MAGNETOSTATIC SURFACE WAVES IN A LEFT HANDED / FERRITE/ METAL-STRIP-GRATING STRUCTURE

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ABSTRACT

The dispersion characteristics for magnetostatic surface waves in a left handed (LHM)/ferrite/ metal-strip-grating structure have been investigated. We found that, the waveguide supports backward TE waves since both permittivity and magnetic permeability of LHM are negative. We also illustrated the dependence of wave frequency on the reduced wave number for a grating shielding parameter, g values restricted by the range $0 \leq g \geq 1$. *It is shown that the grating shielding parameter, g induces magnetostatic backward shorter waves . The leakage through the grating increases with the wave number. The shorter backward magnetostatic waves are guided by the thicker waveguide where the best confinement is achieved .*

KEYWORDS:

Left handed material, , Magnetostatic waves, metal-strip-grating, Wave-guides, Ferrite..

1. INTRODUCTION

Magnetostatic waves, whose wave number lies between those of electromagnetic waves and exchange spin waves, propagate in a magnetized ferromagnetic medium due to dipole- dipole interaction. Since the propagation characteristics of magnetostatic waves depend on the shape of the medium, many theoretical analysis for an infinite plate, an infinite circular rod[1,2] etc. had been reported. The investigation of magnetostatic waves in an infinite plate can be classified into two groups according to the direction of applied magnetic field. One is the case where the direction of the applied magnetic field is parallel to the sample surface, and the other is the perpendicular case where magnetostatic surface waves cannot exist in. In 1961, the magnetostatic mode in the parallel configuration was analyzed by Damon and Eshbach [2]. In this case, two kinds of magnetostatic modes, volume modes and surface modes, exist. The surface modes have attracted the attention of many researchers in various waveguide structures containing semiconductors or dielectrics . They can be applied to nonreciprocal circuit devices and variable delay lines in microwave integrated circuits due to their nonreciprocal propagation characteristics and slow group velocity[3]. Yukawa et.al. had reported the effects of metal on the dispersion relation of magnetostatic surface waves where the dispersion characteristics are affected by the normalized spacing between the sample and the metal [3]. At present, considerable attention is being given to backward waves whose many properties (such as directivity of propagation as well as reflection and refraction laws) differ from those of forward waves [4] . Backward electromagnetic waves can exist in various media, e.g. a left handed materials(LHM) in which the permittivity and the permeability take negative values in certain frequency range[5-8]. Hamada and Shabat [7] et.al investigated the nonlinear magnetostatic surface waves in a ferrite left handed waveguide structure. Mousa, Abadlah and Shabat [8] have examined the propagation characteristics of magnetostatic surface waves in a left-handed material- ferrite -semiconductor waveguide structures. Backward electromagnetic waves can also exist in composite media formed by a planar periodic grating of current conducting strips placed in a dielectric matrix which are called metal strip grating (MSG). These structures have a wide range of applications in electromagnetic radiating and waveguiding devices such as reflection and transmission filters and laser output couplers[9]. Zubkov et.al. studied the dispersion of magnetostatic surface waves in a ferrite/ dielectric / metal –strip –grating structure. They found that, the leakage of the wave field through the grating increases with the wave number. Consequently, the slop of the dispersion curve in the region of backward magnetostatic waves is higher than the slope of this curve corresponding to a ferrite/ dielectric / metal structure[10,11] as a result of the dependence of the grating shielding parameter on the wave number [4]. The investigation of peculiarities of wave processes in periodic gratings comprising left handed materials(LHM) is of considerable interest for the development of new physical principles of electromagnetic waves generation, amplifying and transmission[12]. In this analysis, a theoretical study of the dispersion properties of magnetostatic surface waves guided by an optical structure is presented. This structure consists of a ferrite thin film sandwiched between (LHM) cover and metal –strip –grating substrate . ε_h and μ_h are electric permittivity and magnetic permeability of LHM respectively

2. DERIVATION OF THE DISPERSION RELATION:

The structure geometry of the problem considered here is shown in Fig.(1). The structure consists of the ferrite film(YIG) , which occupies the region $-d \le x \le 0$ bounded by LHM cover of the space $x \ge 0$, and the metal –strip –grating substrate of the space $x \le -d$. The magnetic field H_0 is applied in the plane of the structure and is parallel to Oz axis.

