Dual-Ferrite Slot Line for Broadband, High-Nonreciprocity Phase Shifters

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Abstract **—A novel phase shifting structure that exhibits both broadband operation and high nonreciprocity is presented. This structure is comprised of a slot line between two oppositely-magnetized ferrite substrates. A full-wave, spectral-domain analysis is used, where Green's functions are formulated using a transmission matrix approach. By eliminating the use of relatively thick high-dielectric substrates, a bandwidth of 3:1 and a differential phase of 50° /cm are feasible. The geometry of the present structure can be optimized to increase both the nonreciprocity and the bandwidth. The characteristic impedance of the slot line is presented and shows a strong dependence on the slot width and the state of ferrite magnetization. The addition of thin layers of high-dielectric material increases the differential phase to over 100° /cm without significantly reducing the bandwidth. These layers were found to reduce the variation of characteristic impedance versus the ferrite magnetization.**

I. Introduction

Planar ferrite phase shifters are currently receiving considerable attention due to their improving performance, low cost, small size, and compatibility with monolithic microwave circuits. Several configurations of planar transmission line structures have been developed for phase shifting applications including coplanar waveguide, slot line, microstrip-slot line, and meander line [1]–[10]. These configurations have implemented a single layer of ferrite, with layers of dielectric added to improve the nonreciprocity or flatten the differential phase response versus frequency.

Slot line has been one of the most interesting configurations of planar ferrite phase shifters due to its inherent elliptically polarized magnetic fields [1], [9], compatibility with fin-line and waveguide circuits, and low loss for certain designs [11]. Experimental versions of slot line phase shifters have shown a figure of merit of up to 250° /dB [1], [9]. This compares favorably to other types of printed phase shifters such as meander line (150° /dB) [9] and coplanar waveguide (180° /dB) [5], and is similar to that of the microstrip-slot line (250° /dB) [9]. It has been shown that the simple single-layer ferrite structure (Fig. 1(a)) exhibits relatively low differential phase shift per unit length [1], [3], [4]. In most cases, the nonreciprocity in degrees/unit length is strongly tied to the figure of merit in degrees/dB, since the insertion loss is proportional to the length of the transmission line. Therefore, single layer structures exhibit relatively poor figures of merit (10° –20° /dB) [1], [6]. As mentioned above, the addition of a relatively thick high-dielectric layer (Fig. 1(b)) increases nonreciprocity. Unfortunately, high dielectric layers result in early overmoding which reduces the bandwidth to typically less than one octave [5].

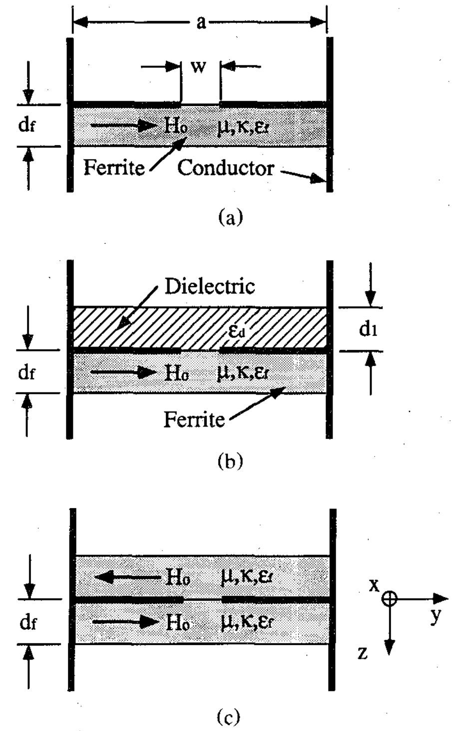

Fig. 1. Cross section of basic slot line planar ferrite phase shifting structures. (a) Single-layer ferrite structure. (b) Sandwich structure. (c) Oppositely magnetized dual-layer ferrite structure.

