalized saturation magnetization

to the insertion loss of the phase shifter. The conductive and dielectric losses are directly proportional to length or inversely proportional to the saturation magnetization while the magnetic loss varies approximately directly as the saturation magnetization. The sum of these losses exhibits a fairly broad minimum value in the range

$$0.2 \leq \frac{\omega_m}{\omega} \leq 0.6$$

where $\omega_m = 2\pi\gamma(4\pi M_s)$, $\gamma = 2.8\text{MHz/Oe}$, $4\pi M_s$ is the saturation magnetization and ω is the microwave radian frequency. Above this range, low field magnetic loss generally precludes operation while below this range the device becomes excessively long, resulting in increased loss and weight. The rotary-field phase shifter has been realized from

S-band through Ku-band (2 GHz - 18 GHz). This design requires a large transverse quadrupole field be realized in a rod whose diameter decreases in direct proportion to an increase in frequency. Twenty gigahertz would seem to be the upper frequency limit for this device. The latching phase shifters have been realized from about 2 GHz to 94 GHz. Theoretical curves of insertion loss versus frequency are shown in Fig. 2 [2]. Experimental data at 60 GHz and 94 GHz agrees well with these curves.

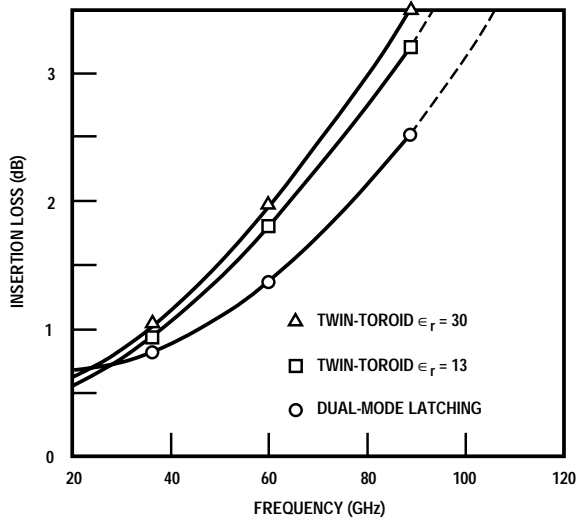


Fig. 2 Insertion loss versus frequency for latching ferrite phase shifters

II. LATCHING PHASE SHIFTERS

The first latching phase shifter used a toroidal geometry. The modern version of this device, the twin-toroid, is shown in Fig. 3. Analytical models have been developed by Ince and Stern [4] and Allen [5]. The correlation of experimental results with the theoretical analyses is extremely good.

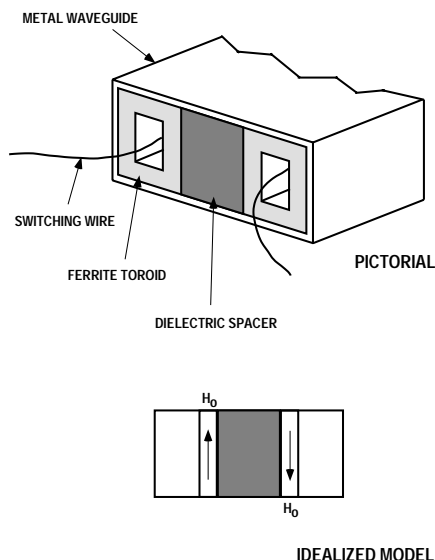


Fig. 3 Geometry of twin-toroid phase shifter

The dielectric spacer is used to concentrate the r-f energy in the center of the waveguide. The walls of the toroids, which contact the dielectric spacer, are located in those regions of the waveguide which support a circularly polarized magnetic field. Letting β_+ designate the propagation constant when a positive bias field saturates the ferrite and β_- be the same for negative bias field, the maximum amount of variable insertion phase per unit length is $(\beta_+ - \beta_-)$. Any amount of phase shift less than this is achievable by reducing the bias field level. The values of β_- and β_+ interchange with the direction of propagation.