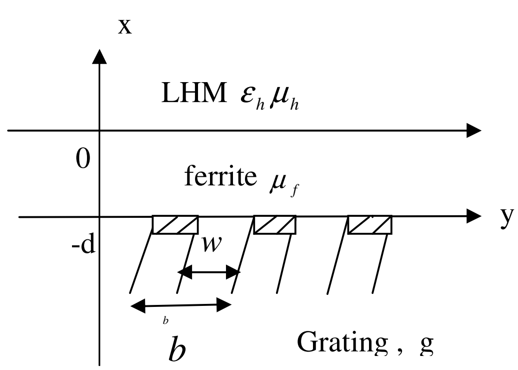


Fig.(1) Magnetostatic surface waves waveguide composed of grating and LHM Layered structure.

We present the dispersion equation for magnetostatic surface waves propagating in the y direction with a propagation wave constant in the form exp $[i(ky - 2\pi ft)]$, where k is the propagation constant, and f is the operating frequency. The magnetic permeability tensor of the gyromagnetic ferrite film is given by[2,13,14] :

$$\mu_f(\omega) = \begin{bmatrix} \mu & i\nu & 0 \\ -i\nu & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Where $\mu = 1 + \Omega_H(\Omega_H^2 - \Omega^2)^{-1}$, $\nu = \Omega(\Omega_H^2 - \Omega^2)^{-1}$. The tensors are called the usual Polder tensor elements, with $\Omega_H = H_0(4\pi M_0)^{-1}$ and $\Omega = \omega(4\pi\gamma M_0)^{-1}$

H_0 is the applied magnetic field, M_0 is the dc saturation magnetization and γ is the gyromagnetic ratio for an electron. In order to quantitatively express the partial leakage of the field, let us introduce a grating shielding parameter, g, such that $0 \le g \ge 1$[5]. The grating, which is considered infinitely thin, is formed from straight metal strips that are parallel to the direction of H_0. The grating spacing is b and the window width is w. The value of $g = 0$ corresponds to completely open slots when the strip width is zero and $w = b$. The structure becomes an LHM/ ferrite/vacuum. The value of $g = 1$ corresponds to completely closed slots when the strip width is equal to grating spacing b and $w = 0$, the grating becomes a completely shielding. The structure becomes an LHM/ ferrite/metal. The intermediate values of parameter g correspond to a grating with a certain value of ratio wb^{-1}.

From Maxwell's equations we can obtain electric and magnetic field components in three regions

2.1 In grating ($x \le -d$)

$$\vec{\nabla} x \vec{H}_1 = 0 \qquad (1a)$$

$$\vec{\nabla} . \vec{b}_1 = 0 \qquad (1b)$$

Where $\vec{b}_1$ is the magnetic induction.

The magnetic potential ψ_1 exist and satisfies $\vec{H}_1 = -\vec{\nabla}\psi_1$. (1c)

Substituting eq.(1c) into eq. (1b), ψ_1 satisfies the following equation

$$\frac{\partial^2\psi_1}{\partial x^2} + \frac{\partial^2\psi_1}{\partial y^2} = \frac{\partial^2\psi_1}{\partial x^2} - k^2\psi_1 = 0 \qquad (2)$$

The solution is written as:

$$\psi_1 = (1 - g)B_1 e^{k_1 x} e^{i(ky - \omega t)} \qquad (3)$$

Substituting eq.(3) into eq. (2), one gets:

$$k_1^2 = k^2$$

The magnetic field components are calculated using $\vec{H}_1 = -\vec{\nabla}\psi_1$ and written as:

$$H_{x1} = -\frac{\partial \psi_1}{\partial x} = -(1-g)kB_1 e^{kx}\, e^{i(ky-\omega t)} \tag{4a}$$

And

$$H_{y1} = -\frac{\partial \psi_1}{\partial x} = -i(1-g)kB_1 e^{kx}\, e^{i(ky-\omega t)} \tag{4b}$$

2.2 In ferrite ($-d \le x \le 0$)

$$\vec{\nabla} x \vec{H}_2 = 0 \tag{5a}$$

$$\vec{\nabla}.\vec{b}_2 = 0 \tag{5b}$$

The magnetic induction $\vec{b}_2 = \mu_0 [\mu_f] \vec{H}_2$

Magnetic potential can be defined in this region too and written as:

$$\psi_2 = g(A_2 e^{k_2 x} + B_2 e^{-k_2 x}) e^{i(ky-\omega t)} \tag{6a}$$

The magnetic potential ψ_2 satisfies $\vec{H}_2 = -\vec{\nabla}\psi_2$. (6b)

