IX-8. RECIPROCAL LATCHING FERRITE PHASE SHIFTER

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In a latching ferrite phase shifter the magnetic material is used in sample shapes such as toroids in which the magnetic flux can be closed onto itself. This has the advantage that in the operation of the device no holding current is required. The switching is performed by means of current pulses. According to their direction, these current pulses either reverse the direction of the magnetization or leave it unchanged.

Latching ferrite phase shifters are usually nonreciprocal, i. e., the phase shift through a given section of waveguide is different for the two directions of propagation. In many applications, however, a phase shifter with reciprocal characteristics has considerable advantages. The present paper shows how such a reciprocal, latching ferrite phase shifter can be constructed in rectangular waveguide.

For a rectangular waveguide containing ferrite slabs that are magnetized perpendicular to the waveguide axis the phase shift associated with TE_{0n} modes is reciprocal if the distribution of magnetization through the cross section of the waveguide is symmetric with respect to the center plane.[1] Figure 1 shows the cross section of a waveguide containing a symmetric distribution of magnetization, in this case a central ferrite slab and two oppositely magnetized toroids. In order to maintain reciprocity the magnetizations of both toroids must be reversed together.

The principle of operation of this device can be understood in the following way: Consider first the field distribution in the waveguide containing the two toroids, but not the center slab. Because of the well known field displacement effect of ferrites, the maximum of the electric field associated with the TE_{01} mode occurs not in the center of the guide, but over on one side of the guide. By the same token, the rf magnetic field at the center of the guide is elliptically (rather than linearly) polarized. If the direction of propagation is reversed the sense of polarization of the magnetic field in the center of the guide remains the same. If the magnetization of the two toroids is reversed, however, the sense of polarization of the magnetic field in the center of the guide is also reversed. Thus the phase shift induced by a magnetized slab of ferrite placed at the center of the guide is dependent upon the direction of magnetization of the two toroids.

A rigorous theoretical analysis of the waveguide shown in Fig. 1 is extremely difficult. The complexity is reduced to manageable proportions, however, if each of the two toroids is replaced by oppositely magnetized ferrite slabs as shown in Fig. 2. The characteristic equation of such a waveguide can readily be constructed by means of the transfer matrix formalism.[2] This characteristic equation can in principle be solved rigorously, but for the present purposes we found it convenient to use an approximate method, which is valid as long as the off-diagonal elements of the permeability tensor (κ) are reasonably small. The dielectric properties of the slabs are rigorously taken into account.

We denote the off-diagonal elements of the permeability of the toroids as $\pm j \kappa_1$, that of the center slab as $\pm j \kappa_2$. For loss-less media both κ_1 and κ_2 are real. The reciprocal, differential phase shift is proportional to the product $\kappa_1 \kappa_2$. Thus it changes sign if the magnetization of either the center slab or the toroids is reversed, but remains unchanged if both magnetizations are reversed.

Figure 3 gives some typical theoretical results concerning the dependence of the differential phase shift upon the thickness of the center slab. The quantity $\Delta \Gamma$ shown in Fig. 3 is related to the phase shift $\Delta\phi$ (in degrees) by

$$\Delta\phi = 360^{\circ} \Delta\Gamma \, \ell/\lambda_0 \qquad (1)$$

where ℓ is the length of the ferrite loaded waveguide section and λ_0 the free space wavelength. The reduced width and spacing D_1, D_2, A_1, and A_2 are related to the physical dimensions shown in Fig. 2 by

$$\begin{aligned} D_{1,2} &= d_{1,2}/2\pi \lambda_0 \\ A_{1,2} &= a_{1,2}/2\pi \lambda_0 \end{aligned} \qquad (2)$$

The highest curve in Fig. 3 has been terminated at that slab thickness D_2 at which the next higher order mode begins to propagate. We have also calculated the magnetic and dielectric contributions to the insertion loss.