One important characteristic of the twin toroid phase shifter is the extremely broad instantaneous r-f bandwidth achievable. Figure 4 is reproduced from Ince and Stern [4] and illustrates that the differential phase shift can be made to be independent of frequency with proper choice of design parameters. These phase shifters have been realized with bandwidths greater than an octave. Attention must be given to mode control in these devices since the switching wire is enclosed by the waveguide, thus allowing a TEM mode to propagate, as well as higher order LSE and LSM modes.

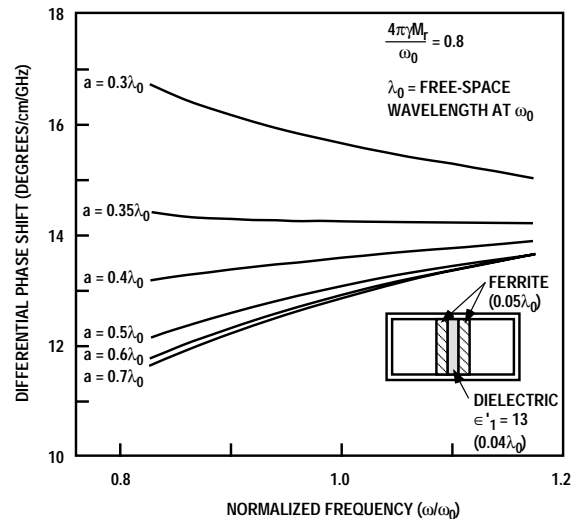


Fig. 4 Differential phase shift vs. frequency for twin-toroid phase shifter

A photograph of a twin toroid phase shifter in a waveguide housing is shown in Fig. 5. The toroids are located in the center of the structure where the housing size is reduced. Dielectric matching transformers are placed at both ends of the toroids to match into the air-filled, rectangular waveguide input and output ports. The switching wires are threaded through holes in the narrow walls of the waveguide and attached to posts for connection to the electronic driver.

The dual-mode phase shifter is shown in Fig. 6. This phase shifter uses either a circular or quadrantally symmetric ferrite rod which is metallized to form a ferrite-filled waveguide [6]. The cross-section must have this symmetry so that circularly polarized energy will propagate through it without change of field distribution. At either end of the rod, nonreciprocal, quadrupole-field ferrite polarizers are used to

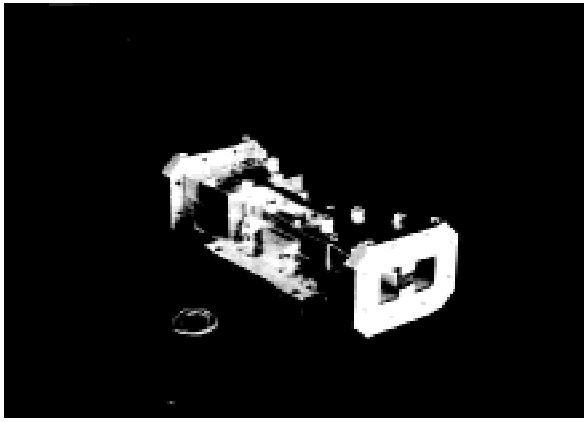


Fig. 5 Photograph of twin-toroid phase shifter

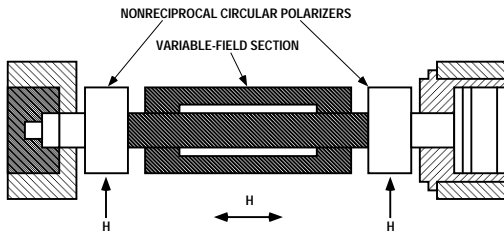


Fig. 6 Geometry of twin-toroid phase shifter

convert linearly polarized fields to circularly polarized fields and vice-versa. External latching yokes are fitted to the ferrite rod to provide a closed magnetic path for latching operation. Resistive films are incorporated in dielectric sections at both ends of the rod to absorb undesired cross-polarized fields. Linearly polarized energy incident on port 1 of the unit is converted to circular polarization by the quadrupole-field polarizer. This circular polarized wave has a rotating transverse magnetic field which interacts with the partially magnetized ferrite in the variable field section and receives an insertion phase dependent upon the magnitude and direction of the variable bias field. This may be described by a variable relative permeability ranging from μ_- for negative saturation to μ_+ for positive saturation. If β_+ is defined as the propagation constant for negative saturation, the variable insertion phase per unit length is $(\beta_+ - \beta_-)$. The circular polarization is reconverted to linear polarization by the second quadrupole-field polarizer and the resistive film absorbs any undesired sense of linear polarization that might occur because of small alignment errors. For signal transmission in the reverse direction, the quadrupole-field polarizer on the right converts incident linear polarization to the opposite sense of circular polarization in the variable field section. However, the same amount of phase shift is produced since the direction of propagation has also changed, which results in transverse-plane rotation of the r-f circularly polarized magnetic field in the same direction as before, and therefore, identical interaction occurs with the magnetized ferrite.

