causing the point to move counterclockwise around the Smith Chart. When the chopper is completely closed, the net susceptance becomes infinite, and this position is described by the point Y_{sc}. Hence the total phase shift is equivalent to twice the length of line $Y_{s1}-Y_{sc}$ or proportional to $(\lambda_g/2)-s$.

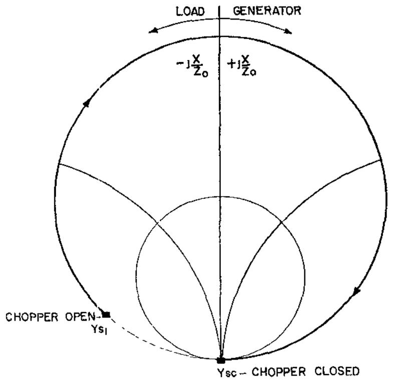

Fig. 3—Smith Chart representation illustrating the operation of the phase shifter.

It is not difficult to demonstrate that, if one provides a chopper which is equivalent to an inductive iris (negative susceptance), then the phase shift would be equivalent to twice the length of line $Y_{s1}-Y_{sc}$ measured in the opposite direction around the chart. In this case the amount of phase shift is proportional to the stub length s.

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Rectangular Waveguide Switches*

Introduction

Since the first disclosure by Reggia and Spencer[1] of the rectangular waveguide phase shifter, a number of investigators have presented qualitative analyses describing observed performances.[2–4] In general, these authors agree on two phenomena that occur. First, upon application of a longitudinal magnetic field to the ferrite (phase-shifter geometry shown in Fig. 1), there is a "trapping" process whereby the RF field is increasingly concentrated in the ferrite acting as if it were a "dielectric" waveguide. Second, there is a mode-conversion process that takes place simultaneously (probably a circularly polarized wave in the ferrite rod) that gives rise to an electric-field component in the ferrite region orthogonal to the electric field in the empty waveguide (TE_{10} mode).

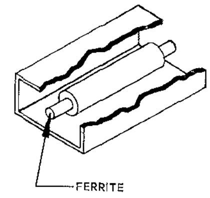


Fig. 1—Reggia-Spencer rectangular waveguide phase shifter geometry.

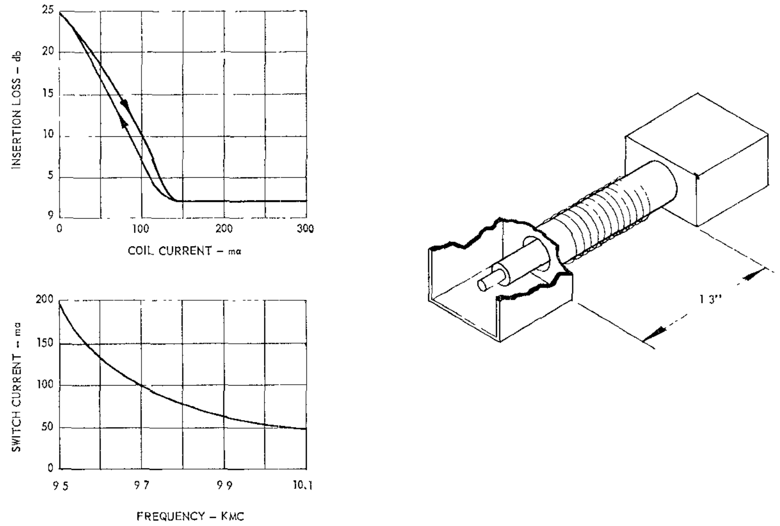


Fig. 2—Insertion loss vs coil current for reactive switch, normally off. Ferrite R-1, 0.260-inch diameter ×2.0 inches long. Cutoff guide section, 1.3 inches long ×0.4-inch diameter. Frequency is 9.6 kMc. Insert shows frequency sensitivity of switching current for minimum loss.

It is possible to utilize these two effects to design a number of different reactive and absorption switches. It is the purpose of this paper to relate these devices to the phase-shifter phenomena and thus classify them. It is also desired to present preliminary experimental and behavioral data.