This paper investigates an innovative structure that can provide high differential phase shift without sacrificing bandwidth. Instead of relying on relatively thick layers of high-dielectric material, this structure (Fig. 1(c)) uses two oppositely-magnetized ferrite layers which interact constructively with the magnetic field ellipticity. Thus, the main reason for early overmoding is eliminated, and an improved figure of merit is achieved. Parameters that influence nonreciprocity and bandwidth are studied in detail.

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The method used to solve for the propagation constant of the planar slot line structures is outlined in Section II. In Section III, the resulting differential phase shift and bandwidth of the new structure are calculated and compared to previous structures. The new structure is then investigated in more detail; the effects of changing the slot geometry and of adding a thin layer of high-dielectric material to the basic configuration are presented. The effects of ferrite magnetization on field ellipticity and characteristic impedance of the slot line are investigated. Before concluding, applications of the dual-layer ferrite structure are discussed.

II. Method of Analysis

A. Green's Function Formulation

This section presents the Green's function used in the full-wave analysis of the multilayer slot line structures. The tangential (x and y) components of the electric fields and surface currents are Fourier-transformed according to [5], [7], [16]

$$\bar{F}(x,y)=\frac{1}{a}\int_{-\infty}^{\infty} e^{jk_x x}\sum_{i=-\infty}^{\infty}\tilde{\bar{F}}(k_x,k_{yi})e^{jk_{yi}y}\,dk_x \quad (1)$$

where the tilde ($\sim$) denotes the Fourier transform. The conducting sidewalls restrict kyi to the values $i\pi/a, i$ even, so the Fourier transform with respect to y is discrete. Green's functions relate the transformed tangential electric fields on one plane to the transformed electric surface currents on the same plane, as

$$\tilde{\bar{J}}_s(k_x,k_{yi})=\tilde{\bar{\bar{G}}}(k_x,k_{yi})\tilde{\bar{E}}(k_x,k_{yi}) \quad (2)$$

To find Green's function at the plane of the slot, the surface current in the slot, $\bar{J}_s$, is split into the superposition of two nonzero equivalent currents $\bar{J}$ and $\bar{J}'$. This allows the definition of two semi-space Green's functions:

$$\tilde{\bar{J}}=\tilde{\bar{\bar{G}}}_s(k_x,k_{yi})\tilde{\bar{E}} \quad (3)$$

$$\tilde{\bar{J}}'=\tilde{\bar{\bar{G}}}_s'(k_x,k_{yi})\tilde{\bar{E}}' \quad (4)$$

which are found in the spectral domain using the transmission matrices of the media [5], [6]. These Green's functions take into account the boundary conditions of each semispace. For multilayer dielectric/ferrite structures, the transmission matrices of individual layers are multiplied together in the correct sequence to find the total transmission matrix for the combined layers. Lastly, the total Green's function is the sum of these semi-space components, which are identical for structures symmetric with respect to the plane of the slot, such as Fig. 1(c).

B. Full-Wave Formulation

The propagation constant of infinitely long slot line structures is found using a full-wave spectral domain analysis [12]. Green's functions, as described in the previous section, are used to find the surface currents $\bar{J}(y)$ in terms of the transformed electric fields $\tilde{\bar{E}}$ using

$$\bar{J}(y)=\sum_{i=-\infty}^{\infty}\tilde{\bar{\bar{G}}}(-\beta,k_{yi})\tilde{\bar{E}}(k_{yi})e^{jk_{yi}y}. \quad (5)$$

The boundary conditions in the slot, $\bar{J}(y)=0$, are enforced by using Galerkin's method, where the electric fields in the slot are expanded and tested using the basis functions [5], [6]

$$E_y(y)=\sum_{n=0}^{N_y} c_n f_{yn} \quad (6)$$

$$E_x(y)=\sum_{n=0}^{N_x} d_n f_{xn} \quad (7)$$

$$f_{yn}=(-1)^n T_n\left(\frac{2y}{W}\right)\Big/\sqrt{1-\left(\frac{2y}{W}\right)^2} \quad (8)$$

$$f_{xn}=(-1)^n U_n\left(\frac{2y}{W}\right)\sqrt{1-\left(\frac{2y}{W}\right)^2} \quad (9)$$

where W is the width of the slot; T_n and U_n are the Chebyshev polynomials of the first and second kinds, respectively. Due to the y-symmetry of the slot line, only even values of n are used in (8) and only odd values of n are used in (9). The Fourier transform of these basis functions can be found in closed form in terms of Bessel functions [5], [6].