Three experimental devices have been tested at frequencies between 8.7 and 10.8 GHz. In all three cases waveguides of reduced cross section [width 0.510 inch, height 0.310 inch] were used. The ferrite loaded section was 1.75 inch long. The dimensions of the toroids and the center slab were such as to correspond to the three cases considered in Fig. 2 at a frequency of 9.4 GHz and taking $D_2 = D_1$. Yttrium-Iron garnet with a remanent magnetization ($4\pi M_r$) of approximately 1000 gauss was used both for the toroids and the center slabs. Thus the value of κ appropriate at 9.4 GHz is $\gamma 4\pi M_r/\omega \simeq 0.3$.

The differential phase shifts measured on the three devices are summarized in Table 1, together with the theoretically expected values. In view of the approximate nature of the calculation the agreement is quite good.

In the first two devices the differential phase shift was found to have a considerable non-reciprocal component. We attribute this to misalignment of the toroids and the center slab in the guide. In the third device the alignment was done very carefully. Even then the differential phase shift was found to have a small non-reciprocal component (of the order of 7°).

Only preliminary measurements of the insertion loss have so far been made. For the third device the insertion loss at 9.7 GHz was 0.8 db. This is considerably higher than expected theoretically on the basis of the measured magnetic and dielectric loss factors ($\epsilon''/\epsilon' \simeq 5 \times 10^{-5}$, $\mu'' \simeq 5 \times 10^{-4}$).

TABLE 1. RECIPROCAL, DIFFERENTIAL PHASE SHIFT OBSERVED IN THREE EXPERIMENTAL LATCHING PHASE SHIFTERS

Device	$\Delta\phi\|_{theor.}$ at 9.4 GHz	$\Delta\phi\|_{ex}$ at 8.7 GHz	9.4 GHz	9.7 GHz	10.8 GHz
1	8.1°		7°		
2	18.9°		19.5°		
3	38.7°	28°		35°	13°

REFERENCES

1. See for instance, B. Lax and K. J. Button, "Microwave Ferrites and Ferrimagnetics," McGraw-Hill Book Co., Inc., New York (1962).
2. W. H. von Aulock, ed., "Ferrite Devices for Microwave Applications," Prentice-Hall, Englewood Cliffs, New Jersey (to be published).

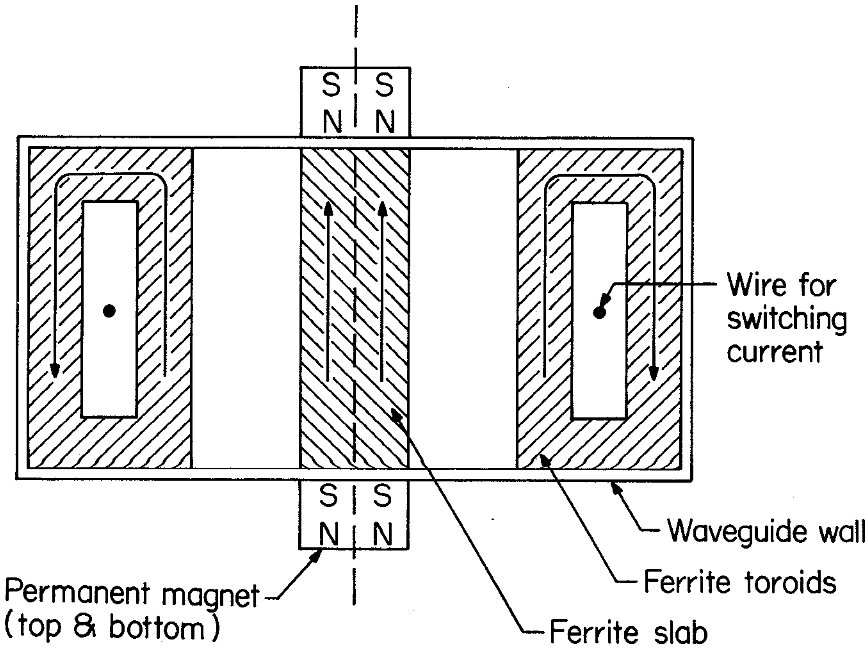

Figure 1. Cross Section of a Rectangular Waveguide Containing a Central Ferrite Slab and Two Symmetrically Positioned Toroids (tubes). Reversal of the Magnetization of the Toroids by Means of a Current Pulse Through the Switching Wire Produces a State with a Different (reciprocal) Phase Shift.

