SLOT LINE BETWEEN OPPOSITELY-MAGNETIZED FERRITE LAYERS FOR BROADBAND, HIGH-NONRECIPROCITY PHASE SHIFTERS

Christopher J. Koza and El-Badawy El-Sharawy

Department of Electrical Engineering
Telecommunications Research Center
Arizona State University Tempe, Arizona 85287

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 addition of thin layers of high-dielectric material is shown to increase the differential phase to over 100°/cm without significantly reducing the bandwidth.

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, and microstrip-slot [1]-[7]. These configurations have implemented a single layer of ferrite, with layers of dielectric added to improve the nonreciprocity or to flatten the differential phase response versus frequency. It has been shown that the simple single-layer ferrite structure (Fig. 1a) exhibits relatively low differential phase shift per unit length [6]. The addition of a relatively thick high-dielectric layer (Fig. 1b) increases nonreciprocity, but results in early overmoding which reduces the bandwidth to less than one octave [4],[5].

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. 1c) uses two oppositely-magnetized ferrite layers which interact constructively with the magnetic field ellipticity. Thus, the main reason for early overmoding is eliminated.

The method used to solve for the propagation constant of the planar slot line structures is outlined in section II, and the resulting differential phase shift and bandwidth are calculated and compared in section III. The new structure is then investigated in more detail; the effects of changing the slot geometry and of adding thin layers of high-dielectric material to the basic configuration are presented.

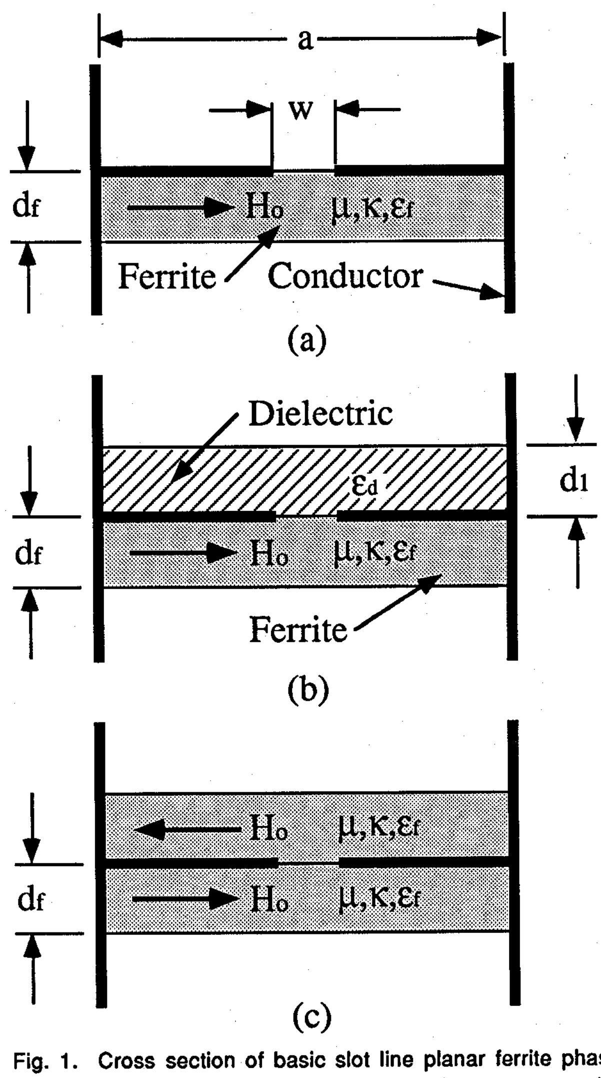

Fig. 1. Cross section of basic slot line planar ferrite phase shifting structures. (a) Single-layer ferrite structure. (b) Sandwich structure. (c) Oppositely-magnetized dual-layer ferrite structure.

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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 ($\varepsilon_d > \varepsilon_f$), and much higher differential phase shift than single layer structures. In general, the nonreciprocity can be explained by the interaction of ferrite magnetization and the magnetic field ellipticity [3]. In the new structure, the field ellipticities in the two layers coact with each other to increase nonreciprocity.

When both nonreciprocity and bandwidth are considered, the new structure (1c) is clearly superior to the single-layer designs. The low-end bandwidth limitation of the phase shifters is due to the ferrite itself; the operating frequency must be kept above $\gamma 4\pi M_r/.6 \cong \gamma 4\pi M_s$ in order to avoid high losses due to ferromagnetic resonance [3]. This frequency is the same for each device under investigation. However, 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), (1b,d1=.254mm), and (1c) but only up to 14 GHz for (1b,d1=1mm). Above these frequencies, higher-order modes have been observed. Previous work [4] has shown that the propagation of higher-order modes results in increased insertion loss and irregular differential phase shift. Therefore, the upper frequency limit is the point where higher-order modes begin to propagate.

