Basic Properties of Microstrip Circuit Elements on Nonreciprocal Substrate-Superstrate Structures

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Abstract

The spectral domain-exponential matrix method is developed to evaluate the dyadic Green's function for generalized anisotropic substrate-superstrate structures. The method of moments is employed to obtain the basic dispersive characteristics of microstrip and inverted microstrip circuit elements on such structures. A collection of results will be presented for the propagation constant and characteristic impedance of microstrip elements on generalized anisotropic layers. Emphasis will be placed on the investigation of microstrip properties on a biased ferrite-semiconductor interface. The modeling accounts for arbitrarily oriented dc bias magnetic fields. The phenomenon of forward and backward wave propagation on this type of nonreciprocal structure will be highlighted.

I. Introduction

Recent technological advances in material processing and circuit and device fabrication have made possible the integration of fundamentally different materials into composite MIC structures. In particular, materials with nonreciprocal properties (such as magnetic materials) can be integrated with isotropic dielectric substrates in planar circuits. Structures such as these can be used to obtain nonreciprocal transmission effects such as nonreciprocal phase shift, isolation, and circulation. A special advantage of using magnetic substrates is that their material parameters can be changed and to some extent controlled by adjusting an externally applied dc magnetic bias field. Hence, various sets of characteristics can be obtained from one particular circuit with fixed dimensions and geometry.

This research is focused on the development of highly accurate models for microstrip and inverted microstrip lines on nonreciprocal substrate-superstrate structures. The permittivities and permeabilities of the layers are described as 3×3 tensors whose elements are completely general, so the analysis employed can be used for structures containing layers with any type of anisotropy. A spectral domain analysis is employed in conjunction with matrix methods to describe the electric and magnetic fields in each layer of the geometry in terms of an exponential matrix characteristic of its material properties. The resulting integral equation is solved rigorously using the method of moments; hence all the pertinent physical phenomena are taken into account.

The results presented will include dispersive properties of microstrip lines printed on semiconductor-ferrite substrate-superstrate structures. The nonreciprocal behavior of wave propagation in these type of structures will be demonstrated. The wide variation in propagation characteristics as the magnetic bias field orientation is changed will also be shown.

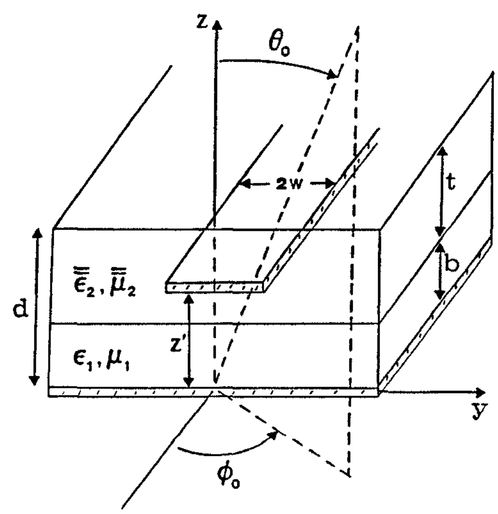


Figure 1. Microstrip transmission line in an isotropic substrate/ anisotropic superstrate structure.

II. Analysis

The geometry for an infinite microstrip transmission line embedded in a grounded two-layer composite structure with a top layer of thickness t and a bottom layer of thickness b is shown in Fig. 1. For nonreciprocal materials such as ferrite, the permeability tensor may have nine nonzero elements depending on the orientation of the dc magnetic bias field. The values of the tensor elements are functions of operating frequency, dc bias level, and dc bias orientation [1-2]. For example, the permeability tensor for a ferrite whose magnetic bias is parallel to the x-y plane ($\theta_0 = 90^o$) is:

$$\begin{bmatrix} \mu + (\mu_0 - \mu)\cos^2\phi_0 & \frac{\mu_0-\mu}{2}\sin 2\phi_0 & -j\kappa\sin\phi_0 \\ \frac{\mu_0-\mu}{2}\sin 2\phi_0 & \mu + (\mu_0 - \mu)\sin^2\phi_0 & j\kappa\cos\phi_0 \\ j\kappa\sin\phi_0 & -j\kappa\cos\phi_0 & \mu \end{bmatrix} \tag{1}$$