Application of Galerkin's procedure results in an admittance matrix; the solution for the propagation constant, β, is the value that forces determinant of this admittance matrix to zero. The difference between the propagation constants of the forward and reverse waves is used to find the nonreciprocal phase shift per unit length, as $\Delta\phi=\beta_f-\beta_r$. Two or three basis function terms in each direction have been found to be sufficient for convergence.

C. Characteristic Impedance

The characteristic impedance of the slot lines presented in this paper is found using the voltage-power relation [14], [15]

$$Z_0=\frac{|V_0|^2}{P} \quad (10)$$

where V_o is the voltage across the slot, and P is the power flowing along the slot line. These quantities can be found as [15], [16]

$$V_0=\tilde{E}_y(0)=\frac{c_0\pi W}{2}J_0(0)=\frac{c_0\pi W}{2} \quad (11)$$

$$P=\frac{1}{a}\sum_{i=-\infty}^{\infty}\int_z\left[\tilde{E}_y(k_{yi},z)\tilde{H}_z^*(k_{yi},z)-\tilde{E}_z(k_{yi},z)\tilde{H}_y^*(k_{yi},z)\right]dz \quad (12)$$

where J_0 is the Bessel function of order zero. In (12), the electric and magnetic fields at any distance z from the slot are determined by multiplying the slot fields by the inverse of the transmission matrix of the medium [16].

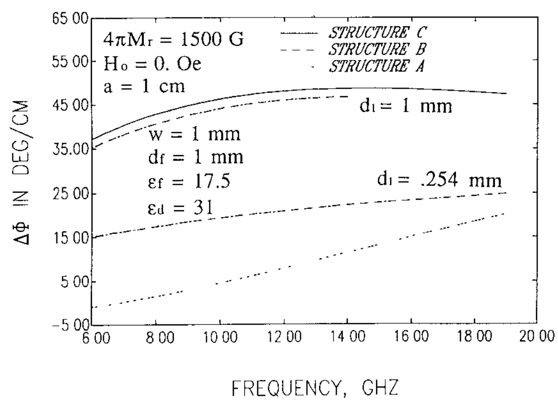

Fig. 2. Calculated differential phase shift versus frequency for the three slot line structures.

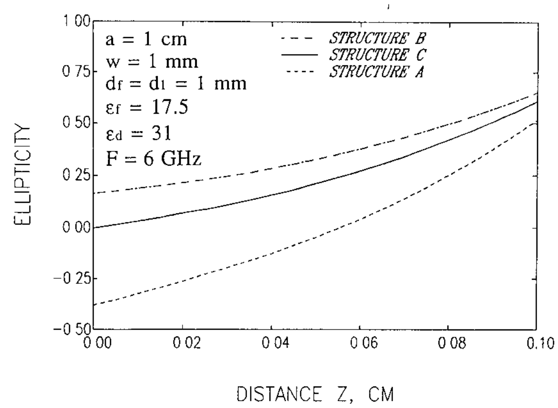

Fig. 3. Calculated magnetic field ellipticity, jHx/Hz, versus distance from slot for the case with the ferrite magnetization set to zero.