Substituting eq.(6b) into eq. (5b), one obtains:

$$\frac{\partial^2 \psi_2}{\partial x^2} + \frac{\partial^2 \psi_2}{\partial y^2} = \frac{\partial^2 \psi_2}{\partial x^2} - k^2 \psi_2 = 0 \tag{6c}$$

Substituting eq.(6a) into eq. (6c), one gets:

$$k_2^2 = k^2$$

Each field component is obtained as :

$$H_{x2} = -\frac{\partial \psi_2}{\partial x} = -gk(A_2 e^{kx} - B_2 e^{-kx}) e^{i(ky-\omega t)} \tag{7a}$$

And

$$H_{y2} = -\frac{\partial \psi_2}{\partial y} = -igk(A_2 e^{kx} + B_2 e^{-kx}) e^{i(ky-\omega t)} \tag{7b}$$

$$b_{x2} = \mu_0 \begin{bmatrix} \mu & i\nu & 0 \\ -i\nu & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} H_{x2} \\ H_{Y2} \\ 0 \end{bmatrix} \tag{7c}$$

Substituting eq.(7a) and eq. (7b) into eq.(7c) we get:

$$b_{x2} = \mu_0 g k [(\nu s - \mu) A_2 e^{kx} + (\mu + \nu s) B_2 e^{-kx})] e^{i(ky - \omega t)}$$

Where s takes +1 or -1 according as the static magnetic field is applied in +z or –z direction respectively.

2.3 In LHM ($x \geq 0$)

$$\vec{\nabla} x \vec{H}_3 = -i\omega\varepsilon_0 \varepsilon_h \vec{E}_3 \tag{8a}$$

$$\vec{\nabla} x \vec{E}_3 = i\omega\mu_0 \mu_h \vec{H}_3 \tag{8b}$$

Where,

$$\varepsilon_h(\omega) = 1 - \frac{\omega_p^2}{\omega^2}, \ \mu_h(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}$$

with plasma frequency ω_p and resonance frequency ω_0.

The wave equation can be found easily from the Maxwell's equations as :

$$\frac{\partial^2 E_{z3}}{\partial x^2} - (k^2 - \omega^2 \mu_0 \varepsilon_0 \varepsilon_h \mu_h) E_z = 0 \tag{9a}$$

The exact solution of Eq(4) has the form

$$E_{z3}(x) = A_3 \, e^{-k_3 x} \, e^{i(ky - \omega t)}, \tag{9b}$$

By eqs.(8b) and (9b) we get the magnetic field as follow

$$H_{x3} = \frac{-k}{\omega\mu_0\mu_h} A_3 \, e^{-k_3 x} \, e^{i(ky - \omega t)}, \ H_{y3} = \frac{ik_3}{\omega\mu_0\mu_h} A_3 \, e^{-k_3 x} \, e^{i(ky - \omega t)}$$

where $k_3 = \sqrt{k^2 - \omega^2 \mu_0 \varepsilon_0 \varepsilon_h \mu_h}$ is decay constant of the waves in LH cover.

A_3 is an amplitude coefficient which can be determined by the boundary conditions

Matching the field components H_y and b_x at the boundary $x = 0$, but at the surface of the grating $x = -d$, the wave field is not completely shielded by the grating and partially leaks through it into free space so the boundary conditions at $x = -d$ are:

(1+g) $H_{y1} = H_{y2}$ and $b_{x1} = b_{x2}$, we have the following equations for A_2 and B_2

$$, \begin{bmatrix} 1-\gamma_1(s\nu-\mu) & 1-\gamma_1(s\nu+\mu) \\ [1+(1+g)(s\nu-\mu)]e^{-kd} & [1+(1+g)(s\nu+\mu)]e^{-kd} \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = 0$$

This system admits a non trivial solution only in case its determinant is zero, the dispersion equation is

$$e^{-2kd} = \frac{[1-\gamma_1(\mu+s\nu)]\,[1+(1+g)(s\nu-\mu)\ ]}{[1-\gamma_1(s\nu-\mu)]\,[1+(1+g)(\mu+s\nu)\ ]} \qquad (10)$$

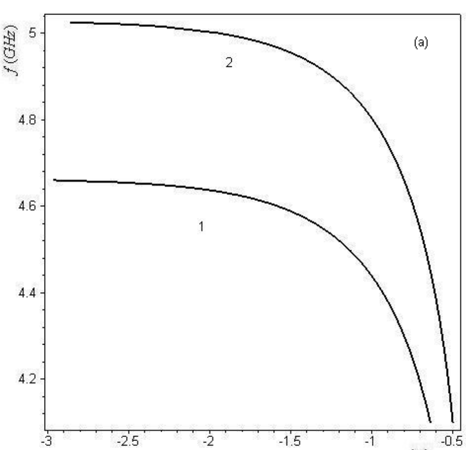
The grating shielding parameter, g, appears in dispersion relation (10), it is supposed that g is related to wave number k as[5]