The normalized propagation constant in the longitudinal direction, $\beta x/k_o$, is plotted versus frequency in Fig. 3 for each slot line configuration. Only the first two modes are shown, although other higher-order modes may exist. The bandwidth for the two-layer ferrite structure (1c) and single-layer ferrite structure (1a) is about 13 GHz, but only 8 GHz for the sandwich structure (1b) when d1=1mm. Thus, the dual-ferrite arrangement provides a much broader bandwidth than the sandwich structure for a given phase shift. The bandwidth of the sandwich structure

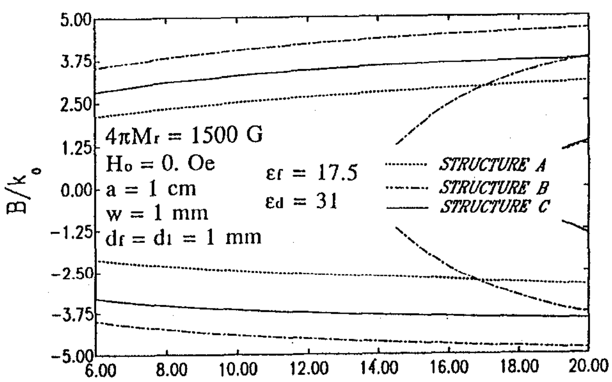

Fig. 3. Normalized propagation constant versus frequency for the three slot line structures.

can be increased by reducing the thickness of the dielectric layer as shown in Fig. 2 for d1=.254mm. 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. 4. 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 flat differential phase shift over the bandwidth is required.

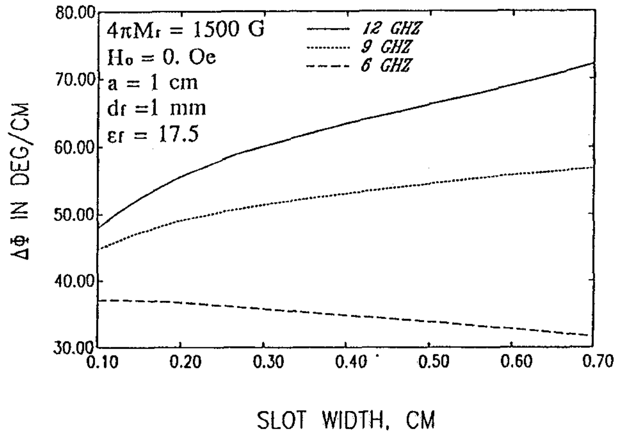

Fig. 4. Differential phase shift versus slot width for the dual-ferrite slot line structure.

In practical devices, a thin dielectric layer is needed between the ferrite layers to prevent magnetic leakage from one ferrite layer to the next, as shown in Fig. 5. This dielectric layer can also be selected to enhance the nonreciprocity. The differential phase shift versus the relative dielectric constant of the layer is plotted in Fig. 6 for different layer thicknesses at 12 GHz. Regardless of thickness, low values of dielectric constant ($\varepsilon_d < \varepsilon_f$) reduce the phase shift. In contrast, thin high-dielectric layers ($\varepsilon_d > \varepsilon_f$) produce the highest phase shifts (>100°/cm)

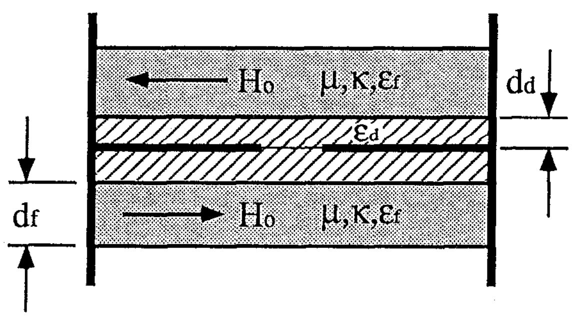

Fig. 5. Modified dual-ferrite structure showing inclusion of thin dielectric layers.

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 transformed from the space domain to the Fourier transform (spectral) domain according to [5]

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

where the tilde (~) denotes the Fourier transform. The conducting sidewalls restrict kyi to the values $i\pi/a$, i even, so that 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

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

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

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

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

which are found in the spectral domain using the transmission matrices of the media. These Green's functions take into account the boundary conditions of each semi-space. 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 [5]. 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 structure (1c).

B. Full-Wave Formulation

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

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

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

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

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

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

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

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 [5].

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 have been found to be sufficient for convergence.