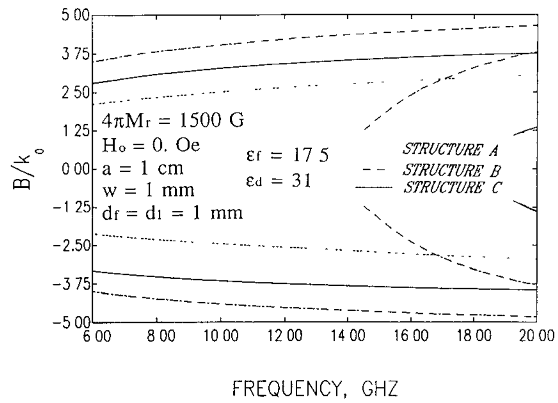

Fig. 4. Normalized propagation constant versus frequency for the three slot line structures.

III. Results

A. Dual-Ferrite Slot Line

In this section, the differential phase shift and bandwidth of the two-layer ferrite configuration (Fig. 1(c)) are calculated and compared to those of the single layer ferrite structures (Fig. 1(a)–(b)). A ferrite substrate having a remanent magnetization of $4\pi M_r = 1500$ G, dielectric constant of 17.5, and thickness of 1mm is common to all of the structures. For the sandwich device Fig. 1(b)), the differential phase is calculated for different dielectric thicknesses d1 and dielectric constants ϵ_d and compared to that of the dual ferrite structure.

The theoretical differential phase shift versus frequency for each configuration is plotted in Fig. 2 It is clear that the two-layer ferrite structure can offer at least as high nonreciprocity as structures which include high dielectric constant materials ($\epsilon_d > \epsilon_f$), and much greater nonreciprocity than single layer structures.

The high nonreciprocity of structure 1c can be explained by investigating the interaction of ferrite magnetization and the ellipticity of the magnetic field components transverse to the direction of magnetization [1], [2], [9]. (The direction of magnetization is perpendicular to the direction of propagation.) This ellipticity (jHx/Hz) is plotted in Fig. 3 for the three structures of Fig. 1 with the ferrite unmagnetized. (Calculation of the ellipticity with the ferrite magnetized shows that the following concept remains valid.) For the single layer structure (1a), the ellipticity changes sign within the ferrite, resulting in low nonreciprocity. For the multilayer designs (1b) and (1c), the field ellipticity is positive throughout the ferrite layer, giving higher nonreciprocity. Although the ellipticity of the sandwich structure is higher than that of the dual-ferrite structure, the dual-ferrite design can have higher nonreciprocity, due to the presence of two ferrite layers, both of which contribute to the differential phase shift.

When both nonreciprocity and bandwidth are considered, the new structure (1c) is clearly superior to both of the single-layer designs. The lowend bandwidth limitation of phase shifters is due to the ferrite itself; the operating frequency must be kept above $\gamma 4\pi M_r/.7 \cong \gamma 4\pi M_s$ in order to avoid high losses due to ferromagnetic resonance [9], [13]. This frequency, denoted by f_l, is about 6 GHz for the ferrite material simulated in this paper and is the same for each device under investigation. On the other hand, the bandwidth at the high end is dependent on the structure itself; note that the differential phase shift in Fig. 2 is plotted up to 19 GHz for structures (1a) and (1c) but only up to 14 GHz for (1b, $d_1 = 1$ mm). Above these frequencies, higher order modes have been observed. Previous work [5] has shown that the propagation of higher order modes results in increased insertion loss and irregular differential phase shift. Therefore, the upper frequency limit, f_u, is the point where higher order modes start to propagate.

The normalized propagation constant in the longitudinal direction, β_x/k_o, is plotted versus frequency in Fig. 4 for each slot line configuration. Only the first two modes are shown. The bandwidth for the two-layer ferrite (1c) and single-layer ferrite (1a) designs is about 13 GHz ($f_u \cong 19$ GHz, $f_l \cong 6$ GHz), but only 8 GHz for the sandwich structure (1b, $d_1 = 1$ mm) ($f_u \cong 14$ GHz, $f_l \cong 6$ GHz). Thus, the dual-ferrite arrangement provides a much broader bandwidth than the sandwich structure for a given phase shift. The bandwidth of the sandwich struc-

