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Propagation characteristic of a ferrite image guide

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The propagation of electromagnetic waves in a ferrite image line was theoretically formulated. The formulation was based upon the effective permeability approach. The ferrite image line consisted of an insulating slab of ferrite with a rectangular cross section overlaid on an electrical ground plane. The ferrite was purposely magnetically biased so that FMR coincided with the band of frequencies in which propagation is allowable in the waveguide structure. Insertion loss and phase shifts of the electromagnetic wave signal was calculated as a function of frequency. We suggest that ferrite phase shifters, isolators, filters, and switches operating at the millimeters wavelength may be feasible using this guided structure.

I. INTRODUCTION

Dielectric image guides have been widely adapted for various millimeter wave and integrated optics.¹⁻⁷ To achieve nonreciprocal effects in passive devices, ferrites have been incorporated in dielectric image guides for this purpose. With new magnetic materials emerging in recent years we propose a new type of guiding structure made of ferrite materials. We believe that ferrite image guides could provide nonreciprocal effects as well as microwave devices operational at millimeter wave frequencies. Nowadays there are a number of mathematical methods that have been applied to calculate *em* wave propagation in planar devices. We have adopted one of the simpler methodology in order to obtain analytical solutions to this problem. The method is referred to in the literature as the effective permeability method presented by Xia, Toullos, and Vittoria.¹

This method is straightforward in terms of solving the wave equations associated with wave propagation in dielectric image lines as will be described here. However, the calculational of the wave dispersion may be approximated near the cutoff frequencies. Away from cutoff frequencies, the propagation dispersion is sufficiently accurate.⁷ For our purpose of being able to predict the feasibility of our design concepts, it is sufficient.

II. THEORETICAL FORMULATION

In Fig. 1 a ferrite image guide is shown on a perfect conducting plane. An exact solution for this problem is extremely difficult. This is due to the singularities at the sharp edge of the guided structure. Nevertheless, reasonable and approximate solutions can be obtained for the propagation characteristic of the guided structure depicted in Fig. 1 using the effective dielectric and the effective permeability method here. We assume that the field decays outside dielectric medium; consequently, most of the energy would be confined within the guided structure.

To begin with, Maxwell's equation are written in the following form:

$$\nabla \times \mathbf{e} = -j\omega\mu_0\tilde{\boldsymbol{\mu}} \cdot \mathbf{h}, \quad (1)$$

$$\nabla \times \mathbf{h} = j\omega\epsilon_0\boldsymbol{\epsilon} \cdot \mathbf{e}, \quad (2)$$

$$\nabla \cdot \mathbf{e} = 0, \quad (3)$$

$$\nabla \cdot (\mu_0\tilde{\boldsymbol{\mu}} \cdot \mathbf{h}) = 0, \quad (4)$$

where $\tilde{\boldsymbol{\mu}}$ and $\boldsymbol{\epsilon}$, are the permeability tensor¹ and the relative dielectric constant of the ferrite slab, respectively.

The guided structure shown in Fig. 1 supports the hybrid mode of propagation, E^y and E^x .⁵ Here, we only consider the fundamental mode of propagation or simply the E^y mode. The E^y mode assumption also implies that the magnetic field h_y component is zero.⁷ Here, the wave equation would take on the following form:

$$\nabla(\nabla \cdot \mathbf{h}) - \nabla^2 \mathbf{h} = \omega^2\mu_0\epsilon_0\boldsymbol{\epsilon}\tilde{\boldsymbol{\mu}} \cdot \mathbf{h}. \quad (5)$$

With some mathematical manipulations of Eq. (5), it yields the following two equations

$$[\omega^2\mu_0\epsilon_0\epsilon_{\mu_{xx}} + (k_x^2 - k^2)]\mathbf{h}_x + (k_x k_z - j\mu_{xz}\omega^2\mu_0\epsilon_0\epsilon_r)\mathbf{h}_z = 0, \quad (6)$$

$$(k_x k_z + j\mu_{xz}\omega^2\mu_0\epsilon_0\epsilon_r)\mathbf{h}_x + [\omega^2\mu_0\epsilon_0\epsilon_{\mu_{xx}} + (k_z^2 - k^2)]\mathbf{h}_z = 0. \quad (7)$$

