A NEW TYPE OF FAST SWITCHING DUAL-MODE FERRITE PHASE SHIFTER

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ABSTRACT

This paper describes a new type of dual-mode phase shifter which uses a variable transverse magnetic field. The device retains the features of the conventional longitudinal field dual-mode phase shifter - low insertion loss, moderate amplitude modulation, moderate frequency bandwidth, simple physical geometry - which allow it to be considered for use in two-dimensional scanning phased-array antennas. However, the transverse magnetic field configuration yields a smaller shorted-turn damping time constant, which results in either reduced switching time or reduced switching energy when compared with the conventional longitudinal field dual-mode arrangement.

INTRODUCTION

The dual-mode phase shifter is shown conceptually in Fig. 1. The conventional dual-mode phase shifter uses the interaction of circularly polarized waves with longitudinally magnetized ferrite. For this design, the circulators of Fig. 1 are realized by permanent-magnet quadrupole field quarter-wave plate sections on either end of the variable field section. These quarter-wave plate sections convert linear polarization nonreciprocally to circular polarization and vice versa. A more detailed description is available in the literature[1,2]. The new design of interest here uses a transversely magnetized ferrite-filled circular waveguide to realize the nonreciprocal phase shifters of Fig. 1. There are two major differences between the new design and the conventional dual-mode design.

1. The r-f field propagating through the phase shift section is linearly polarized rather than circularly polarized, and
2. The transverse magnetic bias field reduces the switching shorted-turn damping time constant.

Figure 2 shows block diagrams of the longitudinal field dual-mode phase shifter and two new realizations using the transverse field section. Figure 2b allows operation with linearly polarized energy, while Fig. 2c is designed for circularly polarized waves. The "nonreciprocal polarizers" consist of 45 degree Faraday rotators at either end of the phase shift section in Fig. 2b, while quadrupole field magnetic quarter-wave plates are used for the realization of Fig. 2c.

PHASE SHIFTER PRINCIPLES

The geometry of the transverse field phase shifter is given in Fig. 3. A four-piece latching yoke is arranged to provide a quadrupole bias field in the microwave ferrite. If the waveguide is excited with a y-polarized TE_{11} mode, the difference in propagation constants for waves traveling in the +z direction and the -z direction is[3]

$$\Delta\beta = \frac{A}{D}\,\frac{\kappa}{\mu}$$

where A is a constant, D is the diameter of the ferrite waveguide and κ and μ are the elements of the Polder tensor. Similarly, an x-polarized TE_{11} mode will experience a difference in propagation constants for waves traveling in the +z direction and the -z direction of

$$\Delta\beta = \frac{-A}{D}\,\frac{\kappa}{\mu}$$

Because of symmetry, identical phase shift is received for a y-polarized TE_{11} mode traveling in the +z direction and an x-polarized TE_{11} mode traveling in the -z direction.

Theoretically the differential phase shift of the ferrite waveguide will increase as

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the diameter decreases. This has been experimentally verified but several adverse effects mitigate against utilizing this phenomenon. First, the insertion loss increases as the diameter of the waveguide decreases. In addition, the problem of impedance matching is aggravated by the greater proximity to waveguide cutoff. Finally, the footprint of the latching yoke on the phase shifter becomes proportionately less as the demagnetizing effect of the airgaps increases and less latched phase shift is obtained. This is shown in Fig. 4 for C-band phase shifters fabricated with two different diameters. In each case the same maximum drive current was applied. The drive current was then removed and the latched phase shift was measured. The smaller diameter rod yielded more peak phase shift but less latched phased shift.

SWITCHING CONSIDERATIONS

One of the important features of the dual-mode phase shifter is the fact that the switching wires and the latching yoke are removed from the microwave circuit. This results in fairly simple fabrication and assembly of the phase shifter. However, the switching performance of the device is affected by eddy currents induced in the waveguide walls whenever the magnetic flux of the bias field is changed to produce phase shift. This has been analyzed by Boyd[4] who demonstrated that the switching energy increases dramatically for a longitudinal field dual-mode phase shifter when the switching time is reduced below a particular reference time which is determined by the structure dimensions and by the resistivity and thickness of the waveguide walls. The transverse field dual-mode device exhibits similar behavior, but the reference time is significantly reduced compared with the longitudinal field device.

