MAGNETOSTATIC WAVES IN A NORMALLY MAGNETIZED WAVEGUIDE STRUCTURE†

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ABSTRACT

In this paper, the propagation of magnetostatic waves (MSW) in a normally magnetized low-loss ferrite slab (such as a yttrium iron garnet (YIG) slab), placed inside a waveguide is investigated theoretically. This case has not been studied before, and is analyzed here for the first time.

The ferrite slab is placed inside and along the waveguide in contact with the two side walls. The external dc magnetic field is assumed to be perpendicular to the plane of the ferrite slab (see Fig. 1).

A dispersion relation for the modes of propagation in terms of an infinite determinant can be obtained. With proper truncation procedures, sample numerical calculations for dispersion relations and group time delay per unit length were obtained and are presented hereforth. The general formulation in this paper contains all the information provided by the degenerate cases previously published. One special case of interest, i.e., that of a multilayer planar structure, is derived from our general formulation. The derivation of other special cases follow the same procedure.

INTRODUCTION

Magnetostatic wave propagation in a ferrite slab completely filling a waveguide has been reported in literature.(1) Recently the analysis of magnetostatic wave propagation in a partially YIG-loaded waveguide was reported.(2),(3) In these recent developments, the direction of the dc magnetic field was assumed to be parallel to the slab and perpendicular to the direction of wave propagation which led to the propagation of magnetostatic surface waves (MSSW). These waves are highly nonreciprocal with regard to the direction of the propagation and unsymmetrical with respect to the slab position in the waveguide.

The case of normally magnetized YIG slab partially filling a waveguide has never been approached and remains yet unsolved.

In this paper, the dc magnetic field is perpendicular to the slab plane. This leads to the propagation of magnetostatic volume waves (MSVW), which are reciprocal and symmetrical.

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THEORETICAL ANALYSIS

For the configuration shown in Fig. 1, the standard mode analysis is effective in finding the dispersion relations for the magnetostatic wave propagation in the guide.

For magnetostatic waves, the small signal magnetic field intensity ($\bar{h}$) is given by:

$$\bar{h} = \nabla\phi$$

where ϕ is the scalar magnetic potential satisfying

$$\phi_{xx} + \phi_{yy} + \phi_{zz} = 0 \qquad (1)$$

in the air regions (I and III), and

$$\mu\,(\phi_{xx} + \phi_{yy}) + \phi_{zz} = 0 \qquad (2)$$

in the YIG region (II), where μ is the diagonal element of the permeability tensor which depends on the magnetic properties of the YIG material, the external magnetic field, and the frequency of operation.

For simplicity of analysis, we assume the demagnetizing fields are negligible. In this case, the external magnetic field becomes equal to the internal magnetic field.

The implied time dependence (t) is assumed to be of the form $e^{j\omega t}$ (where ω is the angular frequency) and is omitted in the following expressions. The variation of ϕ in the axial direction (y) is assumed to be of the form e^{-jKy}, where K is the wave number.

The boundary conditions to be satisfied are: 1) normal components of the magnetic flux density ($\bar{b}$) must be zero at all side walls of the waveguide; i.e., at $x = 0$, a and $z = 0, b$. 2) ϕ and $\partial\phi/\partial z$ must be continuous at the YIG-air interfaces; i.e., at $z = z_1, z_2$.

The following forms of ϕ in the three regions satisfy the first boundary condition and can be expressed as:

$$\phi_1 = \sum_{n=0}^{\infty} A_n \cos n\pi x/a \cosh \gamma_n' (b-z)\, e^{-jKy} \qquad (3)$$

$$\phi_2 = \sum_{n=0}^{\infty} \left(\cos n\pi x/a - \frac{aK_1K}{\mu n\pi} \sin n\pi x/a\right) [B_n \cos \gamma_n z + C_n \sin \gamma_n z]\, e^{-jKy} \qquad (4)$$

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$$\phi_3 = \sum_{n=0}^{\infty} D_n \cos n\pi x/a \cosh \gamma_n' z \, e^{-jKy} \qquad (5)$$

where A_n, B_n, C_n, and D_n are constants, a and b are waveguide dimensions, and K_1 is the off-diagonal element of the permeability tensor which depends on the internal magnetic field, gyromagnetic ratio, saturation magnetization, and the frequency of operation. γ_n and γ_n' are phase constants given by:

$$\gamma_n' = [K^2 + (n\pi/a)^2]^{1/2}$$
$$\gamma_n = \alpha\gamma_n'$$

and

$$\alpha^2 = -\mu, \quad \mu < o.$$

From Eqs. (3), (4), and (5) and with the use of the second boundary condition, two of the constants (i.e., A_n, D_n) can be eliminated. In this manner, an infinite system of linear equations in B_n and C_n can be obtained. These equations (except for the zeroth-order mode) are coupled and one cannot exist without the others. This phenomenon leads to mode coupling between the propagating waves.

