Analysis of Shielded Striplines and Finlines with Finite Metallization Thickness Containing Magnetized Ferrites

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Abstract—**The applicability of the spectral-domain approach is extended to analyze various types of shielded planar transmission lines, taking the anisotropy of the magnetized ferrites and the finite metallization thickness into consideration. The numerical computations include the propagation characteristics of finlines and striplines and the metallization thickness effect in these lines. Numerical data of simpler structures are compared with the available exact solution as well as with published data.**

I. Introduction

Shielded planar transmission lines containing ferrites have received considerable attention from the point of view of applications for nonreciprocal devices in microwave and millimeter-wave integrated circuits [1]–[7]. The transmission line structures with a single-layered ferrite substrate do not exhibit adequate nonreciprocity, and additional layers, such as spacer or overlay, are introduced to increase the nonreciprocity [3], [6]. Analytical methods for multilayered structures containing ferrites have been investigated mainly for the finline structures [3], [6] based on the assumption that the line conductors involved have zero thickness. In these transmission line structures, however, the electromagnetic fields are concentrated near the line conductor edge, which increases the effect of the conductor thickness. In particular, this effect will be notable for the cases with overlay or spacer of high permittivity near the line conductor. The metallization thickness effect has been investigated by the author for the cases with isotropic and/or uniaxially anisotropic media [10]–[14].

This paper presents an analytical method for various shielded planar transmission lines with multilayered media containing magnetized ferrites, taking the finite thickness of the line conductor into consideration. The method is based on the spectral-domain approach (SDA) [8], [9]. Galerkin's procedure used in the spectral domain has been successfully applied to analyze the propagation characteristics of various types of planar transmission lines [3], [8], [9]. The SDA will be extended in the following to take the anisotropy of the magnetized ferrites and metallization thickness effect into consideration without diminishing the versatility of the method. Since the mathematical formulation of the SDA has been discussed extensively in [3], [8], and [9], only the essential steps to the extension will be illustrated.

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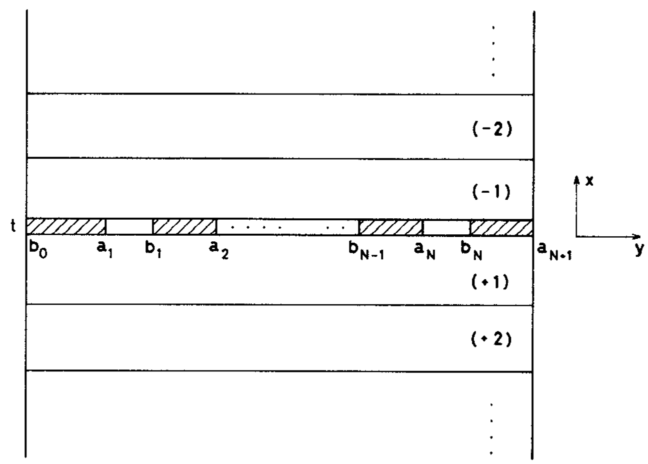

Fig. 1. General structure of shielded planar transmission lines with the stratified media containing the magnetized ferrites.

II. Analytical Formalism of Electromagnetic Fields

Fig. 1 shows the cross section of the general structure of planar transmission lines. The structure consists of a number of printed conductors of finite thickness with the stratified media. These layers are assumed to be lossless, but one or more of them may be magnetized ferrites. When the ferrite in the subregion (m) is magnetized in the y direction, the permeability tensor is expressed as [3]

$$\bar{\bar{\mu}} = \mu_0 \begin{bmatrix} \mu_r & 0 & j\kappa \\ 0 & 1 & 0 \\ -j\kappa & 0 & \mu_r \end{bmatrix} \tag{1}$$

where μ_r and κ are dependent on the operating frequency ω, the applied dc magnetic field H_0, and the magnetization of the ferrite $4\pi M_s$ [3].

Electromagnetic fields in the subregion (m) are expressed by the spectral representation in the y direction, e.g.,

$$E_y^{(m)}(x,y,z) = \sum_{n=-\infty}^{\infty} \tilde{E}_y^{(m)}(n,y) e^{-j\alpha_n y} e^{-j\beta z} \qquad (m = 0, \pm 1, \pm 2, \cdots) \tag{2}$$

where β is the phase constant, and $\tilde{E}_y^{(m)}(n,x)$ is the Fourier transform of $E_y^{(m)}(x,y)$. Fourier variables α_n in each subregion are determined satisfying the boundary conditions at the sidewall [12].