A family of dual-mode phase shifters is shown in Fig. 7 illustrating sizes of C-, X- and Ku-band units in metal housings. The C-band unit (on the right) is designed to be an element in a transmission lens and is complete with electronic driver. The X-band unit (on the left), also with electronic driver, is connected between a waveguide feed manifold and the radiating ground plane. Finally, the Ku-band device (center front) is designed to match into ridge waveguide on either end.

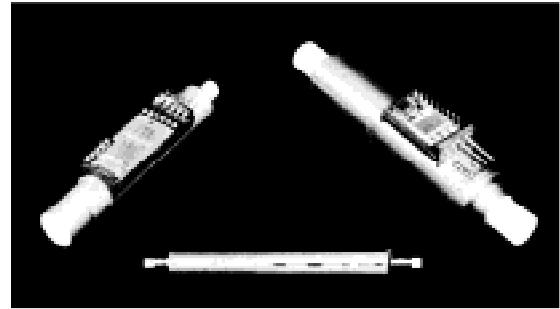


Fig. 7 Photograph of dual-mode phase shifters

III. CONTROL CHARACTERISTICS OF LATCHING PHASE SHIFTERS

Latching phase shifters are controlled by an electronic driver which regulates the flux level existing in the closed magnetic circuit. Changes in flux level required to compensate for changes in either frequency or temperature, are easily affected with this type of control. A typical hysteresis curve for a ferrite material is shown in Fig. 8. A stable reset condition is realized by driving the ferrite into saturation at one end of the loop or the other shown as points A and A' in Fig. 8. The coil current increases sharply when the ferrite becomes saturated. When the current reaches a predetermined value, the drive voltage is removed and the ferrite relaxes to the remanent value shown as points B and B' in Fig. 8. For the reciprocal dual-mode phase shifter, only one reset point is necessary, while for the nonreciprocal twin-toroid phase shifter both A and A' are useful as reset states since the flux in the core

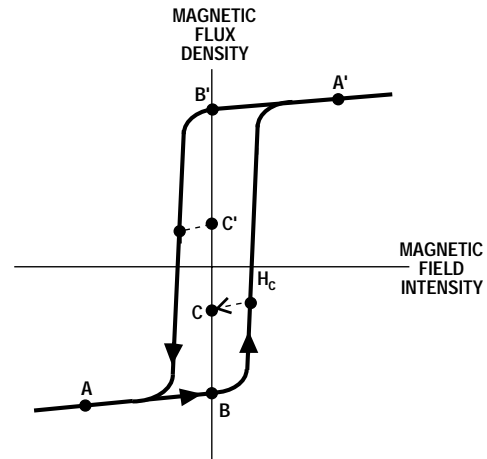


Fig. 8 Typical ferrite hysteresis loop

must be reversed for the different directions of propagation. The graph of Fig. 9 exhibits the RMS phase error versus reset current amplitude for a Ku-band dual-mode phase shifter. The data was obtained by randomly accessing a phase state and then resetting. The phase at the reset point was measured for a large number of phase states and the variation of reset phase was then calculated.