Using the 2-D Fourier transformation

$$\begin{matrix}\vec{E}\\ \vec{H}\end{matrix} = \frac{1}{4\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \begin{matrix}\tilde{E}\\ \tilde{H}\end{matrix}(k_x, k_y)\, e^{-jk_x x} e^{-jk_y y}\, dk_x dk_y, \tag{2}$$

in Maxwell's curl equations and writing them in matrix form, the fields in each region must satisfy the following partial differential equation in Fourier transform space [3]:

$$\frac{\partial}{\partial z}[\tilde{\psi}(z)] = [A]\,[\tilde{\psi}(z)] + [\tilde{f}]\delta(z - z'). \tag{3}$$

In Eq. 3, $[\tilde{\psi}]$ is a 4×1 vector containing the Fourier transforms of the tangential E and H fields. [A] is a 4×4 complex matrix whose elements are completely described by the material parameters $\bar{\bar{\epsilon}}$ and $\bar{\bar{\mu}}$ and the Fourier transform variables k_x and k_y. $[\tilde{f}]$ is a 4×1 vector containing the Fourier transforms of any sources that might be in the layer. The solution of Eq. 3 can be found by using the Cayley-Hamilton theorem [4] or using eigenvector analysis [5]. The results from either method are equivalent and result in terms whose z-depedences are of the form $e^{\lambda_j z}$, where λ_j are the eigenvalues of the [A] matrix. If the medium is isotropic, there will be repeated eigenvalues, but the terms of the exponential matrix can be greatly simplified and exhibit *sinh* and *cosh* behavior. To find the dyadic Green's function in any of the regions of a layered geometry, we describe the fields in each region i by a vector $[\psi_i]$ given by Eq. 3 containing unknown constants, which can then be solved by applying the appropriate boundary conditions at each layer interface. This solution provides the spectral Green's function of the pertinent problem.

To find the propagation characteristics of the microstrip line, the integral equation that needs to be solved (assuming $e^{\pm j\beta x}$ propagation) is [6]

$$\int_{-w}^{w} [G(y - y')] \cdot [J] dy' = 0 \tag{4}$$

on the strip ($-w \leq y \leq w$), where the Green's function $G(y - y')$ is in the form:

$$[G(y)] = \int_{-\infty}^{\infty} \left[\tilde{G}(\beta, k_y)\right] e^{-jk_y y}\, dk_y. \tag{5}$$

The unknown current distribution is expanded as

$$\bar{J}(x, y) = \sum I_n \bar{J}_n(x, y), \tag{6}$$

$\bar{J}_n$ are a family of Chebyshev functions. By using Galerkin's method, an infinite system of coupled equations is produced:

$$[Z_{mn}][I_n] = 0, \;\; \mathrm{m} = 0, 1, 2, \ldots\ldots \tag{7}$$

The propagation constants (β) are given by the roots of the determinant of $[Z_{mn}]$, corresponding to nontrivial solutions of I_n. Once these have been found, values for $[I_n]$ can be determined, which leads to immediate knowledge of the current distribution and quick computation of the characteristic impedance.

