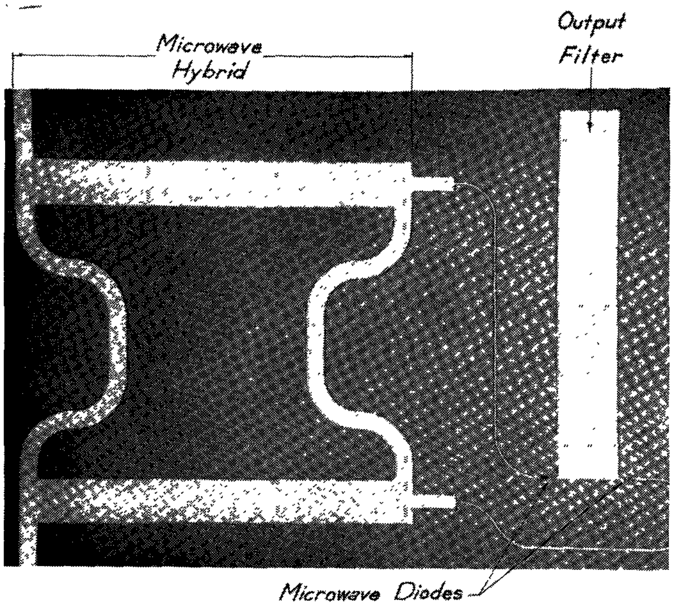

Fig. 8. Contact pattern for balanced mixer integrated circuit.

in the conductors. As nearly all microwave semiconductor devices in operation today are of either silicon or gallium arsenide, the ability to interconnect these devices and perform transmission-line functions in an efficient manner should enable many system advances heretofore limited due to size, cost, or weight of the microwave components.

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REFERENCES

[1] F. Assadourian and E. Rimai, "Simplified theory of microstrip transmission systems," *Proc. IRE*, vol. 40, pp. 1651–1657, December 1952.
[2] K. G. Black and T. Higgins, "Rigorous determination of the parameters of microstrip transmission lines," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-3, pp. 93–113, March 1955.
[3] T. T. Wu, "Theory of the microstrip," *J. Appl. Phys.*, vol. 28, p. 299, 1957.
[4] B. R. Nag and S. K. Roy, "Microwave measurement of conductivity and dielectric constant of semiconductors," *Proc. IRE* (*Correspondence*), vol. 50, pp. 2515–2516, December 1962.
[5] B. R. Nag, S. K. Roy, and C. K. Chatterji, "Microwave measurement of conductivity and dielectric constant of semiconductors," *Proc. IEEE*, vol. 51, p. 962, June 1963.
[6] J. M. C. Dukes, "An investigation into some fundamental properties of strip transmission lines with the aid of an electrolytic tank," *Proc. IEE* (*London*), vol. 103B, p. 319, 1956.
[7] W. R. Runyan, *Silicon Semiconductor Technology*. New York: McGraw-Hill, 1965.
[8] M. Arditi, "Experimental determination of the properties of microstrip components," *Elect. Commun.*, vol. 30, p. 283, 1953, and 1953 *Conv. Rec. I.R.E.*, pt. 10, p. 27–37.
[9] H. F. Lenzing, "How to determine characteristic impedance," *Elec. Design*, p. 58, May 10, 1963.

A Digital Latching Ferrite Strip Transmission Line Phase Shifter

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***Abstract*—This paper is concerned with the development of a new type of latching phase shifter which combines submicrosecond switching with a compact strip transmission line structure. Digital increments of nonreciprocal phase shift are obtained by "latching" or switching the magnetization of appropriate square loop garnet or ferrite materials from one remanent state to another. The following data have been obtained for a four-bit, *C*-band model utilizing yttrium iron garnet ($4\pi M_s = 1600$ G):**

Center Frequency—5.45 Gc/s
Phase Deviation—$\leq \pm 3$ percent over an 8 percent frequency band
Insertion Loss—<0.9 dB
VSWR—<1.50
Switching Time—$<0.3\mu$s with a 130 V, 13 amp pulse
Switching Energy—$<200\ \mu$J for 180° bit
Length—<6 inches.