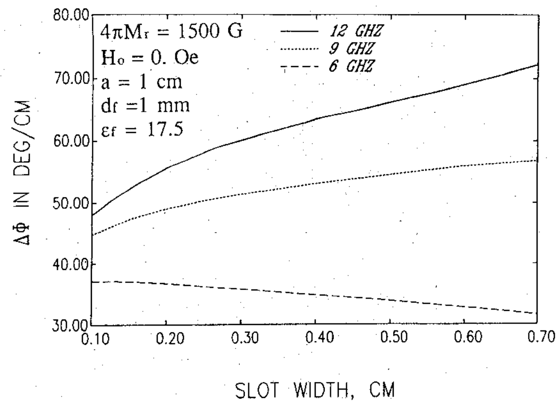

Fig. 5. Differential phase shift versus slot width for the dual-ferrite slot line structure.

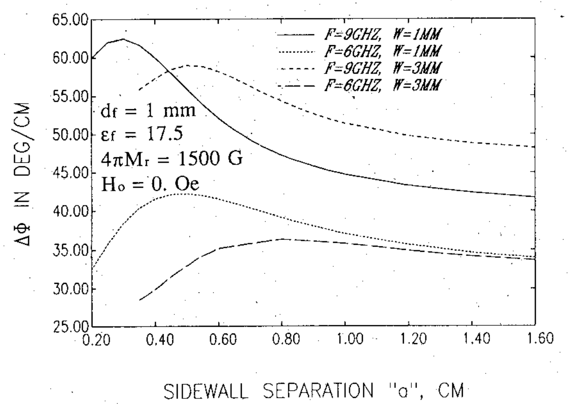

Fig. 6. Effect of sidewall separation on the differential phase shift of the dual-ferrite slot line structure.

ture can be increased by reducing the thickness of the dielectric layer, as shown in Fig. 2 for $d_1 = .254$ mm. However, the differential phase shift in this case is about half that of the dual-ferrite structure for the same bandwidth. This has been found to be true for other combinations of dielectric-layer thickness and permittivity.

The effect of the slot geometry on the phase shift for the two-layer ferrite structure is shown in Fig. 5. Increasing the slot width improves nonreciprocity at the two higher frequencies shown (9 and 12 GHz), but reduces it at the lower frequency (6 GHz). Increasing the slot width also gives more variation in phase shift versus frequency. Narrower slots are more suitable for applications where flatter differential phase shift over the bandwidth is required.

Other effects of the structure geometry include the effects of sidewall separation. As shown in Fig. 6, there is an optimum sidewall separation at which the nonreciprocity is maximum. The optimum value of 'a' decreases with frequency and increases with slot width. The bandwidth was found to increase with decreasing the side wall separation. (The frequency at which higher order modes start to be excited is increased.) Therefore, larger sidewall separation than the optimum value may not be desirable for high-nonreciprocity broadband designs.

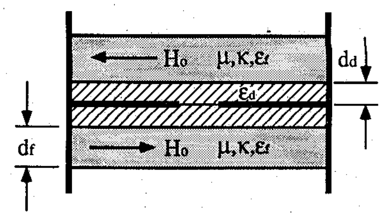

Fig. 7. Modified dual-ferrite structure showing inclusion of thin dielectric layers.

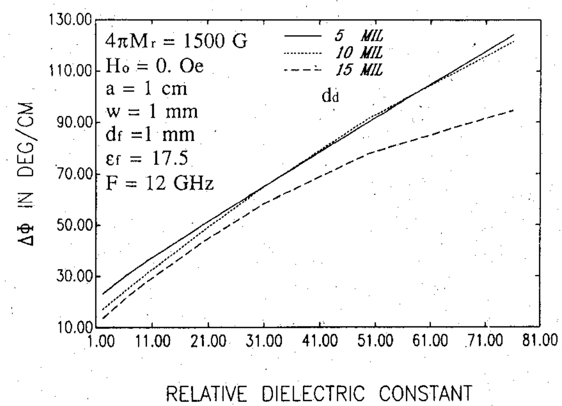

Fig. 8. Differential phase shift versus relative dielectric constant of the thin dielectric layer.