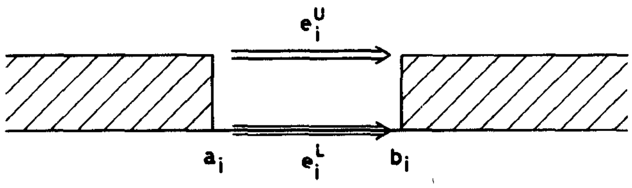

Fig. 2. Aperture fields.

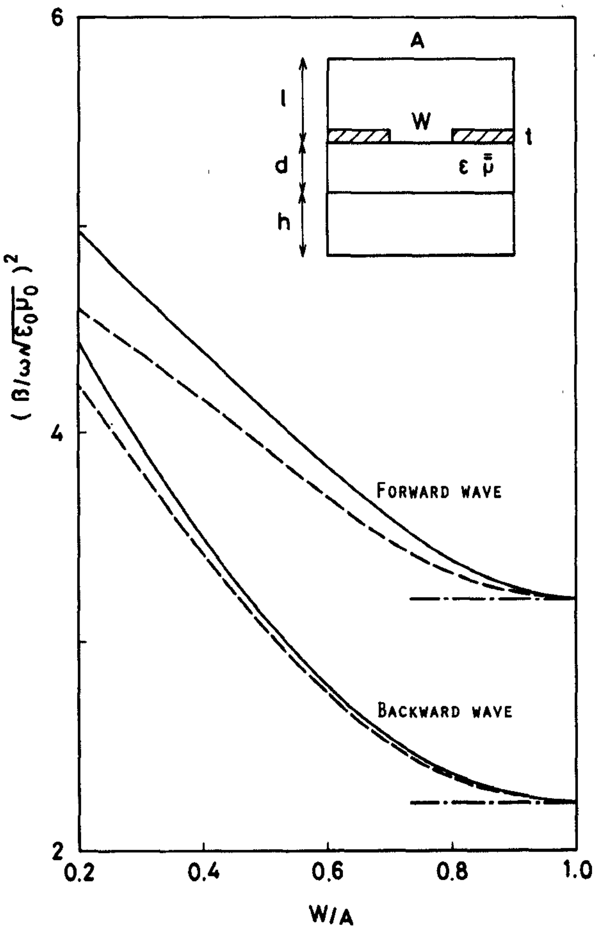

Fig. 3. Variation of the propagation characteristics with slot width for the finline with single-layered ferrite: ——— finline ($t = 0$); ---- finline ($t = 70$ μm); —·—· partially filled ferrite waveguide [14]. $\epsilon_r = 12.5$, $4\pi M_s = 5000$ (G), $H_0 = 500$ (Oe), $l = 3$ (mm), $d = 1$ (mm), $h = 1$ (mm), $A = 3$ (mm), $f = 20$ (GHz).

The wave equations, which determine the Fourier transform $\tilde{E}_y^{(m)}(n,x)$ and $\tilde{H}_y^{(m)}(n,x)$, are derived from Maxwell's equations as [3]

$$\frac{d^2}{dx^2}\tilde{E}_y^{(m)}(n,x) - \left(\beta^2 + \alpha_n^2 - k_m^2\mu_e\right)\tilde{E}_y^{(m)}(n,x) = -j\omega\mu_0\xi\alpha_n\tilde{H}_y^{(m)}(n,x)$$

$$\frac{d^2}{dx^2}\tilde{H}_y^{(m)}(n,x) - \left(\beta^2 + \frac{1}{\mu_r}\alpha_n^2 - k_m^2\right)\tilde{H}_y^{(m)}(n,x) = j\omega\epsilon_m\xi\alpha_n\tilde{E}_y^{(m)}(n,x) \tag{3}$$

where $k_m^2 = \omega^2\epsilon_m\mu_0$, $\mu_e = \mu_r - \kappa^2/\mu_r$, and $\xi = \kappa/\mu_r$.