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INTRODUCTION

RECENT EFFORT has been extended toward the development of digital latching waveguide phase shifters and the associated driver circuitry [1]–[4]. This paper is concerned with the development of a somewhat different type of phase shifter which utilizes the properties of square loop magnetic toroids placed in a strip transmission line geometry.

Before the development of the new phase shifter is described, the basic principles involved need to be reviewed. This will be accomplished by considering, first, the nature of present waveguide latching ferrite shifters. A discussion of the evolution of nonreciprocal TEM mode components follows; finally, the present effort is described.

Waveguide Latching Ferrite Phase Shifters

Most past solid-state, nonreciprocal phase shifters have utilized flat slabs of ferrite material with a biasing direct current magnetic field. For switching, an electromagnet was necessitated with correspondingly slow switching speeds. The development of digital latching phase shifters has eliminated the need for holding fields and has made possible submicrosecond switching speeds [2], [5]. In these designs, ferrimagnetic toroids of various lengths are placed in a waveguide as shown in Fig. 1. Matching transformers and dielectric separators are included as shown while direct current paths are provided through each element. When narrow, full waveguide height toroids are used, this configuration simulates a twin slab, nonreciprocal phase shifter design [2].

Digital increments of phase shift are obtained by switching the magnetization of the component toroids between remanent states. This is accomplished by passing either positive or negative current pulses through the individual toroids. The characteristics of a typical waveguide phase shifter will be compared later to those exhibited by the new design.

Present TEM Mode Nonreciprocal Devices

Coaxial Devices

A TEM wave propagating in a coaxial structure does not exhibit a plane of circular polarization and cannot be utilized directly to obtain nonreciprocal action. Seidel and Button [6], [7] have pointed out, however, that such a line may be antisymmetrically loaded, as shown in Fig. 2, to obtain a radial electric field having a θ dependence. The necessary criteria for obtaining a plane of circular polarization is realized as a longitudinal component of magnetic field H_Z is obtained ($H_Z \propto \partial E_r/\partial\theta$ by solution of Maxwell's equations).

As the maximum electric field gradient occurs at the dielectric interface, nonreciprocal devices have been developed by placing rods or slabs of magnetically biased ferrite materials at the interface [7]–[9]. A set of approximate requirements for designing such devices has been set forth by Button [7]. Some of his key points, which relate to present considerations, are as follows:

1) Sufficiently large coax diameter must be used as the TEM mode must be modified to become a TE like mode exhibiting a cutoff condition.
2) The dielectric loading material must have a large e_r to obtain a large gradient at the interface between the two media.
3) A relatively small dielectric loading factor must be used to avoid excessive concentration of the microwave energy within the dielectric.

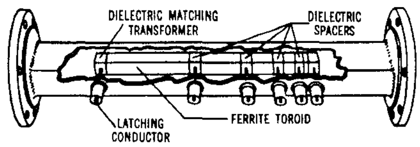

Fig. 1. Five-element latching ferrite waveguide phase shifter.

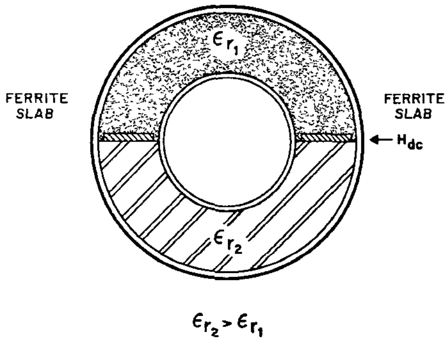

Fig. 2. Dielectrically loaded coaxial line containing thin ferrite slabs.