For a nontrivial solution of h_x and h_z , the determinant of the parameter matrix equation has to be equal to zero. Since the external biasing field is along the y direction, the propagation constant k_y is assumed to be zero. The secular or characteristic equation is the well-known relationship:

$$k^2 = k_0^2\epsilon_{\mu_{\text{eff}}}, \quad (8)$$

where

$$k_0^2 = \omega^2\mu_0\epsilon_0,$$

$$\mu_{\text{eff}} = (\mu_{xx}^2 - \mu_{xz}^2) / \mu_{xx},$$

k_0 is the wave number in free space and μ_{eff} can be defined as the effective permeability¹ of the ferrite slab. Conferring propagation only to the E^y mode of propagation, we may approximate the y component of the electric field in different regions of the guided structure (see the Appendix). From the application of Maxwell's equations, we may relate h_z to e_y in each region. For isotropic dielectric media,

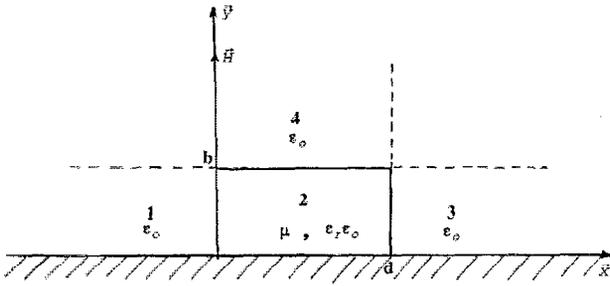


FIG. 1. Ferrite image guide being analyzed ($d=0.5$ cm, $b=0.25$ cm).

relating h_z to e_y is straightforward. However, in the ferrite region, we have derived the following relationship:

$$h_z = \exp(-j\beta_z z + j\omega t) [A_2 Z^+ k_x \exp(jk_x x) + B_2 Z^- k_x \exp(-jk_x x)], \quad (9)$$

$$Z^- = \rho/\omega + \rho\beta_z/(\theta\omega k_x), \quad (10)$$

$$Z^+ = -\rho/\omega + \rho\beta_z/(\theta\omega k_x), \quad (11)$$

$$\rho = -\omega^2 \epsilon_0 \epsilon_r (k_y^2 - k_0^2 \mu_{xx} \epsilon_r) / \Delta, \quad (12)$$

$$\theta = j(k_y^2 - k_0^2 \mu_{xx} \epsilon_r) / (k_0^2 \mu_{xz} \epsilon_r), \quad (13)$$

$$\Delta = k_0^4 (\mu_{xx}^2 - \mu_{xz}^2) + k_y^2 (k_y^2 - 2k_0^2 \mu_{xx} \epsilon_r). \quad (14)$$

Application of boundary conditions for e_y and h_z field components yields the following set of transcendental equations:

$$k_y b = m\pi/2 - \tan^{-1}[k_y/(\epsilon_r k_{0y})], \quad m = 1, 2, 3, \dots, \quad (15)$$

$$(Z^- k_x + Z_0 k_{0x}) \exp(j2k_x d) / (Z^- k_x - Z_0 k_{0x}) = (Z^+ k_x + Z_0 k_{0x}) / (Z^+ k_x - Z_0 k_{0x}), \quad (16)$$

where

$$k_{0y} = (k^2 - k_0^2 - k_y^2)^{1/2}, \quad (17)$$

$$k_{0x} = (k^2 - k_0^2 - k_x^2 - k_y^2)^{1/2}, \quad (18)$$

$$Z_0 = \omega \epsilon_0 / (k_0^2 - k_y^2).$$

We may obtain the propagation constant by solving Eqs. (15) and (16) as a function of frequencies.

III. RESULTS AND DISCUSSIONS

In this section, we present the calculated results for the guided structure shown in Fig. 1. In our calculational procedure, we assumed no demagnetization in any direction. This implies that $\mu_{xx} = \mu_{zz}$ and $\mu_{xz} = \mu_{zx}$. This assumption is based upon the rectangular shape of the guided structure and the anisotropy field is large compared to the demagnetizing field.