Recasting these equations into a matrix form yields an infinite coefficient matrix multiplied by an infinite constant vector. A nontrivial and unique solution exists when the determinant of the infinite coefficient matrix is set to zero. For the purpose of numerical computations which follow in the next session, the infinite determinant is truncated to a finite order.

Degenerate Case

As noted above, the zeroth-order mode is uncoupled and corresponds to the case when $a \to \infty$, i.e., when the YIG slab is placed between two ground planes. This structure has been investigated in literature previously.(4),(5) Setting the determinant of the zeroth-order matrix yields the exact dispersion relations reported by Daniel et al.(6)

COMPUTER SIMULATION AND RESULTS

To obtain a nontrivial solution for higher order mode (other than zero) from the system of linear equations, the determinant of the coefficient matrix must be zero. However, for practical purposes, the matrix was properly truncated for best accuracy. An extensive computer program was developed to find the determinant of the coefficient matrix. The matrix was properly truncated depending on the mode of propagation under study, and with the aid of a proper computer algorithm, the determinant roots of the dispersion relation were found through several iterations.

Fig. 2 shows the effect of lowering the slab position. Besides the zeroth-order mode, two higher order modes are also shown. These higher order modes exist due to finite widths of the slab. In Fig. 3, the corresponding group time delays for different modes are plotted. The time delay increases as the slab is moved toward the middle of the waveguide. These characteristics obtained for the propagating waves are reciprocal and symmetrical. Fig. 4, shows the effect of normal magnetic field for several bias field values. The dispersion curves are simply shifted to higher ranges of frequencies as the bias field value is increased. This effect on the corresponding group time-delay characteristics is shown in Fig. 5.

CONCLUSIONS

The propagation of magnetostatic waves in a ferrite (such as YIG) slab inside a rectangular waveguide was analyzed. The employment of mode analysis technique yielded the dispersion relations in terms of an infinite determinant. Using proper truncation procedure, several important effects were studied. The dependence of the dispersion relation and group time delay per unit length on the position of the YIG slab and value of the bias field were presented.

From all these results, it becomes evident that in order to achieve high time delays, the slab should be positioned in the center of the guide, while for higher device bandwidths, the YIG slab should be positioned at the top or bottom of the guide. Thus there exists a tradeoff between the time delay per unit length and the device bandwidth and some design compromises should be made. Finally, the tunable properties of the waveguide structure (Fig. 1) by means of a normal magnetic bias field was investigated and the results indicate that the waveguide structure can be tuned to any desired frequency range simply by shifting the bias magnetic field to a proper value.

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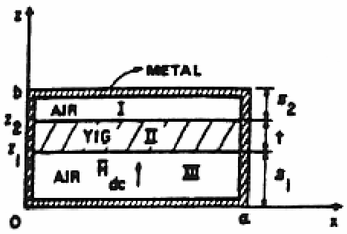

FIG. 1 PARTIALLY LOADED WAVEGUIDE WITH $\bar{H}_{dc}$ NORMAL TO THE YIG SLAB.

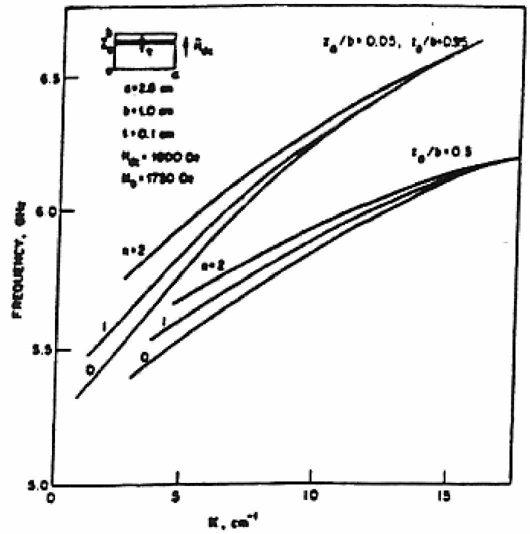

FIG. 2 EFFECT OF SLAB POSITION ON THE DISPERSION CHARACTERISTICS.