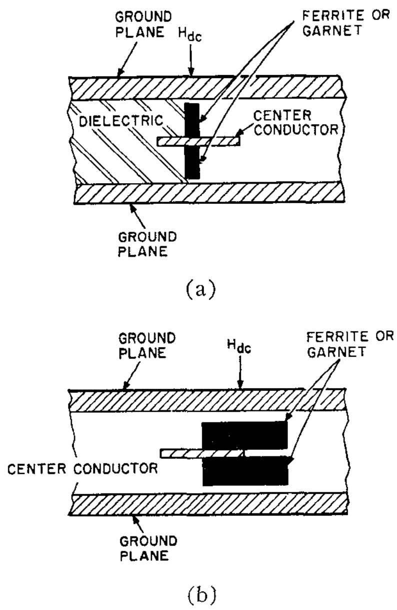

Fig. 3. Past designs of nonreciprocal TEM mode devices. (a) Typical design of stripline phase shifter with dielectric loading. (b) Reported design of stripline isolator without dielectric loading. (After D. B. Swartz, *Proc. IRE*, vol. 49, p. 366, January 1961.)

Strip Transmission Line Isolators and Phase Shifters

Nonreciprocal strip transmission devices have followed the coaxial developments. Koop, et al. [10] and Arams, et al. [11] have reported similar strip transmission phase shifters operating at L-band and UHF frequencies, respectively. Another device, an isolator, has been reported [12] in which the ferrite also serves as the dielectric loading media. Sketches of such configurations are given in Fig. 3.

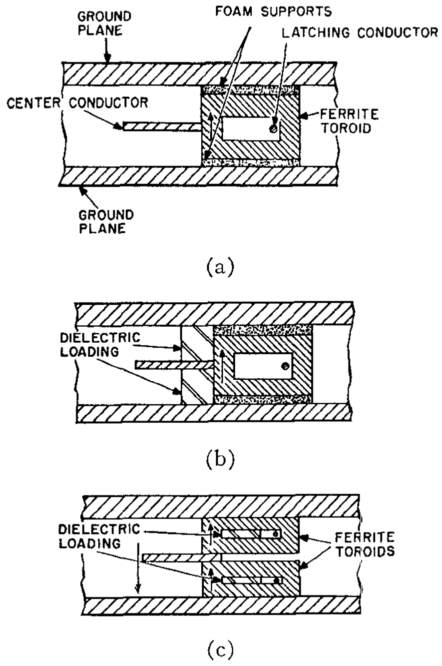

Fig. 4. Configurations which have been investigated.

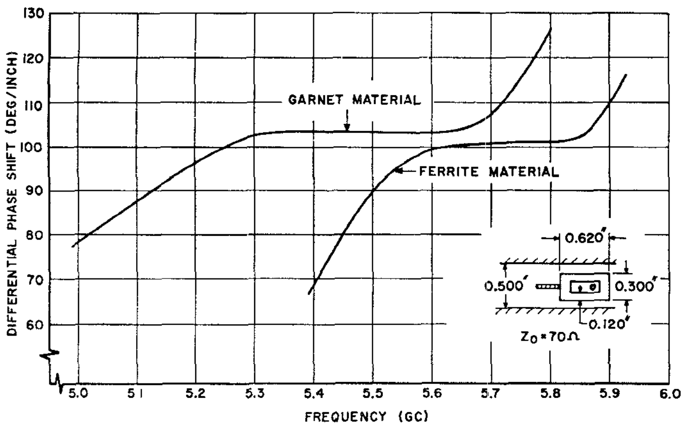

Fig. 5. Measured phase-shift data for one toroid configuration.

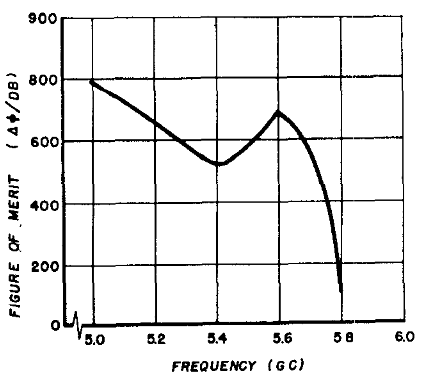

Fig. 6. Figure of merit data for one toroid model.