In the calculation of dispersions for the ferrite guided structure, the following parameters have been assumed for the ferrite material: H_A (anisotropic field) = 11 160 Oe; $4\pi M_s$ (saturation magnetization) = 3000 Oe; and γ (gyro-

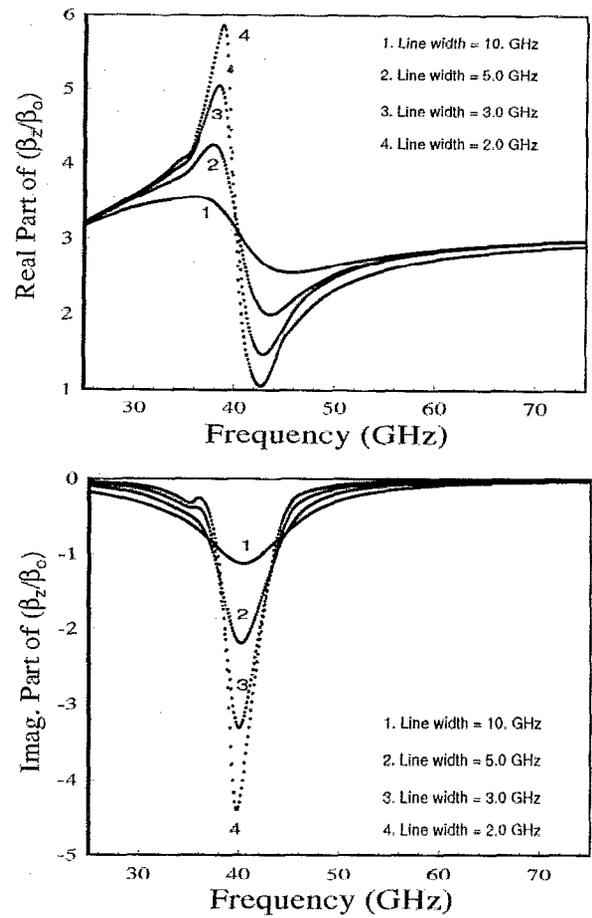


FIG. 2. (a) Real part of the normalized propagation constant as a function of frequency, $H=2000$ Oe. (b) Imaginary part of the normalized propagation constant as a function of frequency, $H=2000$ Oe.

magnetic ratio) = $(2.8 \text{ MHz/Oe}) \cdot 2\pi$. The external biasing field H was fixed at 2000 Oe. The complex propagation constant was plotted as a function of frequencies in Figs. 2(a) and 2(b), respectively. From the real part of the propagation constant, we noticed that the group velocity of the electromagnetic wave tended to slow down at FMR and became negative. This indicated that the energy flow in the guided structure is opposite to the direction of propagation. This type of behavior could be useful in delay line circuits. However, a large amount of energy is being absorbed due to the interaction between the microwave field and precessional motion of the magnetization as shown from the imaginary part of the propagation constant. The amount of attenuation is inversely proportional to the FMR linewidth of the magnetic materials [Fig. 3(b)]. Phase change in the vicinity of FMR tended to be more pronounced for smaller linewidth [Fig. 3(a)]. Since we assumed no dielectric losses in the ferrite image guide, the imaginary part of the propagation constant is diminishing away from FMR. In Figs. 4(a) and 4(b) it is clear that the ferromagnetic resonance frequencies can be varied by varying the external biasing H field.