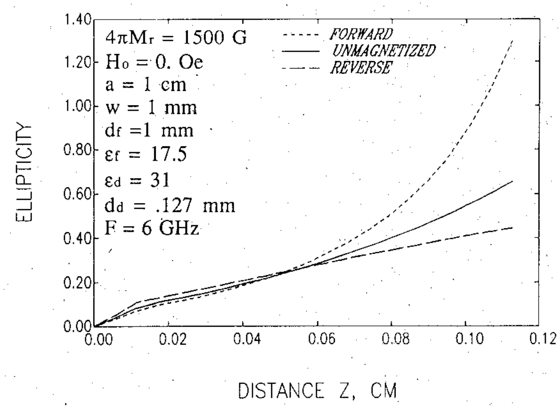

Fig. 9. Magnetic field ellipticity for the modified slot line structure in both magnetized and unmagnetized states.

B. Modified Dual-Ferrite Slot Line

In practical devices, thin dielectric layers may be needed between the ferrite layers to prevent magnetic leakage from one ferrite layer to the other, as shown in Fig. 7. These dielectric layers can also be selected to enhance the nonreciprocity. The differential phase shift versus the relative dielectric constant of the layers is plotted in Fig. 8 for different layer thicknesses at 12 GHz. Regardless of thickness, low values of dielectric constant ($\epsilon_d < \epsilon_f$) reduce the phase shift. In contrast, thin, high-dielectric layers ($\epsilon_d > \epsilon_f$) produce the highest phase shifts ($> 100°/$cm). This indicates a strong interaction between the slot RF magnetic fields and dc magnetization. Fig. 9 shows the magnetic field ellipticity versus distance from the slot for the ferrite layers unmagnetized as well as for

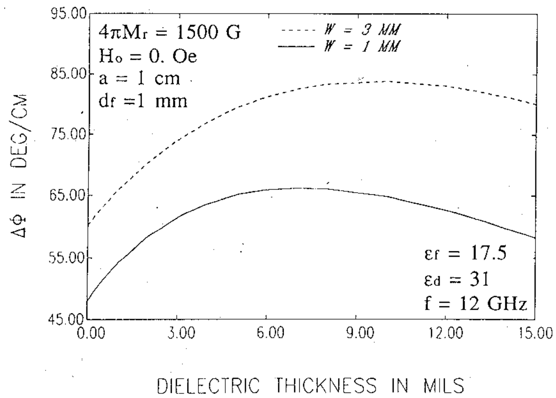

Fig. 10. Differential phase shift versus thickness of dielectric layer.

the two opposite states of magnetization. Comparison of Figs. 3 and 9 shows that the addition of the dielectric layers to the basic structure increases the ellipticity within the ferrite layers, resulting in higher nonreciprocity. Also, magnetizing the ferrite increases the ellipticity in one direction of propagation and decreases it in the opposite direction.

The effect of the dielectric layer thickness on the differential phase shift is shown in Fig. 10 at 12 GHz for two slot widths. The layer thickness that maximizes nonreciprocity increases with slot width. For either width, the optimum thickness of the dielectric is small enough to avoid severely degrading the bandwidth. When a .127 mm (5 mil) layer of $\epsilon_d = 31$ material is used in the modified structure (Fig. 7) with $w = 1$ mm, the differential phase shift is 35–40 percent higher over the entire band than that of the basic structure (1c) with the same slot width. However, overmoding is found to occur at $f_u \cong 17$ GHz, instead of 19 GHz for structure (1c), so the bandwidth is reduced by about 15 percent when the dielectric is added. Still, this is a significant improvement over the sandwich structure (1b).