Applying the continuity conditions at the interfaces $x = x_k (x_k \neq 0, t)$ to the general solution of (3) and introducing

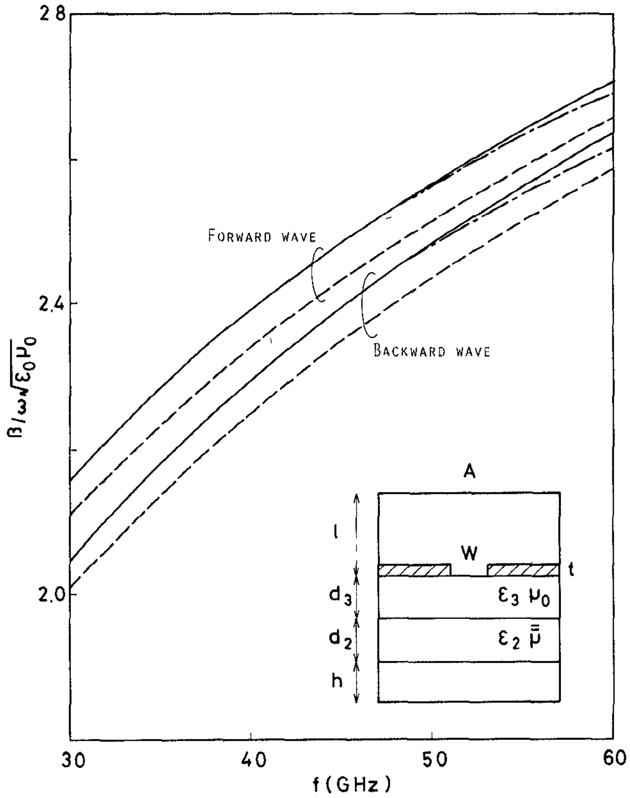

Fig. 4. Frequency-dependent characteristics of the dielectric-ferrite (DF) double-layered finline: ——— present theory ($t/W = 0$); ---- present theory ($t/W = 0.05$); —·—· Ref. [3]. $\epsilon_{2r} = \epsilon_{3r} = 12.5$, $4\pi M_s = 5000$ (G), $H_0 = 500$ (Oe), $l = h = 2.1$ (mm), $d_2 = d_3 = 0.25$ (mm), $W = 1$ (mm), $A = 2.35$ (mm).

the aperture fields at $x = t$, $e_i^U(y)$ and at $x = 0$, $e_i^L(y)$ (Fig. 2), the transverse (to x) components of magnetic fields $H_t^{(m)}(x,y)$ in the subregions can be related to the aperture fields $e_i^U(y)$ and $e_i^L(y)$:

$$H_t^{(m)}(x,y,z) = \sum_i \int_{y'} \left\{ \bar{\bar{Y}}_{Ui}(x,y|y')e_i^U(y') + \bar{\bar{Y}}_{Li}(x,y|y')e_i^L(y') \right\} dy' e^{-j\beta z} \tag{4}$$

where the $\bar{\bar{Y}}$'s are the dyadic Green's functions.

Finally, the applying the continuity conditions of the magnetic fields at the aperture planes $x = t$ and 0 to (4), we obtain the integral equations on the aperture fields $e_i^U(y)$, $e_i^L(y)$ and implicitly the propagation constant β. Then, applying Galerkin's procedure [3], [8]–[14] to the integral equations, we obtain the determinantal equation for β. In this procedure, the unknown aperture fields $e_i^U(y), e_i^L(y)$ are expanded in terms of the appropriate basis functions, which are similar to those in [8]–[14] and take the edge effect into consideration. Three or four basis functions for each quantity are sufficient for most cases, but more basis functions are required for extremely wide aperture widths.

III. Numerical Examples

To show the validity of the present method, preliminary computations have been carried out. Fig. 3 shows the slot width dependence of the propagation constants for the special case of the single-layered finline. The metallization