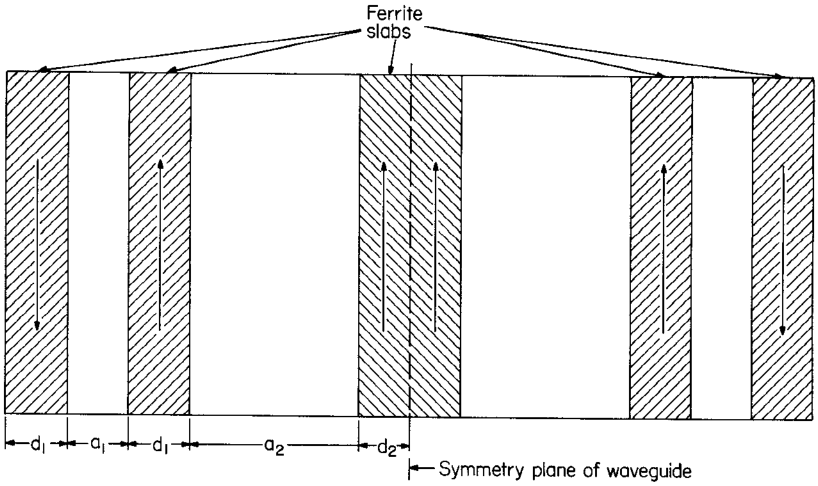

Figure 2. Cross Section of a Rectangular Waveguide Containing Five Ferrite Slabs. The Propagation Characteristics of this Waveguide are Expected to be Quite Similar to Those of the Waveguide Shown in Figure 1.

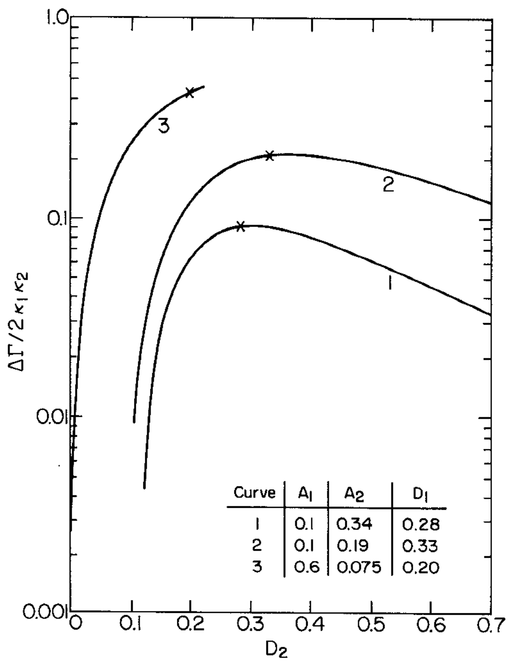

Figure 3. Differential Phase Shift (in reduced units) Versus Thickness of the Central Ferrite Slab (in reduced units) for Three Sets of Slab Thicknesses and Spacings, Assuming $\epsilon = 16$. The Three Crosses Correspond to the Configurations Used in Three Experimental Devices (see table 1).

HENDRICK BOSMA, author of the following paper, is being awarded the 1965 Microwave Prize of the IEEE G-MTT at the 1966 G-MTT Symposium Banquet, with the following citation:

" For a very significant contribution to the field of endeavor of the IEEE G-MTT in his paper entitled 'On Stripline Y-Circulation at UHF' published in the IEEE Transactions MTT-12, January 1964. The paper was an exceptionally well worked-out and useful treatment of an important subject."