IX-5. A RECIPROCAL TEM LATCHING FERRITE PHASE SHIFTER

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Considerable work has been done previously on latching ferrite phase shifters of the nonreciprocal variety. However, the requirement herein for reciprocity imposes new design problems and demands new thinking about switching techniques.

Reciprocal ferrite phase shifters have been known for a long time, and a great amount of work has gone into the development of suitable strip line and waveguide structures for such devices. However, to satisfy the latching and fast switching requirements of interest here, it is clear that ferrites with closed magnetic paths should be employed, and that these ferrites should have good square loop properties. To satisfy the reciprocal requirement, these ferrites must be utilized in appropriate microwave configurations similar to those which have been studied for more conventional reciprocal phase shifters.

In the nonreciprocal latching ferrite phase shifter a change in phase shift is usually accomplished by switching between two opposite collinear magnetization states for which the magnitude of the magnetization is the same (e.g., between two opposite "saturated" remanent states on a single hysteresis loop). It is important to realize, however, that if the phase shifter is to be reciprocal, the switching must be accomplished between two orthogonal (or at least noncollinear) magnetization states, or between two magnetization states of different magnitudes. This is true because in a reciprocal structure simple reversal of magnetization (with no change in magnitude) is equivalent to reversal of direction of propagation, and this, by definition, produces no change in phase shift.

The words "orthogonal switching" or "orthogonal technique" are used to refer to the first switching process, in which the magnetization is switched from a remanent value Mr_a in some given direction to a new remanent value Mr_b in a different (usually orthogonal) direction. The process of switching then does not involve simply switching around a single hysteresis loop, but the energy requirements and switching times for this orthogonal switching technique will be similar to those requirements for switching around a single hysteresis loop. It should be pointed out that this method of switching does not require a current pulse of controlled magnitude; rather, it lends itself to fast switching since arbitrarily large pulses can be applied.

To refer to the other method of switching for reciprocal devices, i.e., switching between two magnetization states of different magnitudes, the words "magnitude switching" may be employed. There are at least three methods of magnitude switching which may be called by the names "controlled current switching," "biased switching," and "switching by demagnetization" ("ringing" technique of switching). The controlled current technique, as applied to a reciprocal latching phase shifter, would consist of switching from, say, a selected saturated reference state to some other non-saturated (collinear) state of magnetization by means of a controlled pulse of magnetic field. Changing from one phase shift to another would normally require two pulses; the first "resets" the magnetization in the reference state, after which a new controlled pulse would set the magnetization at the desired new level. Switching time to the reference state can be fast, since large currents can be applied; but the minimum time of switching to the new magnetization state would be determined by material constants, since the second pulse is limited in value. In the case of biased switching, a biasing magnetic field equal to the coercive field is applied to the toroidal sample. A large positive pulse of short duration, producing a field in the same direction as the biasing field, switches the magnetization rapidly to a positive, almost-saturated value. A change in phase shift is accomplished by applying a large negative pulse which initially reverses the magnetization; after this negative current pulse passes, the magnetization is then driven back to zero by the positive biasing field. Here again the switching speed is limited; furthermore a constant biasing current is required, and the negative current pulse width must be limited to obtain moderately high speeds. Finally, in the "ringing" technique of switching, the magnetization is set at some (nearly saturated) remanent value by application of a large pulse of current. To accomplish a change in phase shift, the magnetization is reduced to zero by switching around successively smaller hysteresis loops, i.e., by "ringing" down. Clearly this process cannot be made very rapid, and energy requirements are increased. It should be clear that the electronic driver design will be somewhat more complicated for all types of magnitude switching than for orthogonal switching.

A reciprocal TEM latching phase shifter could probably be constructed with structures which are basically nonreciprocal, by using for each bit two equal toroidal ferrite elements, oppositely magnetized and placed either one above the other or in tandem. These structures appear to have some disadvantages including the requirement that the bit pairs be carefully balanced over the required bandwidth and temperature ranges; they also lend themselves naturally to magnitude switching (discussed above).

The approach here has been a more direct one of employing a configuration amenable to orthogonal switching, with its inherent simplicity, between two orthogonal magnetization states each of which is reciprocal, but which exhibit different phase shifts. The basic configuration used here is illustrated in Figure 1. The ferrite is driven into saturation in closed magnetic paths for both states, comprising longitudinal and transverse magnetization as illustrated. Since the effective permeability of the ferrite is different in these two states, the phase shift thus changes; since both states are reciprocal, the device is reciprocal.