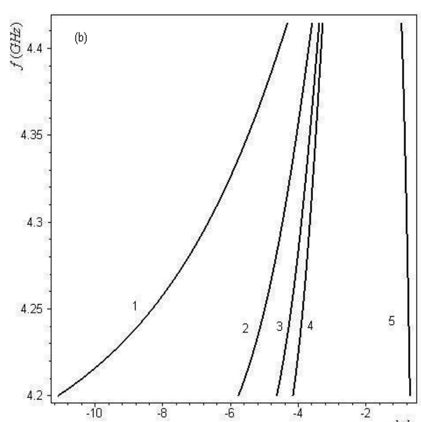
$$g(k) = \left(A_0 + \sum_{n=1}^{\infty} A_n k_n \right)^{-1} \qquad (11)$$

Where A_0 and A_n are unknown coefficients that can be found from electro-dynamic calculations[4]. Let us consider the changes that dispersion curves undergo as parameters A_0 and A_n are varied. Parameter A_0 is determined by the spacing of the grating. When A_0=2 , the slot width is equal to the strip width and to half the spacing of the grating: $w = 0.5b$. The problem is simplified by restricting our analysis to use of only the following parameter pairs: A_0=2 and one of coefficients A_n.

3. NUMERICAL RESULTS AND DISCUSSION:

In this paper, the numerical calculations for LHM/ferrite/grating waveguide are taken with the following parameters: $\omega_p / 2\pi = 10GHz$, $\omega_0 / 2\pi = 4GHz$ and $F = 0.56$ [3], $4\pi M_0 = 1750Gs$, $H_0 = \pi M_0$ Oe [4,14]. The frequency range in which both ε_h and μ_h are negative is from 4 to 6 GHz. In this range, and at a definite thickness such as $d = 30\mu m$, the solution for TE wave frequency f as a function of reduced wave number, kd is found by solving Eq.(10) . Figure (2a) displays the TE wave frequency $(f = \omega / 2\pi)$ versus the reduced wave number kd for two values of a grating shielding parameter, g, (i.e., for curves ("1", "2") where g increases to the values (0, 1)the higher frequency value is respectively observed in (4.66, 5.02GHz). This means that when g =0, the structure becomes LHM/ferrite/vacuum and when g =1, the structure becomes LHM/ferrite/metal. The metal affects the longer waves more strongly than the shorter waves. As a result, the metal behaves as a shielding for the longer waves and no wave leakage is occurred where the wave frequency is maximum. The effect of LHM layer is also observed through the negative values of the kd (-0.5 to -3) where the magnetostatic TE waves are all backward travelling. Figure (2b) describes the dispersion curves, $f(kd)$ for g dependence on the wave number k. Values of g are restricted by the range $0 \prec g \succ 1$. In this case, the structure is LHM/ferrite/grating. According to Eq.(11), the curves ("1", "2", "3" and "4") are obtained at A_0=2 and one of coefficients A_n as: A_0=2 and $A_2 = 10^{-10} m^2$, $A_4 = 10^{-20} m^2$, $A_6 = 10^{-30} m^2$ and $A_8 = 10^{-40} m^2$ respectively. The dispersion curves are different from that in Fig.(2a). By decreasing n to the values of (8, 6, 4 and 2), the dispersion curves of the magnetostatic backward waves are shifted to increasing kd of values (-4.2, -4.8, -6 and -11.4) with decreasing slop respectively. It is obvious that these waves are shorter than the waves affected by the metal and with lower frequencies than them(about 4.42 GHz). This means that, the leakage through the grating increases with the wave number. This is the same that obtained by Zubkov et.al.[4]. They found that, the leakage of the wave field through the grating increases with the wave number in the region of backward magnetostatic waves existing in a ferrite/ dielectric / metal –strip –grating structure .Figure (3) illustrates the effect of the thickness of the ferrite layer on the dispersion curves, $f(kd)$ for $A_4 = 10^{-20} m^2$. As the thickness d increases to the values $(20, 25, 30 \mu m)$, the curves are shifted to increasing kd of values (-3.9, -4.9, and -5.9) where the shorter backward magnetostatic waves are guided by the thicker waveguide . As noticed in Fig.4, the dispersion curves, $f(kd)$ for $A_4 = 10^{-20} m^2$ and (s=1, -1) are plotted for different magnetic field values. At s=1, increasing of the magnetic field H_0 to the values of(1750/4, 1770/4, 1800/4 Oe) will guide the shorter waves while at s=-1, the longer waves of higher frequency are observed.