Practical applications of the slot line between two oppositely magnetized ferrite layers include the dual-toroidal structure (Fig. 11). The slot line configuration (Fig. 11(b)) can be approximately modeled by replacing each toroid's horizontal walls with a dielectric layer which separates the vertical walls and has an effective dielectric constant ϵ_e [6], as shown in Fig. 11(c)). The value of ϵ_e can be calculated using the following relation [6]:

$$\epsilon_e = \left[1 - \frac{2d_f(\epsilon_f - 1)}{a\epsilon_f}\right]^{-1}. \tag{13}$$

Thus, $\epsilon_e = 1.23$ for a square toroid of wall thickness $d_f = 1$ mm and outer dimensions $a = 1.$ cm. Because this dielectric constant is close to unity, the effects of the horizontal walls of the toroid were found to be numerically insignificant. Furthermore, the outer vertical ferrite slabs were found to have a negligible effect on the differential phase and bandwidth due to the confinement of RF fields near the slot. Therefore, Fig. 7 can be used to approximately model the dual-toroid structure with a slot line. The advantages of the new structure (Fig. 11(b)) include better field confinement than the regular slot line (Fig. 7) and improved compatibility with a ridged-waveguide feeding circuit than the slotless configuration (Fig. 11(a)).

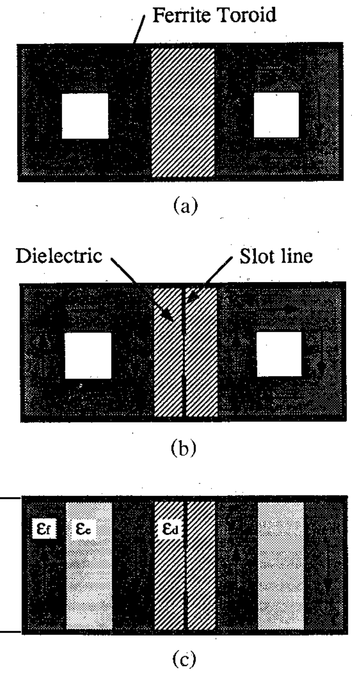

Fig. 11. Geometry of the dual-toroidal phase shifter. (a) Without a slot line. (b) With a slot line. (c) Model used to analyze dual-toroidal structure with a slot.

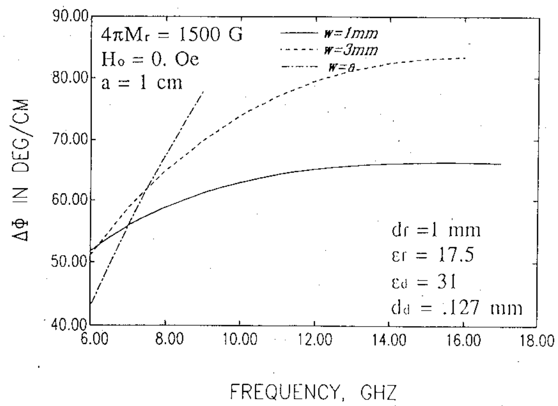

Fig. 12. Effect of slot width on phase shift of modified dual-ferrite structure.

In general, as the slot width increases, overmoding occurs at a lower frequency, which reduces bandwidth, with the minimum occuring when the slot width equals the sidewall separation; i.e., no slot exists in the structure. For the modified structure (Fig. 7) with $w = a$, the phase shift varies significantly over frequency and overmoding occurs at $f_u \cong 9.5$ GHz (Fig. 12), reducing the bandwidth by about 65 percent. Since Fig. 7 can be used to model the dual-toroid phase shifter, the addition of a slot to these structures can almost double their bandwidth with the possibility of increasing and equalizing nonreciprocity over the bandwidth.

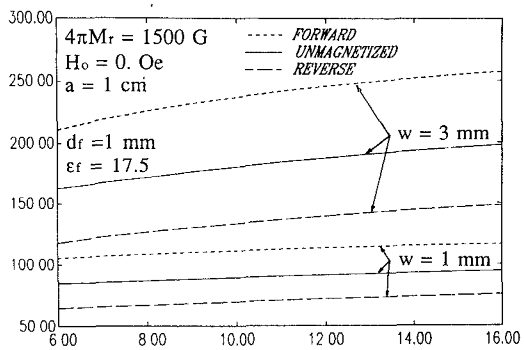

Fig. 13. Characteristic impedance versus frequency for the dual-ferrite slot line structure.