In a number of previous investigations[1], the predictions of the theory of propagation of electromagnetic waves in (fully loaded) parallel plane waveguides have been used with considerable success in interpreting the operation of (nonlatching) longitudinally magnetized strip line devices. According to this theory[2], the propagation constant of the Quasi-TEM mode in longitudinally magnetized parallel plane waveguide is given by

$$\Gamma_L = j\omega\sqrt{\epsilon\mu_o\mu_{eff}} \tag{1}$$

where

$$\mu_{eff} = \frac{\mu^2 - k^2}{\mu} \tag{2}$$

Here μ and k are the usual components of the intrinsic permeability tensor. In the case of interest here, with zero applied field and magnetization M_r, the real part of μ_{eff} is given by the equation

$$\mu'_{eff} \doteq 1 - \frac{(\gamma 4\pi M_r)^2}{\omega^2 + \frac{(\gamma \Delta H)^2}{4}} \tag{3}$$

where γ is the gyromagnetic ratio for the ferrite and ΔH is the line width.

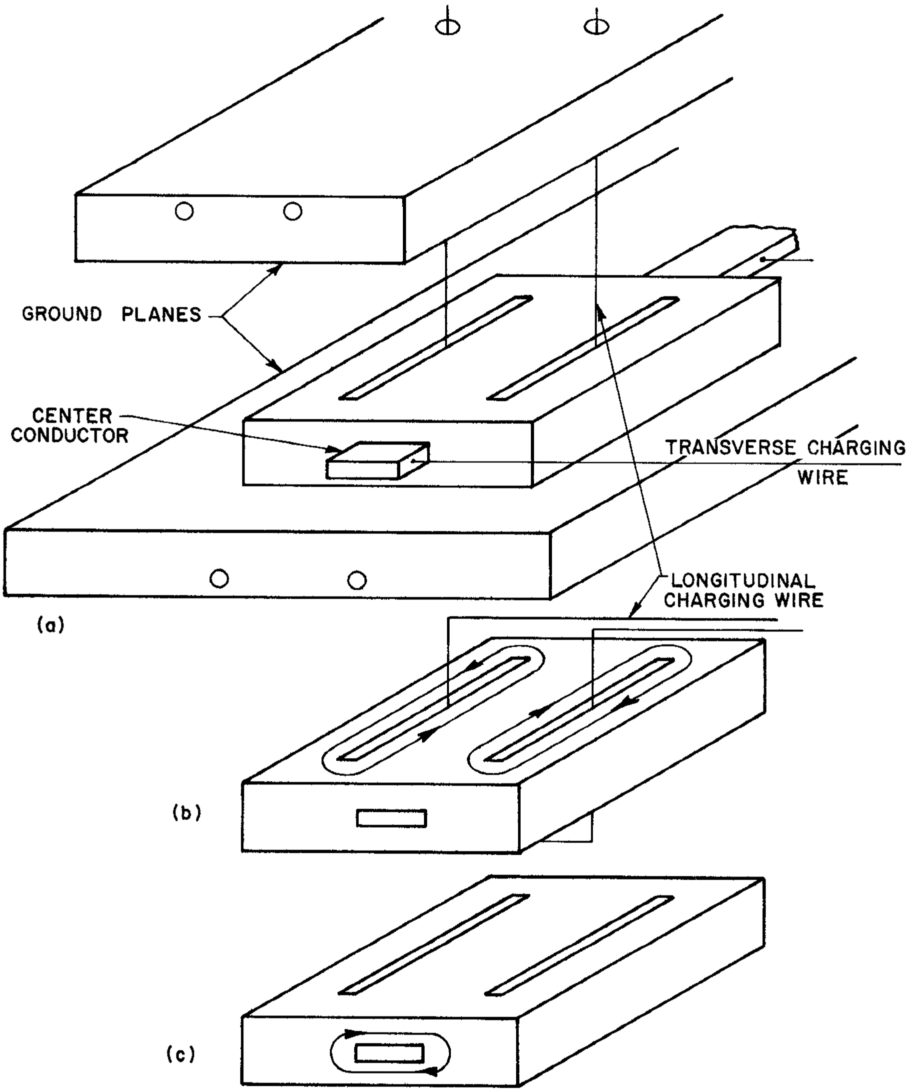

Figure 1. Basic TEM reciprocal phase shifter design.
(a) The composite structure
(b) Ferrite bit longitudinally magnetized
(c) Ferrite bit transversely magnetized