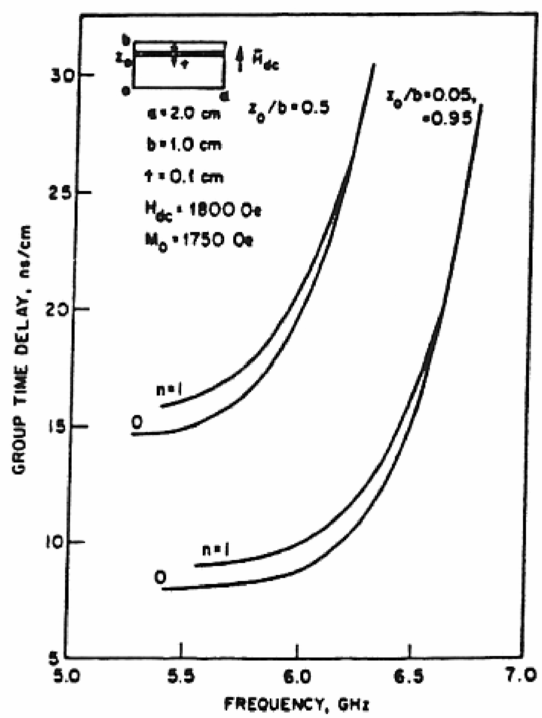

FIG. 3 GROUP TIME DELAY VS. FREQUENCY.

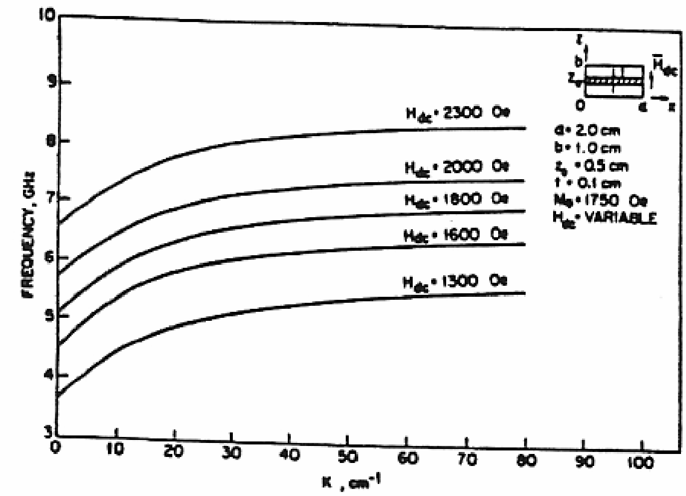

FIG. 4 DISPERSION CHARACTERISTICS FOR VARIOUS MAGNETIC FIELDS.

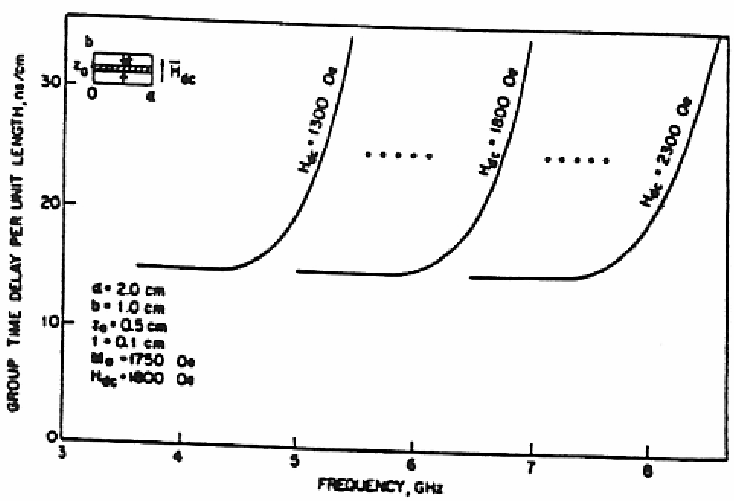

FIG. 5 GROUP TIME DELAY CHARACTERISTICS.