Figure(2a,b). Dispersion curves of magnetostatic TE waves for (a) (1) g = 0, (2) g = 1. (b) A_0=2 and $A_2 = 10^{-10} m^2$, $A_4 = 10^{-20} m^2$, $A_6 = 10^{-30} m^2$ and $A_8 = 10^{-40} m^2$ (curves 1-5, respectively). The curves are labeled with values of $\omega_p / 2\pi = 10\, GHz$, $\omega_0 / 2\pi = 4 GHz$, $H_0 = (1750 / 4) Oe$, $d = 30\, \mu m$, s =1 , and $\varepsilon_h \prec 0$, $\mu_h \prec 0$.

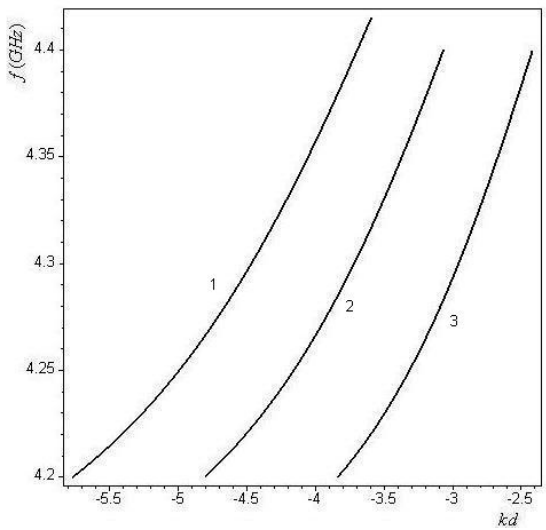


Figure 3. Dispersion curves of magnetostatic TE waves for (1) $d = 30\mu m$, (2) $d = 25\mu m$ and (3) = $d = 20\mu m$ (b). The curves are labeled with values of A_0=2 and $A_4 = 10^{-20} m^2$,$\omega_p / 2\pi = 10GHz$, $\omega_0 / 2\pi = 4GHz$,$H_0 = (1750/4)Oe$, s =1 .

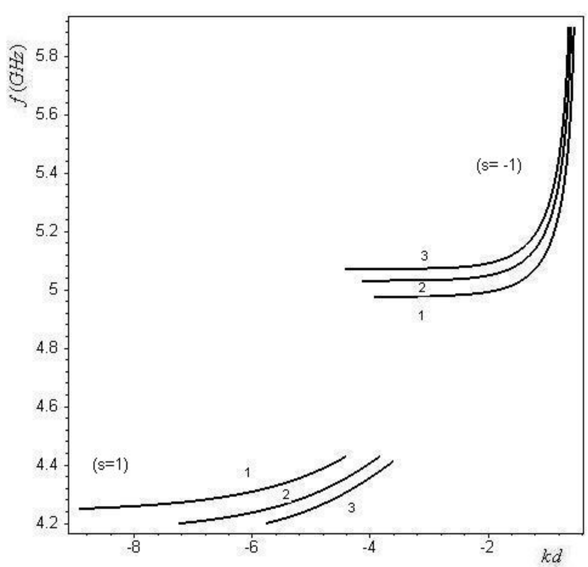


Figure 4. Dispersion curves of magnetostatic TE waves for (1) $H_0 = (1800/4)Oe$, (2) $H_0 = (1770/4)Oe$ and (3) = $H_0 = (1750/4)Oe$. The curves are labeled with values of A_0=2 and $A_4 = 10^{-20} m^2$,$\omega_p / 2\pi = 10GHz$, $\omega_0 / 2\pi = 4GHz$, $d = 30\mu m$.

4. CONCLUSIONS:

The dispersion of the magnetostatic surface waves existing in an LHM/ferrite/grating structure has been investigated. It is shown that LHM induces the waves to be backward in all dispersion regions, the dependence of the grating shielding parameter on the wave number induces the existence of shorter waves which have more leakage through the grating. Consequently, their frequency is lower than that of the waves existing in an LHM/ferrite/metal structure. These characteristics properties could be used in design future applications in microwave technology.

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