In the transversely magnetized state (Figure 1), the dc magnetization is essentially parallel to the RF magnetic field which exists in the normal TEM mode; thus it seems reasonable to take for the propagation constant simply that of the unmagnetized ferrite loaded line (the ferrite behaves like a dielectric material). Using equation (1) to describe the longitudinal state, the variation in phase shift obtained by switching from a transverse to longitudinal state then becomes

$$\Delta\phi = (\beta_T - \beta_L) L_{eff} \doteq \frac{360}{\lambda_o} \sqrt{\epsilon_r} \, (1 - \sqrt{\mu'_{eff}}) L_{eff} \qquad \text{(degrees)} \qquad (6)$$

provided $\mu'_{eff} >> \mu''_{eff}$. Here L_{eff} is some value between the actual length of the ferrite sample and the length of the longitudinal slots in the sample.

Since the device operates by switching the ferrite between two states with different permeabilities, impedance matching requires some compromise between the two states. Thus far, this problem has been adequately handled by use of dielectric quarter wave transformers designed to match to the geometric mean of the impedances presented in the two states.

Some early results obtained by C-band with a ferrite sample cut from a single two-inch piece (the center hole was made with an ultrasonic grinder) are shown in Figure 2. A figure of merit of approximately 100 deg/db was obtained. A small amount of nonreciprocity (approximately 5°) was observed and radiation problems were present. Investigation suggested that many of the difficulties (high insertion loss, erratic VSWR, nonreciprocity, radiation) arose from imperfect fit between the ferrite, with its high dielectric constant, and the center conductor. Thus a number of experiments were made on phase shifters using several variations (Figure 3) on the basic geometry in an attempt to obtain a more perfect fit, with the results generally supporting the initial assumption. This investigation has led at the present time to the structure indicated by the inset in Figure 4, where the center hole has been made oversize deliberately, with teflon spacers (having a low dielectric constant) used to mask the slight variations in spacing caused by imperfect surface grinding and machining. Experimental results obtained with this configuration, shown in Figure 4, are very much improved over the earlier work. Nonreciprocity is absent (less than 1°, the accuracy of measurement), and a figure of merit of 212 deg/db is obtained. This would suggest that a 337.5° four-bit reciprocal phase shifter could be constructed with approximately 1.6 db of loss. Experiments are continuing, and a complete four-bit phase shifter is under construction. Switching time for this phase shifter is less than 1 microsecond; switching energy requirements for a one-piece, two-inch ferrite piece (approximately 180° bit) is 20 microjoules when switching from longitudinal to transverse states, and 47 microjoules when switching the other way. For the "two-piece" sample illustrated in the inset of Figure 4, the switching energy is somewhat higher.

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[1] For example, see C.E. Fay, "Ferrite switches in coaxial or strip transmission line," Trans.IRE MTT-10, 455(1962). "Final Report for UHF Phase Shifter," Contract No. AF19(604)-6171, 15 March 1961, Solid State Electronics Department, Motorola, Inc., Scottsdale, Arizona.

[2] H. Suhl and L.R. Walker, "Topics in guided wave propagation through gyromagnetic media," Part 3, Bell Sys. Tech. J. 33, 1133 (1954).

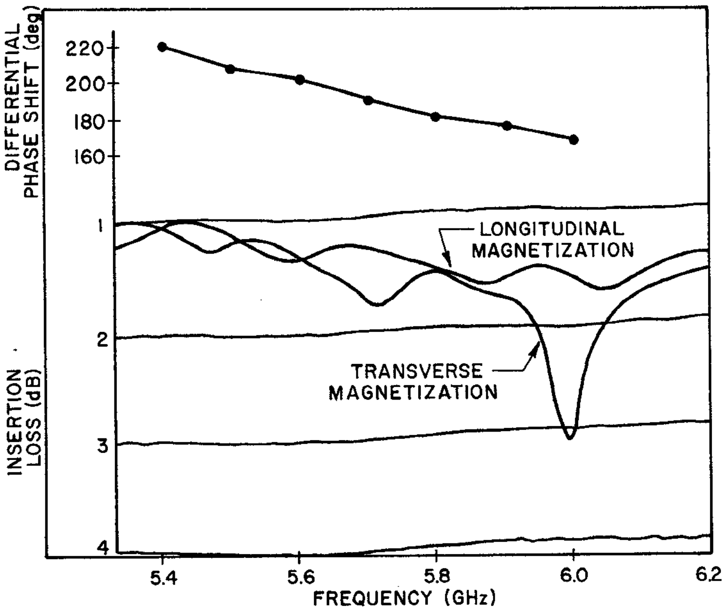

Figure 2. Reciprocal Phase Shift and Insertion Loss observed with early "single-piece" ferrite sample, two inches long. Ferrite material was TT 1-105.