III. RESULTS

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

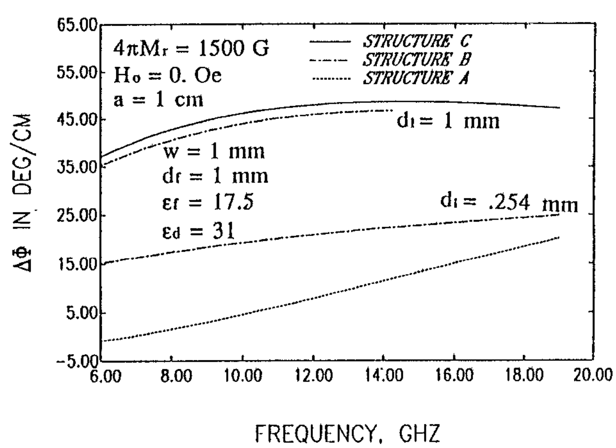

Fig. 2. Calculated differential phase shift versus frequency for the three slot line structures.

The effect of the thickness of the high-dielectric layer on differential phase shift is shown in Fig. 7 at 12 GHz for two slot widths. The optimum layer thickness (in terms of high nonreciprocity) increases with slot width. For both widths, the optimum thickness of the dielectric is low enough to avoid degrading the bandwidth severely. When a .127mm layer of ε_d=31 material is is used in the modified structure (Fig. 5) with w=1mm, 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 occurs near 17 GHz (Fig. 8), instead of 19 GHz for structure (1c). Thus, the bandwidth is reduced by about 15 percent when the dielectric is added. Still, this is a significant improvement over the sandwich structure (1b).

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 with w=a, the phase shift varies significantly over frequency and overmoding occurs at about 9.5 GHz (Fig. 8), reducing the bandwidth by about 65 percent.

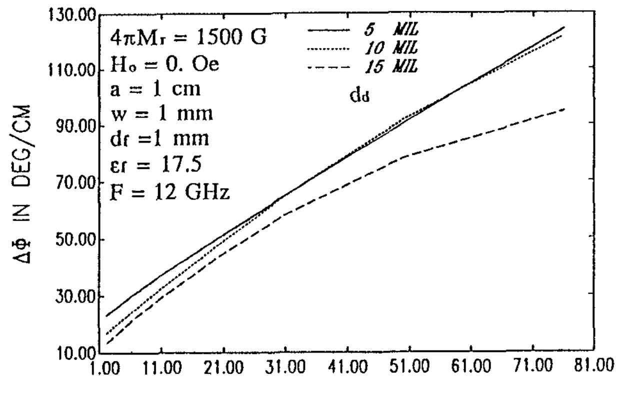

Fig. 6. Differential phase shift versus relative dielectric constant of the thin dielectric layer.

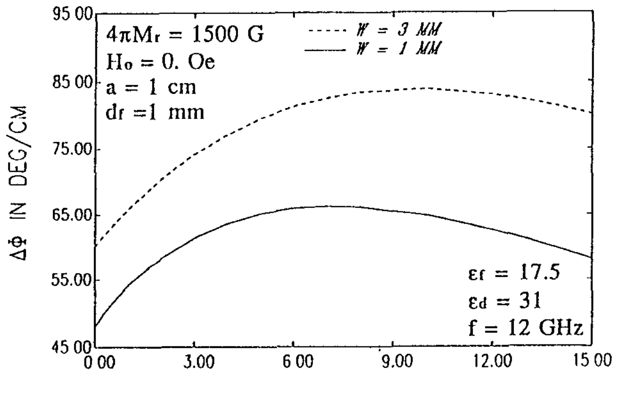

Fig. 7. Differential phase shift versus thickness of dielectric layer.

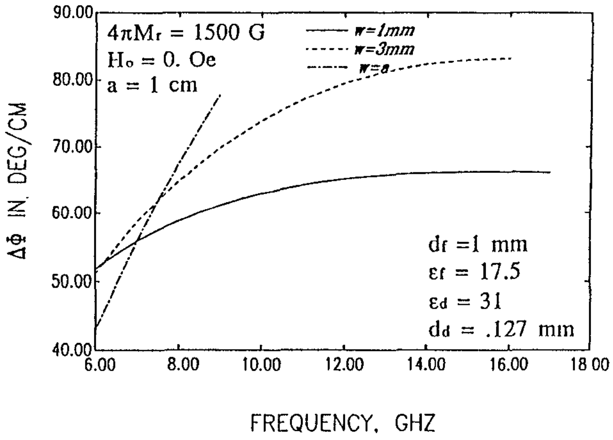

Fig. 8. Effect of slot width on phase shift of modified dual-ferrite structure.

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 layers of 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 a thin layer 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 nonreciprocity increases with slot width, but remains very small in all cases of interest.

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