III. Results

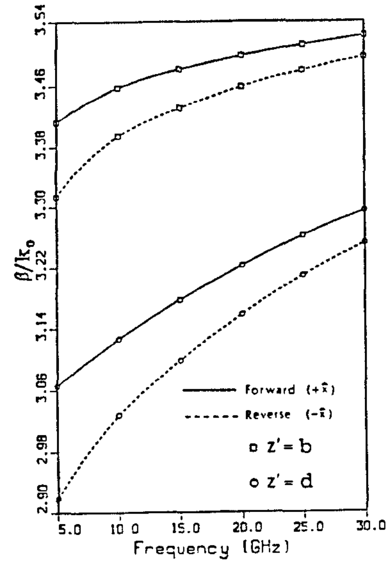
Propagation characteristics are shown for an infinite transmission line printed on a structure made up of a ferrite superstrate over an isotropic substrate. In all the results shown, a typical ferrite with $\epsilon_2 = 12.6$ and saturation magnetization $\mu_0 M = 0.275T$ is assumed as the top layer. Except for Fig. 3 (the inverted microstrip), the substrate layer is taken as GaAs ($\epsilon_1 = 12.9$, $\mu_1 = 1$). The strength of the dc bias field is set to a tenth of the magnetization ($\omega_0 = 0.1\omega_m$), and the dimensions of the configuration are $b = t = 10$ mil, and $w = 2b$.

The frequency behavior of the propagation constant and characteristic impedance are shown in Fig. 2. Here the bias field is oriented at $\theta_0 = \phi_0 = 90^0$ (transverse to the transmission line). Plots are shown for a microstrip line printed at the interface between the ferrite and semiconductor layers ($z' = b$) and for a line printed on top of the ferrite superstrate ($z' = d$). All the curves show a similar monotonically increasing behavior, although the curves for the dipole on top of the entire structure exhibit noticeably more change with frequency (β by $\approx 10\%$, Z_c by $\approx 20\%$). One point to note is that the differential phase shift $\Delta\beta = (\beta_+ - \beta_-)$ also changes with frequency.

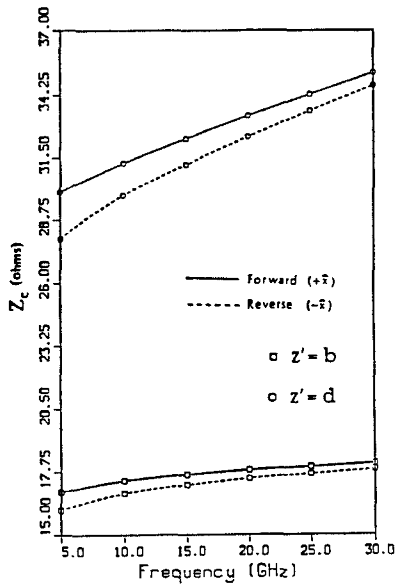
Fig. 3 shows the frequency variation of the propagation characteristics of an inverted microstrip configuration ($\epsilon_1 = 1$ and other parameters are the same as those for Fig. 2). It is seen that in contrast to the results shown in Fig. 2, for inverted microstrip, the propagation constant for the backward waves is larger than that for the forward waves.

Propagation properties for a line at the semiconductor-ferrite interface at 10 GHz are plotted as a function of bias angle in Figs. 4 and 5. In Fig. 4, the propagation constant is plotted against θ_0 for different ϕ_0. The forward and backward traveling waves have the same constant when $\phi_0 = 0^0$ (not shown), and all curves coincide at $\theta_0 = 0^0$ (along the z - axis). As θ_0 approaches 90^0 , the difference in phase shift reaches its peak. It is seen that the propagation constant for backward waves decreases when the bias field angle *theta*$_0$ increases.

Fig. 5 shows the microstrip characteristics as a function of ϕ_0 when θ_0 is held at 90^0. The variation in differential phase shift with respect to bias angle suggests a way to achieve a nonreciprocal phase shifter whose phase shifting properties are adjustable. Conversely, if the bias angle is fixed, its phase shifting behavior could be controlled by changing the frequency, as shown in Fig. 2. It is also seen that the propagation constant and the characteristic impedance are largest when the bias H field is transverse to the microstrip.



(a)



(b)

Figure 2 Microstrip line Characteristics as a function of frequency.

(a). Propagation constant.

(b). Characteristic impedance.