Types of Switches

1) *Reactive Switch, Normally Off:* Fig. 2 shows the geometry of the reactive switch.[5] Its operation depends upon the "trapping effect" mentioned earlier. Since the small tube containing the ferrite is normally at "cutoff," there is no energy propagation. When the magnetic field is applied, the energy is trapped in the ferrite and propagates through the cutoff section with low insertion loss. The input and output waveguides can be either in-line or crossed. This switch is similar to the tetrahedral junction described by Weiss[6] and Caswell.[7]

2) *Reactive Switch, Normally On:* Fig. 3(a) shows a reactive switch which is normally on. It is constructed with a thin metal septum, normal to the electric field of the dominant mode, soldered to the waveguide narrow-wall and extending to the ferrite in close proximity. With the absence of an applied field, energy is transmitted with low insertion loss. When a field is applied, the "mode-conversion" process takes effect, and an orthogonal electric-field component is generated so that the energy is reflected. The performance of the reactive switch is shown in Fig. 3(b).

3) *Absorption Switch, Normally On:* The switch shown in Fig. 3 is easily modified into an absorption switch by replacing the thin metal septum with a thin sheet of resistive material. The absorption switch is shown in Fig. 4(a) and its performance is plotted in Fig. 4(b). This switch would normally have a low VSWR for all coil currents. Reggia[8] has recently suggested a switch of this type. This switch design splits the ferrite and sandwiches the lossy material between the ferrite halves. In the design of Fig. 4, a resistive material was mounted close to the ferrite.

* Received by the PGMTT, May 8, 1961.

[1] F. Reggia and E. G. Spencer, "A new technique in ferrite phase shifting for beam scanning of microwave antennas," Proc. IRE, vol. 45, pp. 1510–1517; November, 1957.

[2] P. A. Rizzi and B. Gatlin, "Rectangular guide ferrite phase shifters employing longitudinal magnetic fields," Proc. IRE., vol. 47, pp. 446–447; March, 1959.

[3] A. Clavin, "Reciprocal ferrite phase shifters in rectangular waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, p. 334; July, 1958.

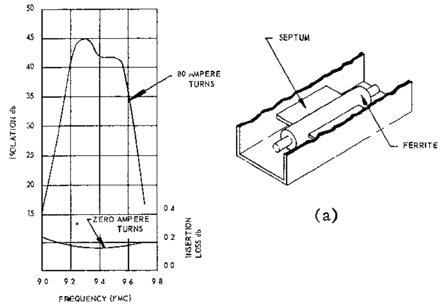
[4] Jerold A. Weiss, "A phenomenological theory of the Reggia-Spencer phase shifter," Proc. IRE, vol. 47, pp. 1130–1137; June, 1959.

[5] A. Clavin, "Problems Associated with Rectangular Waveguide Phase Shifters," presented at PGMTT Natl. Symp., San Diego, Calif.; May 9–11, 1960.

[6] J. A. Weiss, "The tetrahedral junction as a waveguide switch," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 120–121; January, 1960.

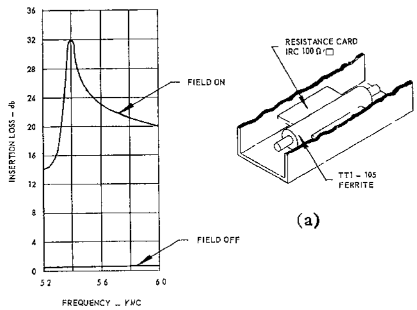
[7] P. A. Caswell, "Performance of Tetrahedral Junction Waveguide Switches," presented at the 6th Symp. on Magnetism and Magnetic Material, New York, N. Y.; November, 14–17, 1960.

[8] F. Reggia, "A new broadband absorption modulator for rapid switching of microwave power," Internatl. Solid State Circuits Conf., University of Pennsylvania, Philadelphia, Pa.; February, 1961.



(b)

Fig. 3—Two-port reactive switch, normally on, utilizing mode-conversion properties of magnetized ferrite.



(b)

Fig. 4—C-band absorption switch, normally on.

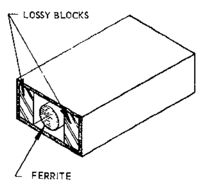


Fig. 5—Absorption switch, normally off. Field off, high insertion loss. Field on, low insertion loss.