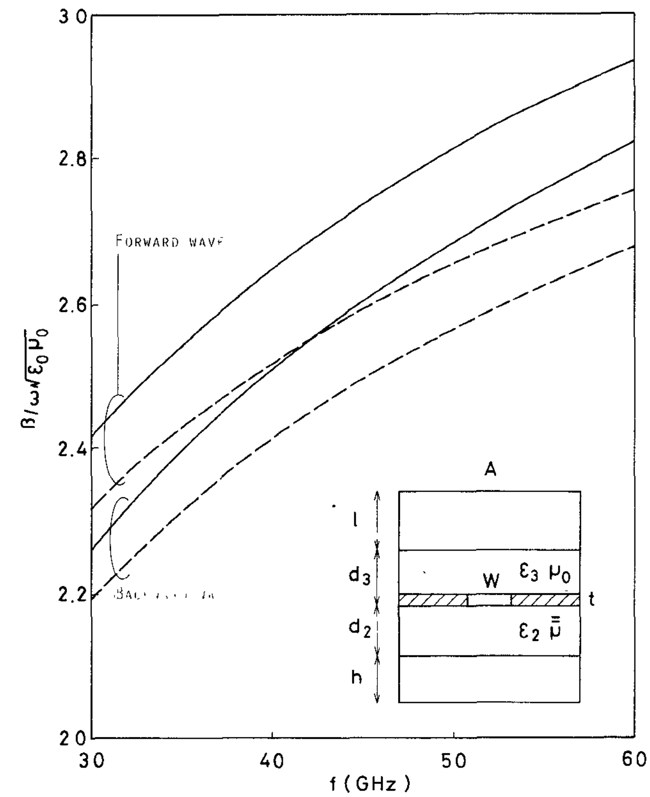

Fig. 5. Frequency-dependent characteristics of the sandwich finline: —— $t/W=0$; ---- $t/W=0.05$. $\epsilon_{2r}=\epsilon_{3r}=12.5$, $4\pi M_s=5000$ (G), $H_0=500$ (Oe), $l=h=2.1$ (mm), $d_2=d_3=0.25$ (mm), $W=1$ (mm), $A=2.35$ (mm).

thickness effect in finlines decreases with the aperture width W. It should be noted that the limiting case $W=A$ is reduced to the partially filled ferrite waveguide problem, which can be analyzed easily [15]. The numerical results presented here converge to those of the partially filled ferrite waveguide for both zero thickness and finite thickness of metallization, as slot width W approaches A, which show the accuracy of the computations. Also, it is observed that there is significant difference in the effect of the conductor thickness between the forward and backward wave cases, i.e., the thickness effect of the forward wave case is more than twice as large as that of the backward wave case for W/A larger than 0.2. In the forward wave case, the electromagnetic fields are more concentrated near the aperture.

Fig. 4 shows the dispersion characteristics of the dielectric ferrite (DF) double-layered finline. Our results for the zero-thickness cases ($e_t^U=e_t^L$ in Fig. 2) are in good agreement with results in [3], although slight discrepancies appear at high frequencies.

Fig. 5 shows the dispersion characteristics of the sandwich finline. If the effect of the metallization thickness is neglected ($t=0$), the sandwich structure gives higher nonreciprocity than the DF double-layered finline, as pointed out in [6]. However, the effect of metallization thickness cannot be neglected in this configuration, and the thickness effect of the forward wave is larger than that of backward wave. Therefore, the nonreciprocity is significantly diminished when the metallization thickness effect is taken into consideration.

In Fig. 6, the differential phase shifts $\Delta\beta=\beta_f-\beta_r$ for the dielectric-ferrite (DF) double-layered and the sandwich fin-

