A Dual-Mode Latching, Reciprocal Ferrite Phase Shifter

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I. Introduction

An attractive method for producing reciprocal phase shift is to use a pair of identical nonreciprocal phase shifters with circulators at input and output, as shown in Fig. 1. In this scheme, signals passing from left to right are sent through the lower phase shifter, while signals passing from right to left are sent through the upper phase shifter. By switching the phase shifters in a complementary manner, equal variable insertion phases can be provided for either direction of propagation. This approach to achieving reciprocal phase shift yields the desirable bandwidth, figures of merit, and temperature stability advantages of nonreciprocal phase shifter, except that it is more complicated and has the additional losses of the input and output circulators. However, the added complexity can be significantly reduced by employing a dual-mode transmission line in which the two nonreciprocal phase shifters occupy the same physical space. It is the purpose of this paper to describe the principle of operation, physical realization, and performance parameters for a reciprocal phase shifter of this latter type.

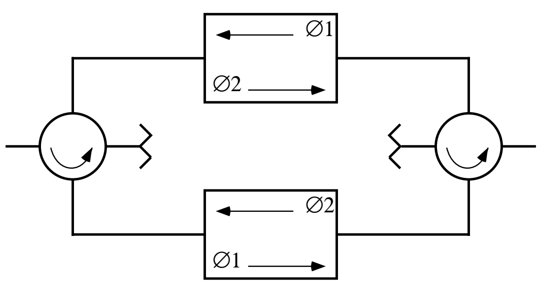

Fig. 1: Basic concept – dual channel phaser

II. Principle of Operation

Reduced to simplest terms, the structure consists of a quadrantally symmetric waveguide loaded with ferrite or ceramic of similar dielectric constant. The arrangement of ferrite and dielectric elements is shown in Fig. 2. The center portion of the assembly is the switched ferrite, which is axially magnetized to the desired level for a given amount of phase shift. On either side of this central section are short ferrite sections which are transversely magnetized with a fixed quadrupole field to achieve the function of nonreciprocal circular polarizers. At the extreme ends of the structure are dielectric members containing thin resistive- film elements whose purpose is to absorb one sense of linearly polarized r-f energy, while allowing the orthogonal sense to pass with minimal insertion loss. This whole assembly is carefully metallized to form a waveguide. Impedance matching elements are typically incorporated at the ends to couple to standard waveguides or other transmission systems. Finally, a ferrite yoke is fitted over the metallized surface in register with the central ferrite section to enhance the remanent field of that section and thus permit latching operation of the phase shifter.

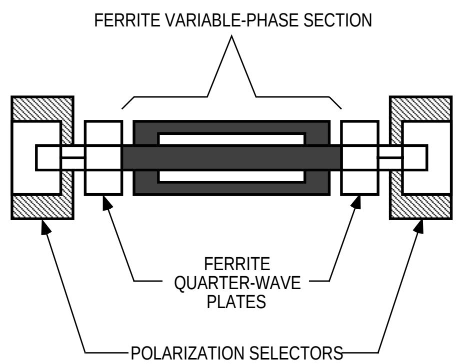

Fig. 2: Phase shifter configuration

The basic structure of a variable-field ferrite section between reciprocal quarter-wave plates is well-known as a form of nonreciprocal phase shifter [1]. A linearly polarized wave entering at 45° relative to the principal axes of the quarter-wave plate is converted to one sense of circular polarization, which propagates through the ferrite-loaded section with an insertion phase that depends on the magnitude and direction of the applied axial bias field. The output quarter-wave plate then converts the emerging circularly polarized wave back into a linearly polarized wave. A reciprocal version of this phase shifter was also described many years ago [2]. This structure used fixed 45° Faraday rotators beyond the reciprocal quarter-wave plates to achieve the functions of nonreciprocal circular polarizers, i.e. to cause oppositely traveling waves to propagate through variable-field section with opposite senses of circular polarization. This ensures equal insertion phases for both directions of propagation. In the current design, the nonreciprocal polarizer is accomplished by means of a fixed transverse quadrupole magnetic bias field that provides a nonreciprocal 90° differential phase shift between principal axes of the dual-mode guide. This eliminates the need for dielectric quarter-wave plates and allows polarizers and variable-phase sections to be achieved on a single ferrite rod.

The resistive-film load elements beyond the polarizer sections are important to keep small errors from causing reflections at the ends of the structure which can lead to large resonance dips in the insertion loss. Because the variable-field ferrite section has the form of a long, slender rod, it is easily magnetized axially and will exhibit remanent magnetization values approaching that of a solid toroid when an external yoke is used.

III. Experimental Results

A number of reciprocal phase shifter assemblies have been built and tested at X-band. The ferrite material used is a commercially available magnesium-manganese type, and the ceramic dielectric is also a commercially available type. Total length of the structure is 3.5 inches. Figure 3 shows a photograph of a typical phase shifter assembly.