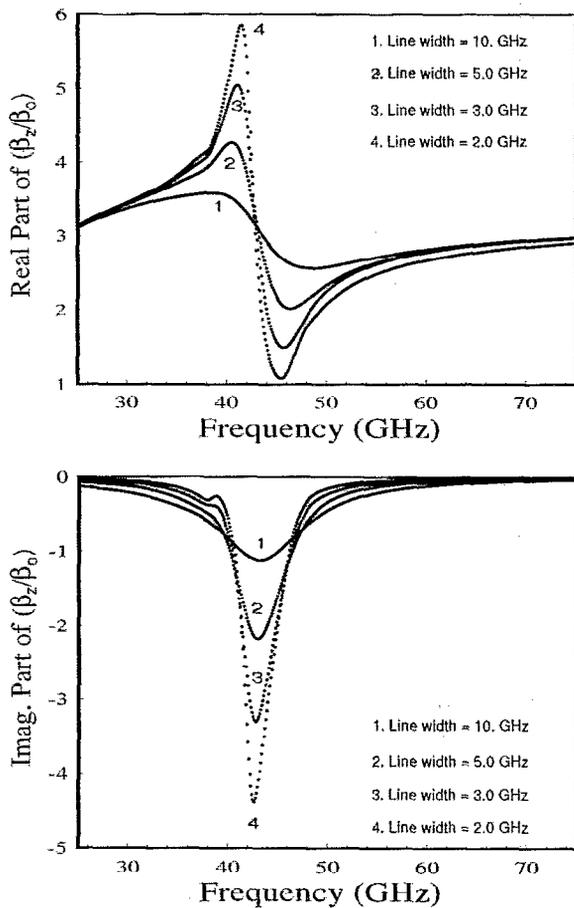


FIG. 3. (a) Real part of the normalized propagation constant as function of frequency, $H=3000$ Oe. (b) Imaginary part of the normalized propagation constant as a function of frequency, $H=3000$ Oe.

IV. CONCLUSIONS

We have presented an approximate analysis for the rectangular ferrite image guide. The theoretical model was based on the effective permeability method. Complex dispersion relationships were obtained by using the single mode approximation. Phase and magnitude of the electromagnetic wave signal was investigated in the regime near

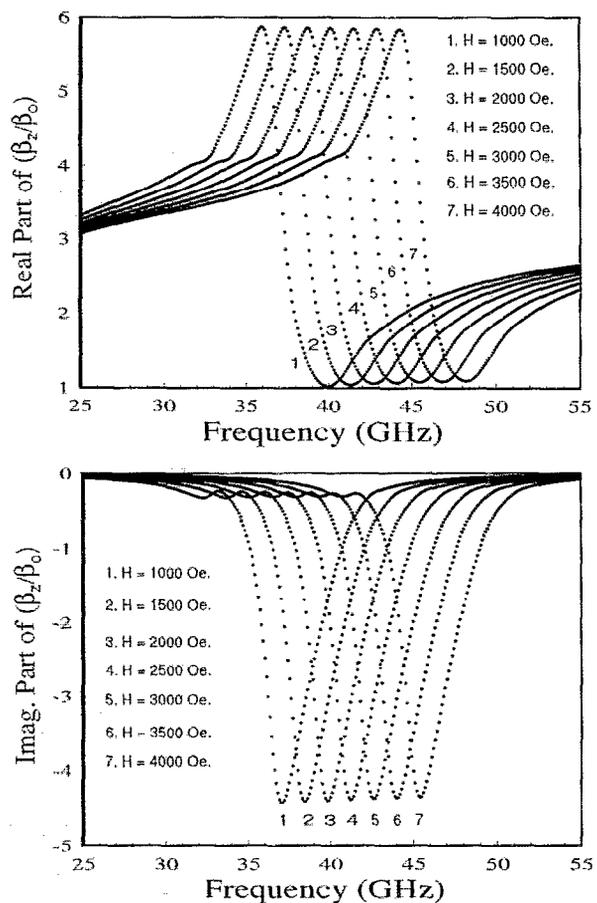


FIG. 4. (a) Real part of the normalized propagation constant as function of frequency, FMR linewidth=2 GHz. (b) Imaginary part of the normalized propagation constant as a function of frequency, FMR linewidth=2 GHz.

ferromagnetic resonance. In practical applications, guided structures using ferrite materials can be useful at millimeter wavelength frequencies.

APPENDIX

The electric field distribution of the E_y components for various regions are shown below:

$$E_y = [\exp(-j\beta_z z + j\omega t)] \begin{cases} A_1 \exp(jk_{0x}x) \cos(k_y y + \beta_y) & \text{region 1} \\ [A_2 \exp(jk_x x) + B_2 \exp(-jk_x x)] \cos(k_y y + \beta_y) & \text{region 2} \\ A_3 \exp(-jk_{0x}x) \cos(k_y y + \beta_y) & \text{region 3} \\ [A_4 \exp(jk_x x) + B_4 \exp(-jk_x x)] \exp[-k_{0y}(y-b)] & \text{region 4,} \end{cases}$$

where A and B are the field amplitude coefficients.

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