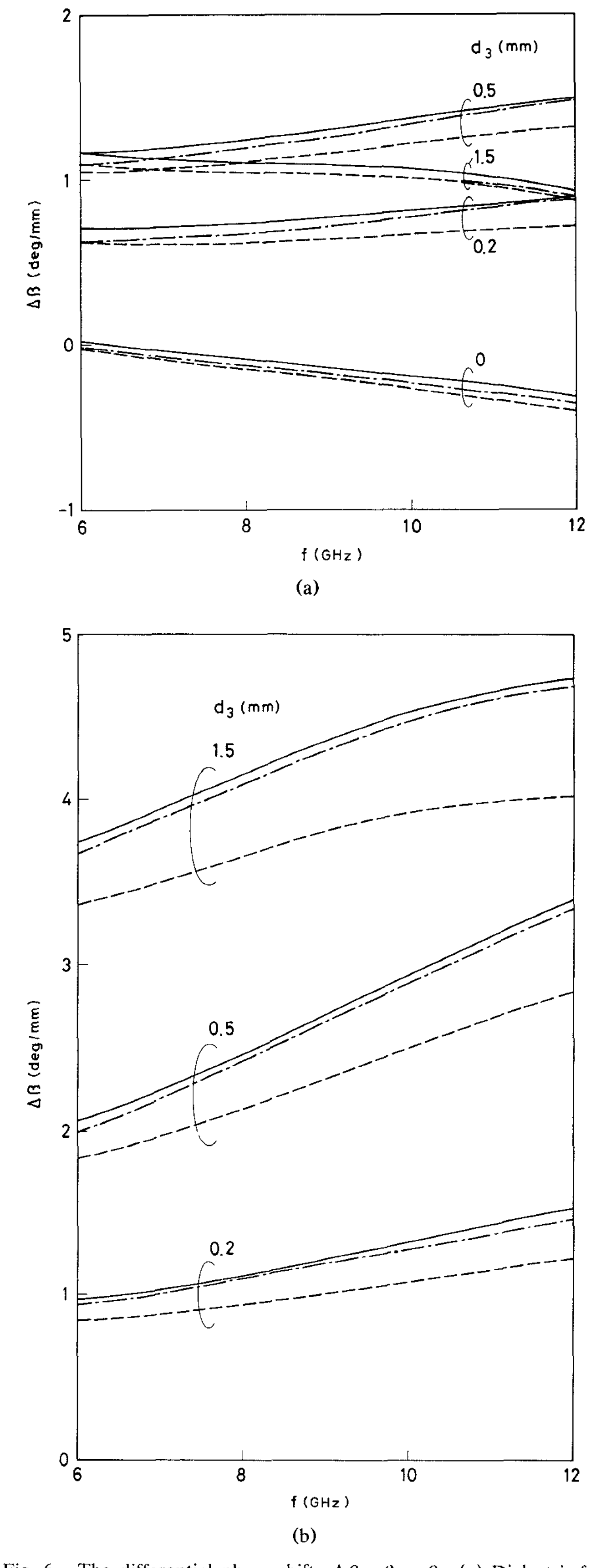

Fig. 6. The differential phase shifts $\Delta\beta=\beta_f-\beta_r$. (a) Dielectric-ferrite (DF) double-layered finlines. (b) Sandwich finlines. —— present theory ($t=0$); ---- present theory ($t=70$ μm); —·—· Ref. [6] ($t=0$). $\epsilon_{2r}=11.6$, $\epsilon_{3r}=20.0$, $M_s=1800$ (A/cm), $H_0=300$ (A/cm), $l=h=10$ (mm), $d_2=0.635$ (mm), $W=1.27$ (mm), $A=20$ (mm).

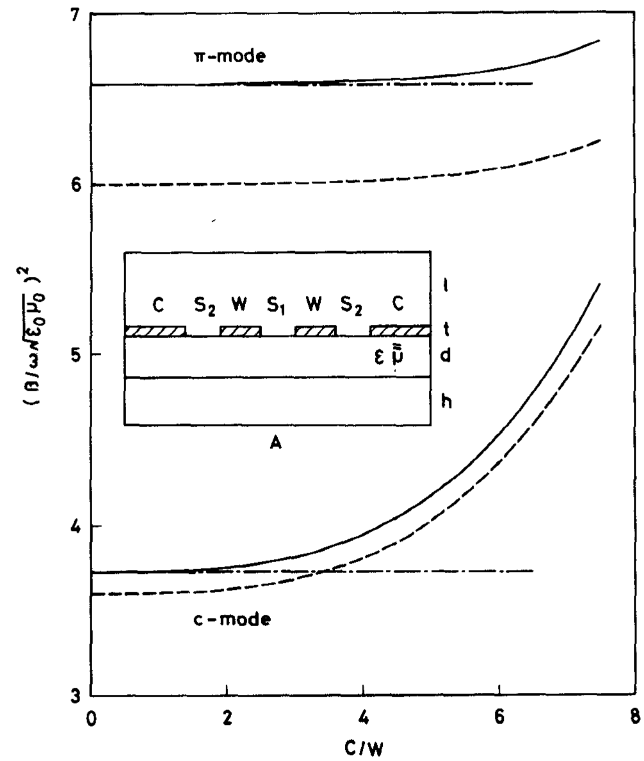

Fig. 7. Variation of the propagation characteristics with fin width for the single-layered coupled coplanar waveguide (C-CPW): ——— C-CPW ($t = 0$); ---- C-CPW ($t = 70$ μm); —·—· shielded coupled striplines. $\epsilon_r = 12.7$, $M_s = 1.71$ (kA/cm), $H_0 = 7.96$ (kA/cm), $h = 1$ (mm), $d = 1$ (mm), $l = 4$ (mm), $S_1 = 0.5$ (mm), $W = 1$ (mm), $A = 20$ (mm), $f = 10$ (GHz).