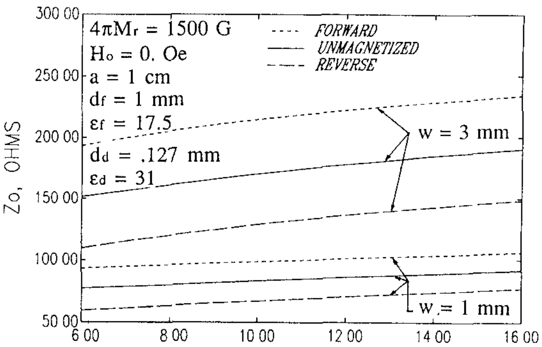

Fig. 14. Characteristic impedance versus frequency for the modified dual-ferrite slot line structure.

If only bandwidth is to be considered, narrow slots will be better than wide slots. However, to keep losses as low as possible, wide slots must be used. Theoretical analysis of slot line losses [11] shows that both conductor and dielectric losses remain fairly flat for a wide range of slot-to-sidewall separation ratios, (typically $0.4 < w/a < 1.0$). Losses per unit length start to increase sharply as slot width is decreased below a certain limit ($w/a \approx 0.2$). Therefore, the bandwidth of dual toroidal phase shifters can be improved while retaining low loss by adding a relatively wide slot.

The present theory was compared with published results [3], [4] for the single layer and the sandwich structures and compared with [13] for the dual ferrite structure without a slot ($w = a$). A good agreement with [3], [4] (within 5 percent) and an excellent agreement with [13] (within 1 percent) were observed.

C. Characteristic Impedance

Slot line characteristic impedance has been calculated using the formulation described in Section II. The computed impedance for the basic dual-ferrite structure (Fig. 1(c)) is plotted in Fig. 13 versus frequency for two slot widths. The 'forward' and 'reverse' curves represent the characteristic impedance for opposite directions of propagation (or states of magnetization); the impedance with the ferrite layers unmagnetized is also shown. Impedance increases with slot width and frequency. Also, at a given frequency, a variation of up 25 percent in the characteristic impedance can occur by magnetizing the ferrite.

The calculated impedance for the modified structure of Fig. 7 is plotted versus frequency in Fig. 14. Compared to the impedance of the dual-ferrite structure, the impedance of the modified structure is reduced by the addition of the high-dielectric layer, but only by 10 percent for $\epsilon_d = 31$, $d_d = .127$ mm. (These values gave nearly optimum nonreciprocity, as shown in Fig. 10). The layers also reduce the variation in impedance between opposite states of magnetization. This effect can be quite useful in the design of matching and feed circuits.

IV. Conclusion

This paper has presented the analysis and theoretical performance of a slot line dual-ferrite phase shifter. This novel configuration has been shown to compare favorably to previous slot line structures. It can provide high differential phase shift since both layers of ferrite contribute to the nonreciprocity; meanwhile, broadband operation is not sacrificed because the use of relatively thick high-dielectric constant materials is avoided.

Further investigation of this new structure has shown that an optimum slot width can be found and that it increases with frequency. Adding thin layers of high-dielectric material has been found to increase nonreciprocity but reduce bandwidth only slightly. For a given permittivity, the layer thickness required for maximum phase shift increases with slot width, but remains very small in all cases of interest. These layers also reduce the variation of the characteristic impedance versus the state of ferrite magnetization.

Practical applications of this new structure were discussed, and it was shown that significant improvement in nonreciprocity, bandwidth, and flatness of dual-toroidal phase shifters can be obtained by adding a slot line to the structure. A good agreement between our theory and published theories was observed.

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