Consider a ferrite rod which has been metallized to form a waveguide. Onto this is placed a winding of N turns and a latching yoke. This assembly may be modelled by the circuit shown in Fig. 5. Here R_c is the effective resistance of the ferrite core during switching, L is the inductance of the assembly and R_{st} is the shorted-turn resistance of the waveguide metallization multiplied by N^2 to reflect its apparent value in the primary circuit of the N:1 transformer. To change the flux from its maximum negative remanent value to its maximum positive remanent value, a constant voltage V is applied for a time T. The energy to switch the ferrite is

$$W_H = 2B_{max}H_c\text{Vol.}$$

where B_{max} is the maximum remanent flux density, H_c is the coercive force and Vol. is the volume of ferrite being switched. This may also be written $W_H = V^2T/R_c$. The energy dissipated by the eddy currents may be written $W = V^2T/R_{st}$ so that the total energy furnished is

$$W = W_H\left(1 + \frac{R_c}{R_{st}}\right) = W_H\left(1 + \frac{\tau}{T}\right)$$

Where τ is the reference time, e.g. The shorted-turn damping time constant. The core resistance, R_c, is proportional to the square of the turns ratio, which means that the ratio of R_c to R_{st} is independent of the turns ratio. The effective resistance of the ferrite core may be adjusted through the turns ratio to present a wide range of levels to the electronic driver without changing the energy requirements, as long as the switching time T is held constant.

The length and the diameter of the switched ferrite are approximately the same for the transverse field device and the longitudinal field device. Let D represent the diameter of the microwave ferrite, ℓ the length, S the thickness of the metallization and ρ the resistivity of the metallization. The following are easily derived for the longitudinal field device

$$R_c = \frac{\pi D^2N^2B_{max}}{4TH_c\ell},\quad R_{st} = \frac{\pi D^2N^2\rho}{S\ell},\quad \tau = \frac{SDB_{max}}{4\rho H_c}$$

The evaluation of the resistances for the transverse field case is assisted by the sketches shown in Fig. 6. Here N is the number of turns in a single slot of the yoke. For a quarter of the volume

$$R_c = \frac{\pi N'^2\ell B_{max}}{4TH_c},\quad R_{st} = \frac{32N'^2\rho\ell}{\pi SD},\quad \tau = \frac{\pi^2SDB_{max}}{128\rho H_c}$$

These equations imply that the shorted-turn damping time constant τ for the transverse field device may be about 30% of that for the longitudinal field device. Consequently, a switching time for the transverse-field device equal to 30% of the time for an equivalent-geometry longitudinal-field type should produce the same shorted-turn energy dissipation.

CONCLUSIONS

A new type of reciprocal, dual-mode ferrite phase shifter has been described. The device uses a transverse magnetic bias field in the differential phase shift region. Because of the distribution of this bias field, the waveguide wall eddy currents are significantly reduced which results in a reduced shorted-turn damping time constant when compared with the conventional dual-mode unit using a longitudinal magnetic bias field.

BIBLIOGRAPHY

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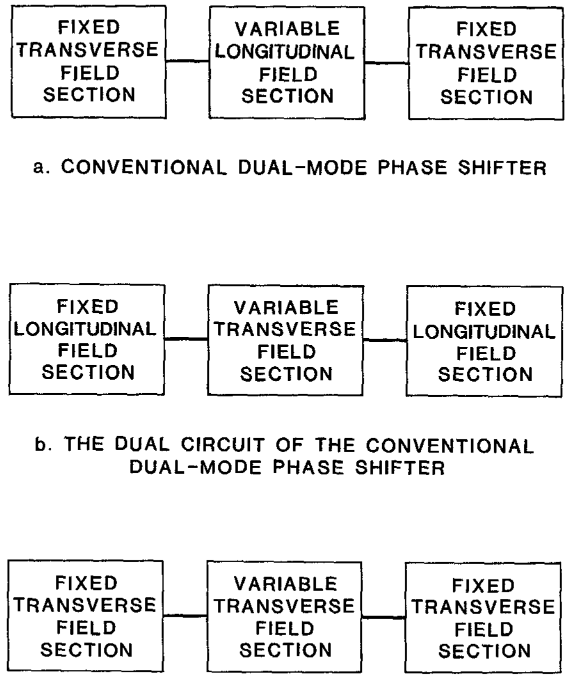
4. C.R. Boyd, Jr., "Comments on the Design and Manufacture of Dual-Mode Reciprocal Latching Ferrite Phase Shifters," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-22, No. 6, June 1974, pp. 593-601.