Experimental Investigation

The purpose of the work reported here has been to determine the feasibility of combining the desirable characteristics of a latching ferrite device and the compactness of a strip transmission line geometry. The basic problem has been to satisfy the requirements for nonreciprocal action while maintaining a closed path for the magnetic circuit. Configurations which have been explored are depicted in Fig. 4. These arrangements have utilized 70-ohm air dielectric lines of 0.500 inch ground plane spacing at C-band frequencies.

The One Toroid Model

The configurations of Fig. 4(a) and (b) are nearly identical except for the inclusion of dielectric material in the second case. In either design, a single toroid is used to simulate twin slab arrangements illustrated in Fig. 3. The arm of the toroid nearest the center conductor interacts strongly with the microwave energy. The distance across the toroid is sufficiently large that the microwave energy interaction with the distant arm is small. The remaining arms complete the magnetic path and provide dielectric loading.

It has been found that the first design largely satisfies the requirements for nonreciprocal action. The incorporation of additional dielectric does not improve the performance significantly. The toroid geometry has been investigated for two materials, a ferrite having a $4\pi M_s$ of 1700 G and an yttrium iron garnet with a $4\pi M_s$ of 1600 G. The resulting phase-shift data for the two materials are shown in Fig. 5. In excess of 100° of phase shift per inch is obtained for both materials.

A plot of the figure of merit (degrees phase shift/dB loss) vs. frequency for the garnet toroid design is given in Fig. 6. At frequencies below 5.7 Gc/s, a figure of merit in excess of 500 is obtained which compares favorably with waveguide designs.

The Two Toroid Configurations

The configuration depicted in Fig. 4(c) has been investigated also. For this arrangement, considerably less phase shift is obtained. In addition, it is found that the amount of differential phase shift is dependent on the dielectric constant of the material used for loading the toroids.

Design of Phase Shifter

A four-bit C-band phase shifter has been designed using the basic configuration depicted in Fig. 5. In this design garnet toroids, whose lengths are adjusted to give nominal values of differential phase shift of 180, 90, 45 and 22.5 degrees when positioned as shown in the figure, are cascaded in series. As in previous waveguide designs, dielectric separators having a dielectric constant equal to that of the garnet toroids ($\epsilon_r = 16$) are placed between adjacent elements [2]. These separators serve to support the latching conductors for each element, maintain an electrical match, and prevent harmful demagnetizing effects when switching adjacent elements. Separator lengths of 0.090 inch have been used. A photograph of the partially assembled phase shifter showing some of the design features is shown in Fig. 7, along with a corresponding waveguide model.

As shown, dielectric matching transformers are included at either end of the series of elements. Simple quarter wavelength toroidal transformers having a dielectric constant ϵ_r equal to 4 have been used. The polystyrene supports shown in the figure serve only to position the material toroids against the center strip.

A summary of the experimental data which has been obtained for the model is given in Table I, along with corresponding data for a present waveguide design. As indicated in the table, a ±3 percent deviation in differential phase shift is obtained for each bit across the 5.25–5.65 Gc/s frequency band. The frequency dependence for each bit is in agreement with the data listed in Fig. 5. The indicated switching speeds are determined primarily by the electronic driver used in switching the individual elements. For increased switching speeds, the switching energy would be increased.

Even though the characteristics of the new device compare favorably with its waveguide counterpart, further optimization in ground plane spacing and toroidal geometry would probably result in greater bandwidth, increased figure of merit, and increased material activity. Additional compactness in the design can be obtained by eliminating the dielectric separators between toroidal elements. This could be accomplished by using a partial switching technique reported by the authors in an earlier publication [4].