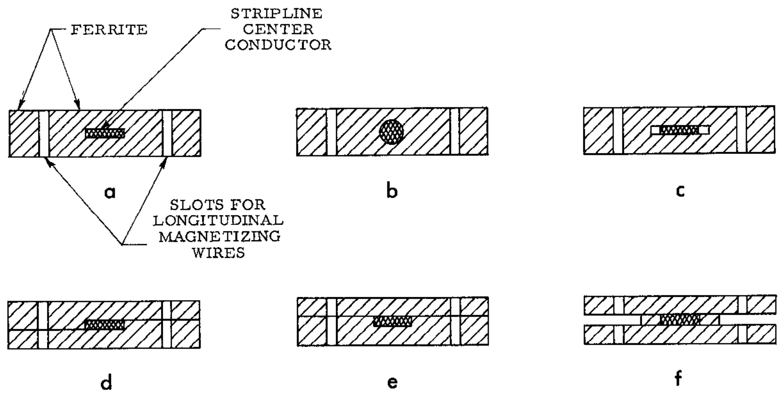

Figure 3. Illustration of various ferrite sample configurations investigated. View is cross-section of ferrites having the general configuration of Figure 1. Samples (a, b, c) are made from one piece, with center hole being made with ultrasonic grinder. Samples (d & e) illustrate "two-piece" construction with surface grinder. Sample (f) illustrates "four-piece" construction with surface grinder.

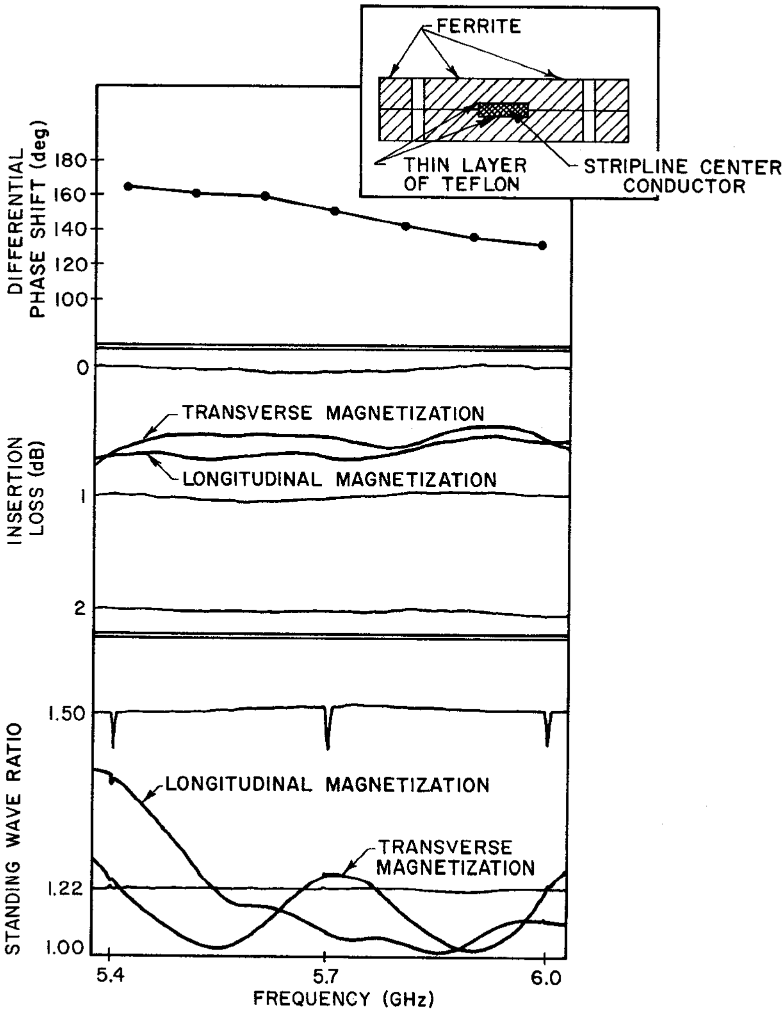

Figure 4. Experimental results observed on strip line structure with ferrite configuration shown in inset. Ferrite sample was TT 1-105, two inches long. Phase shift is reciprocal.