a. CONVENTIONAL DUAL-MODE PHASE SHIFTER

b. THE DUAL CIRCUIT OF THE CONVENTIONAL DUAL-MODE PHASE SHIFTER

c. ANOTHER REALIZATION OF THE DUAL CIRCUIT

FIGURE 2

BLOCK DIAGRAM OF DUAL-MODE FERRITE PHASE SHIFTERS

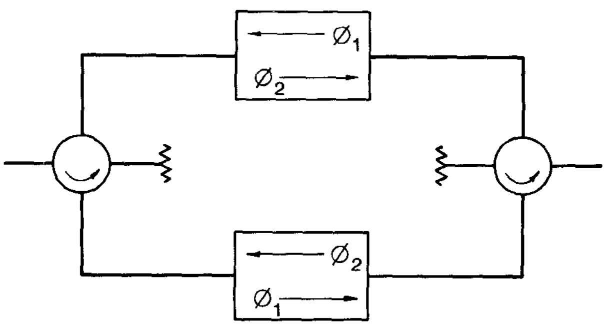


FIGURE 1

BASIC CONCEPT OF THE DUAL-MODE FERRITE PHASE SHIFTER

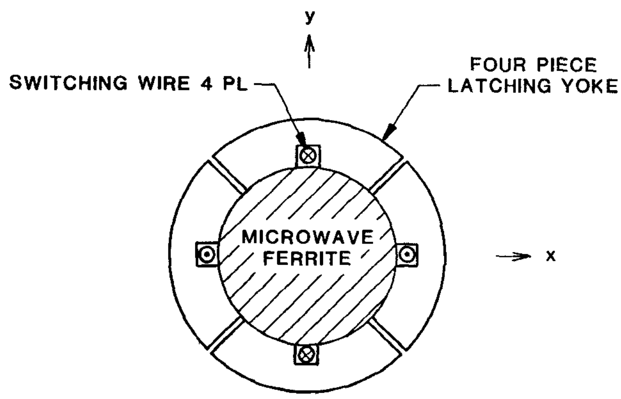


FIGURE 3

GEOMETRY OF TRANSVERSE FIELD SECTION

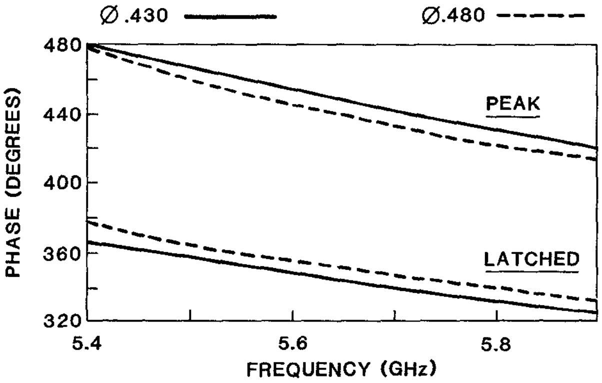


FIGURE 4
PHASE SHIFT VS. FREQUENCY

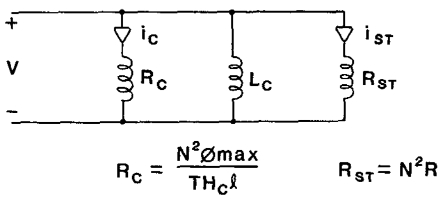
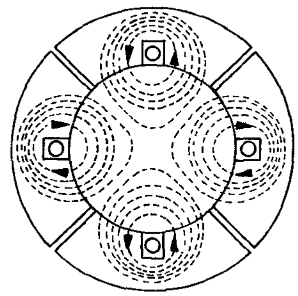
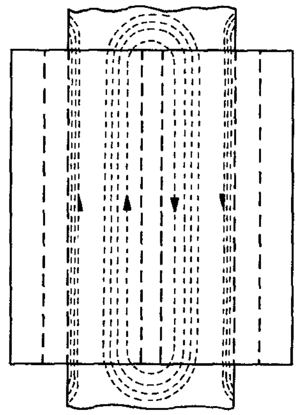


FIGURE 5
FERRITE EQUIVALENT CIRCUIT DURING SWITCHING



a. MAGNETIC BIAS FLUX DISTRIBUTION



b. EDDY CURRENT DISTRIBUTION

FIGURE 6
TRANSVERSE FIELD DEVICE FLUX AND EDDY CURRENT DISTRIBUTIONS