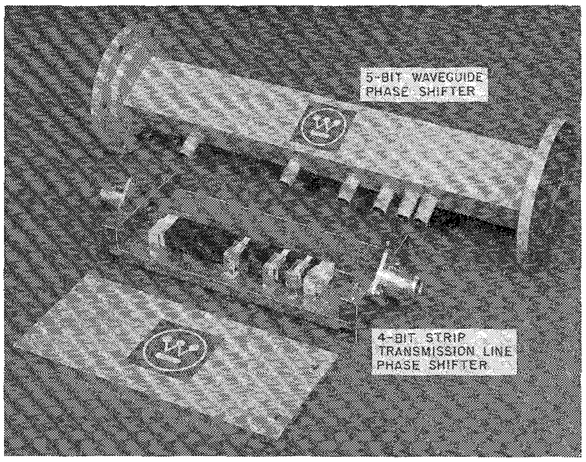

Fig. 7. Photograph of developed strip transmission line phase shifter and similar waveguide device.

TABLE I

CHARACTERISTICS OF TYPICAL WAVEGUIDE AND STRIP TRANSMISSION LINE PHASE SHIFTERS

Item	Strip Transmission Line Phase Shifter	Typical Waveguide Phase Shifter
Frequency Band	5.25–5.65 Gc/s	5.40–5.90 Gc/s
Phase Deviation	±3 percent over band	±3 percent over band
Switching Energy	≤200 μJ for 180° bit	≤300 μJ for 180° bit
Switching Speed	≤0.3 μs with 130 V	≤0.3 μs with 130 V
Insertion Loss	<0.9 dB	approximately 0.8 dB
VSWR	<1.50	<1.50
Length	<6 inches	8 to 12 inches

CONCLUSIONS

The characteristics of the device as described in this paper offer advantages over waveguide designs. These include reduced switching energy requirements, compact form factor, and systems compatibility. In particular, this design is suited for phased array applications where printed circuit techniques may be employed. Feed problems associated with waveguide arrays are largely eliminated. The new device may prove to be of even greater value at lower frequency bands.

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REFERENCES

[1] G. S. Blevins, J. A. Kempic, and R. R. Jones, "C-band digital ferrite phase shifter" (classified paper), presented at the 1964 Symposium on Electronically Scanned Array Techniques and Applications, Rome Air Development Center, Griffiss AFB, N. Y.

[2] J. A. Kempic and R. R. Jones, "High power C-band phase shifter," Westinghouse Electric Corp., Baltimore, Md., First Quarterly Rept., Contract DA-28-043-AMC-0028, January 1965.

[3] D. R. Taft, "Development of digital phase shifter using square loop garnet materials," presented at the 1964 Magnetism and Magnetic Materials Conf., Minneapolis, Minn.

[4] L. R. Whicker and R. R. Jones, "A digital current controlled latching ferrite phase shifter," presented at the 1965 IEEE Convention, New York, N. Y.

[5] L. M. Silber and A. Weis, "A fast-switching high power C-band circulator," *1964 IEEE Convention Rec.*, pp. 32–36.

[6] H. Seidel, "Ferrite slabs in transverse electric mode wave guide," *J. Appl. Phys.*, vol. 28, pp. 218–226, February 1957.

[7] K. J. Button, "Theory of non-reciprocal ferrite phase shifters in dielectric-loaded coaxial line," *J. Appl. Phys.*, vol. 29, p. 998, August 1958.

[8] B. J. Duncan, L. Swern, K. Tomiyasu, and J. Hannwacker, "Design considerations for broad-band ferrite coaxial line isolators," *Proc IRE*, pp. 483–490, April 1957.

[9] M. Sucher and H. J. Carlin, "Coaxial line non-reciprocal phase shifters," *J. Appl. Phys.*, vol. 28, p. 921, August 1957.

[10] W. S. Koop and A. K. Jordan, "Design note on an L-band strip-line circulator," *IRE Trans. on Microwave Theory and Techniques* (*Correspondence*), Vol. MTT-9, pp. 571–572, November 1961.

[11] F. Arams, B. Kaplan, and B. Peyton, "Octave-bandwidth UHF/L-band circulator," *IRE Trans. on Microwave Theory and Techniques*, Vol. MTT-9, pp. 212–216, May 1961.

[12] D. B. Swartz, "A practical compact UHF isolator," *Proc. IRE* (*Correspondence*), Vol. 49, p. 366, January 1961.