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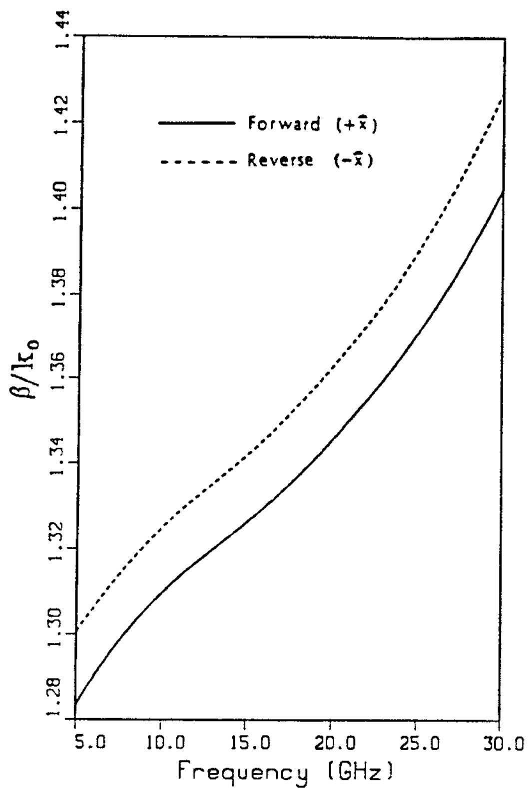

Figure 3. Propagation constant as a function of frequency for inverted microstrip ($zl = b$, $\epsilon_1 = 1$).

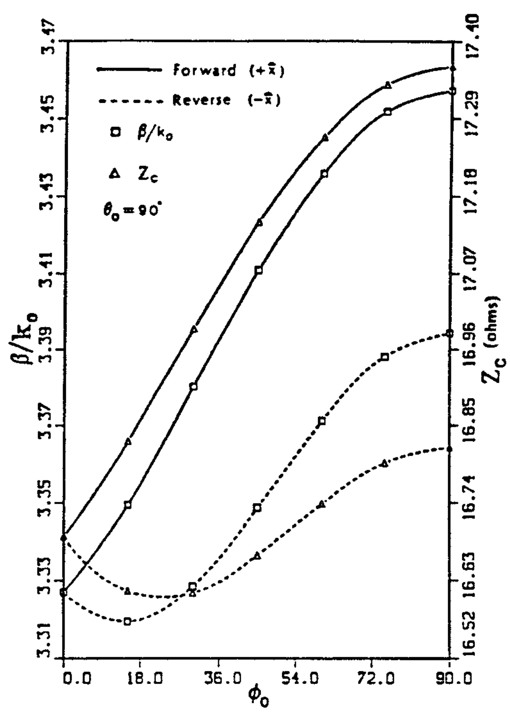

Figure 5. Propagation constant and characteristic impedance as a function of ϕ_0 $\theta_0 = 90^\circ$, f = 10 GHz, $zl = b$.

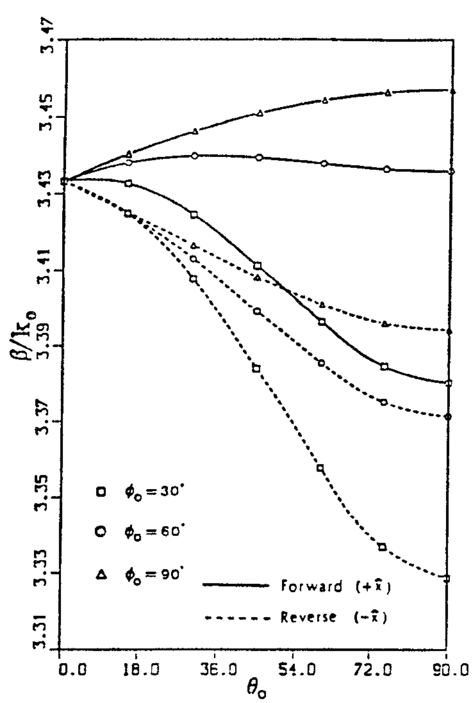

Figure 4 Propagation constant as a function of θ_0 for various ϕ f = 10 GHz, $zl = b$.