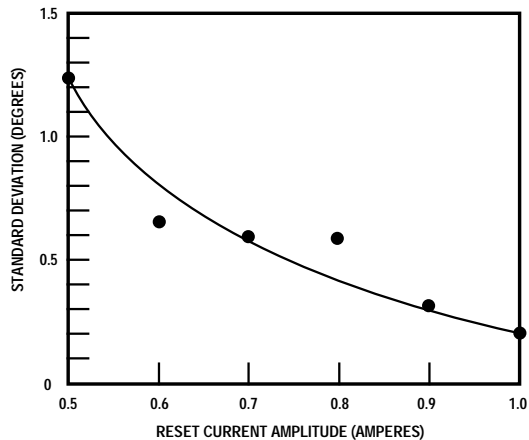


Fig. 9 Phase accuracy of reset state vs. current amplitude

To achieve a desired set state of the phase shifter, flux is metered out to the core in accordance with Faraday's Law

$$\Delta\phi = \frac{1}{N} \int_{t_0}^t u(t) dt$$

The simplest method of control is to apply a constant voltage for various lengths of time. Thus, if the voltage is constant,

$$\Delta\phi = \frac{V}{N} \Delta t$$

By controlling the time, Δt , the flux level is easily and accurately established. Normally, digital control is achieved by the conversion of an input digital data word to an output pulse whose duration is quantified with the smallest pulse width equal to $T/2^n$ where T is the maximum length of the set pulse and n is the quantization level.

A plot of differential phase shift versus data command to the electronic driver is shown in Fig. 10 for eight-bit quantization. A production lot of phase shifters will exhibit similar, but not identical, control characteristics. Rather than requiring all phase shifters to have identical control characteristics, a conversion table may be inserted between the data input and the driver and used to linearize the control characteristic. Accuracy is then limited by the number of calibration tables the user is willing to generate. For a production lot of 500 X-band phase shifter which were designed to meet a 5 degree RMS error specification, 46 tables were used. The same lot required 25 tables for 6 degree RMS error, 15 tables for 7 degree RMS error and only 10 tables for 8 degree RMS error.

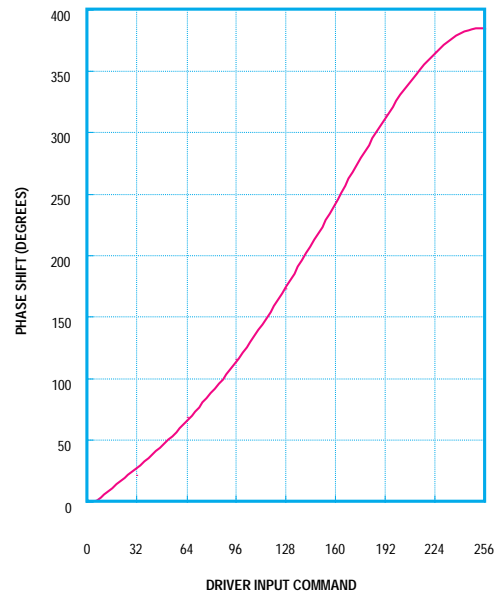


Fig. 10 Control characteristics of rotary-field phase shifters

IV. SWITCHING CONSIDERATIONS FOR LATCHING PHASE SHIFTERS

Switching time and switching energy are generally of key importance to users of ferrite phase shifters. The switching time is determined by the sum of the maximum reset pulse width, the dead time between reset and set and the maximum set pulse width. Normally, the maximum reset pulse width plus dead time is less than or equal to the maximum set pulse width which means the switching time equals $2T$ with T being the maximum set pulse width.

An equivalent circuit of a latching phase shifter during switching is given in Fig. 11. The resistance R_C and L_C are core resistance while R_{St} is the shorted-turn resistance which is infinite for the twin-toroid phase shifter but not for the dual-mode device. The core is primarily resistive during switching since the application of the voltage V results in a current of essentially constant amplitude dependent upon ferrite parameters, number of turns and core geometry.

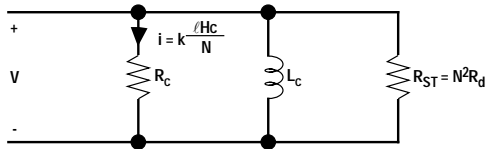
The switching energy may be written

$$W = W_H \left(1 + \frac{t}{T} \right)$$

where $W_H = 2B_r H_c \text{ Vol}$ is the energy required to switch the flux from negative remanence to positive remanence in the ferrite core, τ is the shorted-turn time constant, T is the maximum width of the set pulse, B_r the remanent flux density, H_c the coercive force and Vol is the volume of ferrite being switched. For the twin-toroid device τ is zero while for the dual-mode

$$\tau = \frac{SDB_r}{4\rho H_c}$$

with S being the thickness of waveguide walls, D the waveguide diameter, and ρ the resistivity of the waveguide walls.