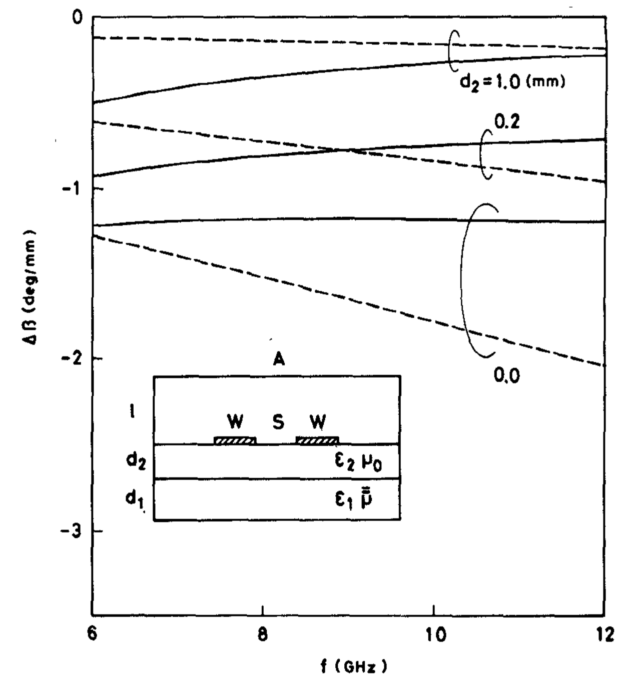

Fig. 8. Differential phase shifts for dominant c and π modes of coupled stripline with composite dielectric-ferrite (DF) substrate: ——— c mode; ---- π mode. $\epsilon_{1r} = 11.6$, $\epsilon_{2r} = 20.0$, $M_s = 1800$ (A/cm), $H_0 = 300$ (A/cm), $d_1 = 0.635$ (mm), $l = 10$ (mm), $S = 0.4$ (mm), $W = 1$ (mm), $A = 10$ (mm).

line are compared with those from [6]. It should be mentioned that the results in [6] neglect the metallization thickness, and the dimensions of the shielding in [6] were chosen so large that they have no influence on the results.

Fig. 7 shows the propagation constants of the backward wave of the single-layered coupled coplanar waveguide (C-CPW) as a function of the fin width C. When C is diminished to zero, the structure is reduced to shielded coupled striplines on a magnetized ferrite. The shielded coupled striplines with isotropic and/or uniaxially anisotropic media have been analyzed mainly by applying the spectral-domain approach and using the current densities on the strips as source quantities [8]. This conventional approach can be extended to analyze the striplines of zero thickness with magnetized ferrite, and numerical values based on the current density are included in Fig. 7 for comparison. The values of C-CPW based on the aperture fields converge monotonically to that of the stripline based on the current, as the fin width C approaches 0, which again shows the validity of the present method. A similar convergence is observed for forward waves. It should be noted that the conventional approach based on the current density cannot be applied to thick strip cases, whereas the approach based on the aperture fields is applicable to thick as well as thin ($t = 0$) conductor cases.

Fig. 8 shows the differential phase shifts for the dominant c and π modes of the coupled stripline with the composite dielectric-ferrite (DF) substrate. The differential phase shifts for c modes decrease with frequency, whereas those for π modes increase with frequency.

Frequency ranges for the numerical computations are chosen to be higher than the resonance frequency. In the resonance region, losses have to be taken into consideration, and loss evaluation is scheduled for a future work.

IV. Conclusions

The spectral-domain approach (SDA) is extended to analyze various types of shielded planar transmission lines with multilayered media containing magnetized ferrites, taking the metallization thickness effect into consideration. Numerical computations are performed based on Galerkin's procedure, and they include the propagation characteristics of various planar transmission lines to show the validity and the versatility of the method. The numerical data of simpler structures are compared with the available exact solution as well as with published data. For the first time, the metallization thickness effect is revealed for planar transmission lines containing magnetized ferrites.

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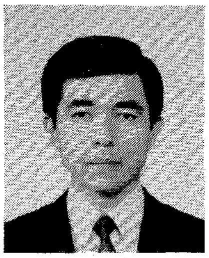

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