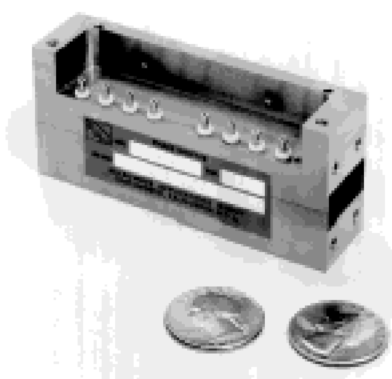

Fig. 3: Typical X-band phaser

The most difficult task in development of the phase shifter was minimizing insertion loss. Once a suitable combination of ferrite, ceramic, and end matching was achieved, a base transmission loss for the ferrite-ceramic guide was determined experimentally. However, rather higher phase state dependent losses were observed for developmental models of completed phase shifters. On the basis of an error analysis, these additional losses were attributed to fabrication and alignment errors in the nonreciprocal polarizers that caused a significant cross-polarized wave to appear and be absorbed in the resistive film. These problems were corrected by a succession of minor design improvements.

Figure 4 shows the insertion loss of a typical phase shifter as a function of frequency for randomly selected values of phase shift. It is evident that a residual dependence of insertion loss on phase state exists, but is small over most of the frequency band shown. The return loss of this phase shifter was a contributing factor to insertion loss, as Fig. 5 shows.

The total amount of phase shift available from this phase shifter with major-loop switching was approximately 460 degrees at room ambient temperature. Control of the phase shifter is by a partial switching method, in which the phase shift from a reset reference depends on the magnitude and duration of the "phase set" voltage pulse applied to a drive coil wound around the ferrite rod. Fig. 6 shows a hyseresis loop of insertion phase versus bias current at a frequency near 9 GHz. Peak power threshold for this unit is in excess of 3 kilowatts, at room ambient temperature.

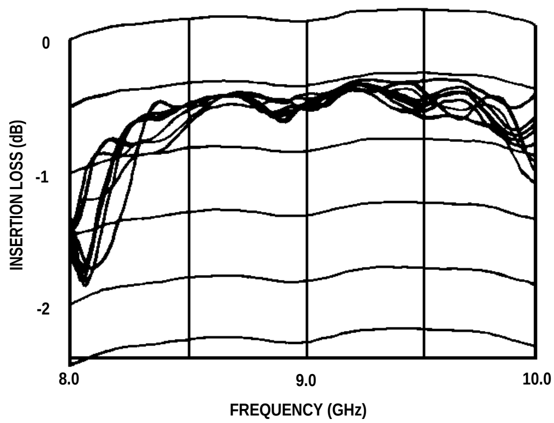

Fig. 4: Insertion loss at random phase states

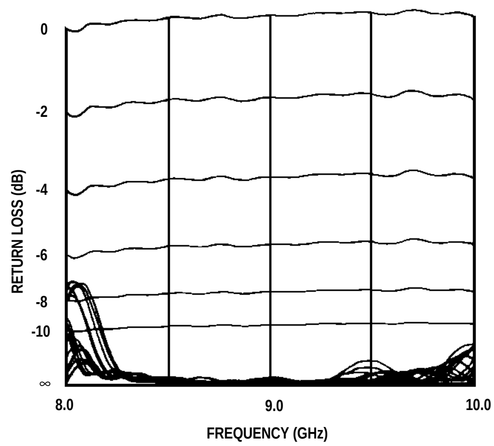

Fig.5: Impedance match at random phase states

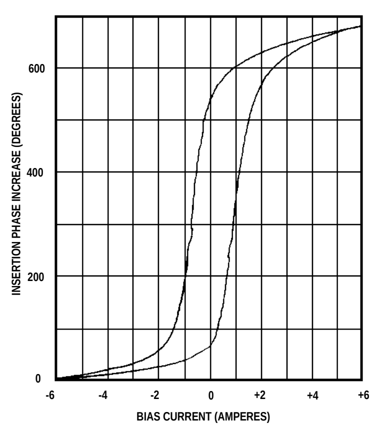

Fig. 6: Phase shift vs. current characteristic

IV. Conclusions

The reciprocal, latching ferrite phase shifter described in this paper offers many advantages to the system designer. Not only is its geometry very simple, but it offers a lower insertion loss than any other known passive configuration producing latching reciprocal phase shift at X-band or Ku-band. Insertion loss modulation over the phase states of the structure is minimal, and the characteristics of the phase shift are remarkably stable with temperature compared with other types of reciprocal ferrite phase shifter. The phase shift variation with frequency is also moderate, and could probably be essentially eliminated by adjusting the rod cross-sectional dimensions and/or the ferrite material magnetic moment. Finally, the maximum cross-sectional dimensions required are small enough to be compatible with application in two-dimensional electronically scanned arrays.

V. Acknowledgment

The phase shifter described in this paper represents the culmination of about fours years of more or less continuous engineering development. During this time, and in various organizations, the author has been privileged to associate and collaborate with many individuals. A partial listing would include Drs. S. B. Cohn, F. J. Rosenbaum, and W. E. Hord, and Messrs. R. W. Jansen, G. E. Hambleton, H. C. Bell, R. G. Roberts and J. V. Strahan. Additional thanks go to D. W. Prigge for assistance in carrying out the measurements presented here.

VI. References

1. A. G. Fox, S. E. Miller, M. T. Weiss, “Behavior and Applications of Ferrites in the Microwave Region”, B.S.T.J., Vol. 31, No. 1, p. 98, January 1955.

2. N. G. Sakiotis, A. J. Simmons, H. N. Chait, “Microwave-Antenna Ferrite Applications”, Electronics, p. 157, June 1952.