R_c = EFFECTIVE RESISTANCE OF FERRITE CORE DURING SWITCHING
 L_c = EFFECTIVE INDUCTANCE OF FERRITE CORE DURING SWITCHING
 $R_{ST} = N^2 R_d$
 $N : 1$ TRANSFORMER

Fig. 11 Latching phase shifter equivalent circuit during switching

V. CHARACTERISTICS OF LATCHING PHASE SHIFTERS

Table 1 gives some of the important characteristics for the dual-mode phase shifter and the twin-toroid device. Insertion loss, switching energy and physical dimensions are listed for five frequency bands. Switching time is also given for the dual-mode device since the switching energy is a function of the switching time. Weights for the various elements may be calculated by multiplying the volume of the device by the density of ferrite — approximately 5 grams/cm³. The insertion loss and physical dimensions given in Table 1 are for the ferrite phase shifting element only. Overall length figures would be modified by the length of matching transitions and, if a housing is used, the housing dimensions will increase the cross-sectional dimensions given.

Return loss between -17 dB and -20 dB can be achieved over a ten percent bandwidth using two-section quarter-wave matching transitions between the ferrite loaded waveguide and rectangular air-filled waveguide. If more bandwidth is desired, the number of transformer sections may be increased at the expense of additional loss and weight.

The peak r-f power capability of the device is limited by the rapid increase in insertion loss once the r-f power exceeds a certain threshold value. Since the threshold may be increased by reducing the saturation magnetization, r-f peak power may be increased at the expense of additional weight.

VI. THE ROTARY-FIELD PHASE SHIFTER

A series of rotary-field phase shifters are shown in Fig. 12 for S-, C-, X- and Ku-band frequencies. Performance characteristics are tabulated in Table 2. All of the units have been produced in more than prototype quantities and all use either free convection cooling, forced air cooling are attached to a cold plate.

The rotary-field phase shifter is the electronic equivalent of the rotary vane phase shifter described by Fox [7]. 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

TABLE 1
CHARACTERISTICS OF LATCHING PHASE SHIFTERS

PHASE SHIFTER TYPE	PARAMETER	FREQUENCY (GHz)				
		10	17	35	44	60
TWIN-TOROID	LOSS (dB)	0.4	0.5	1.1	1.2	1.6
	SWITCHING ENERGY					
	(μJoules)	200	100	70	50	40
	WIDTH (INCHES)	0.270	0.190	0.090	0.080	0.058
	HEIGHT (INCHES)	0.180	0.125	0.065	0.053	0.038
	LENGTH (INCHES)	2.3	1.2	0.7	0.9	0.9
DUAL-MODE	LOSS (dB)	0.6	0.7	0.8	-	1.5
	SWITCHING ENERGY					
	(μJoules)	400	250	150	-	100
	SWITCHING TIME					
	(μSECONDS)	100	50	30	-	20
	OUTER DIAMETER (INCHES)	0.480	0.350	0.300	-	0.250
	LENGTH (INCHES)	1.6	1.5	1.45	-	1.2

NOTES : 1. ALL PARAMETERS ARE FOR THE FERRITE PHASE-SHIFTING ELEMENT ONLY, WHICH INCLUDES THE QUADRUPOLE POLARIZERS FOR THE DUAL-MODE UNIT.