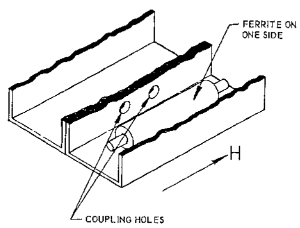


Fig. 6—Proposed variable coupler. With field applied, coupling to auxillary guide is reduced.

This indicates that there is a considerable field outside the ferrite even when saturated.

4) *Absorption Switch, Normally Off:* This configuration has not been fabricated as yet, but in principle should work well. The switch conception is illustrated in Fig. 5 and is similar to the reactive switch of Fig. 2. In this switch, the metal is replaced by lossy material so that, with zero field applied, most of the energy is absorbed. With an applied field, the RF energy is trapped to the ferrite and passes through the material with low insertion loss.

5) *Variable Coupling Devices:* A pair of coupled waveguides, one of which contains the phase-shifter geometry, is depicted in Fig. 6. When a field is applied, the energy is trapped in the ferrite and changes the coupling coefficient.

Conclusions

The suggested types of switches have a number of features which make them valuable. First, the magnetic field required is low, thus facilitating rapid switching. Second, they cannot be over-driven as in a Faraday rotation switch. Once saturated, additional field has little effect on the passage or reflection of RF energy. Excellent ratios of isolation to insertion loss can be obtained.

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Comments on "Stepped Transformers for Partially-Filled Transmission Lines"*

The use of a lumped equivalent circuit for the transverse section of a waveguide has been used to determine the cutoff frequency of ridged guide.[1,2] In essence, the transverse section of the guide is equated to an LC tank and the resonant frequency of the tank is determined by the usual formula. Sullivan and Parkes[3] have extended this method to the analysis of a ridged guide partially loaded with dielectric. They account for the additional capacitance introduced by the dielectric and include this capacitance as part of the LC tank to be analyzed for the resonant frequency. While the simplified lumped-network equivalents are always desirable in analyzing microwave networks, we should be wary of overgeneralizing them. In the case of dielectric slab loading in a waveguide, the location of the added capacitance as well as its magnitude has an effect in determining the cutoff frequency. (This can also be said of the discontinuity capacitance at the edge of a ridge.) Note how a dielectric slab when centered in a rectangular waveguide will lower the cutoff frequency far more than when flush with the sidewall.[4] This is not accounted for in the LC tank equivalent. The effect of each increment of capacitance due to each lamina of dielectric will be largely determined by the distance from the lamina to the short-circuit walls. Therefore, the author believes that the case of a partially dielectric-loaded guide can only be genuinely analyzed by the transverse resonance method or by some other method which accounts for the distributed parameters involved.

Another point for consideration in analyzing dielectric slab-loaded guide is the relationship between the guide wavelength and the cutoff wavelength—or rather the lack of relationship. Formulas for guide wavelength are based upon the right triangle relationship that exists between the propagation constants k_{0,κ_t,κ_g}. These are, respectively, the propagation constants for free space, for the waveguide transverse direction, and for the waveguide longitudinal direction.

$$k_0^2 = \kappa_t^2 + \kappa_g^2, \qquad (1)$$

where

$k_0 = 2\pi/\lambda_0$, λ_0 = wavelength of the traveling wave in free space,

$\kappa_t = 2\pi/\lambda_t$, λ_t = transverse resonant wavelength,

$\kappa_g = 2\pi/\lambda_g$, λ_g = guide wavelength.

* Received by the PGMTT, July 19, 1960.

[1] S. Ramo and J. R. Whinnery, "Fields and Waves in Modern Radio," John Wiley and Sons, Inc., New York, N. Y., 2nd ed., pp. 409–410; 1953.

[2] T. S. Chen, "Calculation of the parameters of ridge waveguides," IRE Trans. on Microwave Theory and Techniques, vol. MTT-5, pp. 12–17; January, 1957.

[3] D. J. Sullivan and D. A. Parkes, "Stepped transformers for partially filled transmission lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 212–217; March, 1960.

[4] N. Marcuvitz, "Waveguide Handbook," McGraw-Hill Book Co., Inc., New York, N. Y., p. 390; 1951.