2. SWITCHING ENERGY IS AVERAGED OVER ALL PHASE STATES.

3. TWIN-TOROID DATA PROVIDED BY ELECTROMAGNETIC SCIENCES INC., NORCROSS, GA.

4. DUAL-MODE DATA PROVIDED BY MICROWAVE APPLICATIONS GROUP, SANTA MARIA, CA.

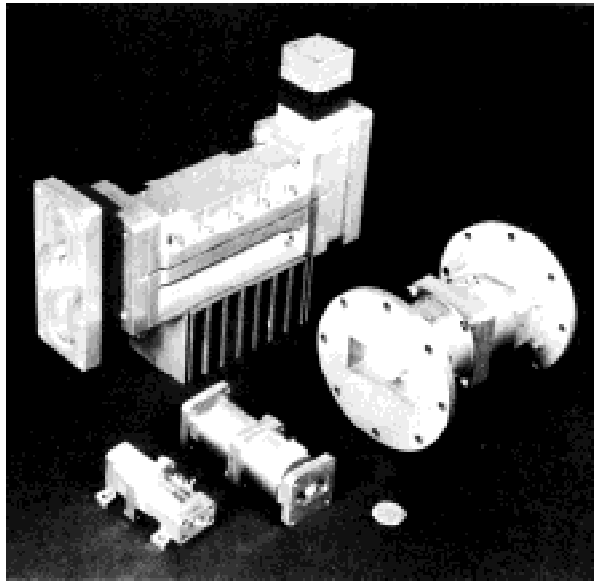


Fig. 12 Photograph of rotary-field phase shifters

twice the relative rotation of the half-wave plate is reconverted to the TE₁₀ 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.

Physically, the rotary-field phase shifter consists of a composite ferrite/dielectric rod which has been coated with a 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 photograph of Fig. 11, can be machined in the housing to provide for increased power dissipation.

Yttrium-iron garnet is used almost exclusively in these phase shifters because of the extremely low dielectric loss tangent and good power handling capability exhibited by garnets. For the garnets used, the peak r-f power level is inversely proportional to the saturation magnetization. Thus, r-f power handling capability may be achieved at the expense of greater length (weight).

The ferrite half-wave plate uses a quadrupole field geometry [8] 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 their 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.

TABLE 2
PERFORMANCE CHARACTERISTICS OF
ROTARY-FIELD PHASE SHIFTERS

PARAMETER	FREQUENCY			
	<i>S-BAND</i>	<i>C-BAND</i>	<i>X-BAND</i>	<i>KU-BAND</i>
<i>PERCENT BANDWIDTH</i>	12.7	8.8	10.5	5.0
<i>AVERAGE INSERTION LOSS (dB)</i>	0.6	0.6	0.7	0.7
<i>INSERTION LOSS MODULATION (dB)</i>	0.3	0.3	0.3	0.3
<i>MAXIMUM RETURN LOSS (dB)</i>	-14.0	-15.6	-17.7	-17.0
<i>PEAK RF POWER (KWATTS)</i>	40	25	4	2
<i>AVERAGE RF POWER (WATTS)</i>	600	250	60	40
<i>TYPICAL RMS PHASE ERROR</i> <i>(DEGREES)</i>	1.0	1.0	1.0	1.0
<i>SWITCHING TIME (μSECONDS)</i>	300	250	200	200
<i>SWITCHING TIME WITH BOOST</i> <i>(μSECONDS)</i>	100	100	100	100
<i>COIL CURRENT (MILLIAMPERES)</i>	900	500	230	160
<i>COIL RESISTANCE (OHMS)</i>	1.0	3.0	9.5	14.0
<i>SIZE (INCHES)</i>	2.0 x 6.6 x 8.0	2.0 x 3.0 x 4.8	1.25 x 1.25 x 3.2	10 x 125 x 20
<i>WEIGHT (OUNCES)</i>	62	30	6	4
<i>OPERATING TEMPERATURE</i> <i>RANGE (DEGREES CELSIUS)</i>	0 TO 50	-20 TO 50	-40 TO 70	-40 TO 90

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 small switching times are generally desired. 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 is used during the switching cycle which, to increase the voltage per turn, results in faster switching. This increases the complexity, and consequently the cost, of the driver.

VII. CONCLUSION

Three types of ferrite phase shifters have been discussed and their performance characteristics described. The latching phase shifters — the twin-toroid and dual-mode — have found extensive use in two-axis electronic scanning arrays, while the nonlatching rotary-field phase shifter has generally been used in single-axis scanning applications.

Good computational models exist for all phase shifters and computer-aided design is routinely used in phase shifter development. The rotary-field phase shifter has been produced in quantity in the microwave range, 2-20 GHz, but is probably not practical at frequencies above 20 GHz. The latching phase shifters have been realized up through 94 GHz. The latching phase shifters have been realized up through 94 GHz, but the insertion loss tends to degrade quite rapidly above 60 GHz.

VIII. ACKNOWLEDGMENTS

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IX. REFERENCES

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