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Characteristics of surface waves in LHM-ferrite-semiconductor waveguides

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The paper is concerned with the propagation characteristics of magnetostatic surface waves in a layered structure consisting of a ferrite (yttrium iron garnet) slab, semiconductor, a left handed material (LHM)and metal plate. In (LH) cover both permittivity and magnetic permeability are negative in definite frequency range. We study dispersion properties of the magnetostatic surface waves. We found that the existence of the left handed material stimulates the forward traveling magnetostatic surface waves to be backward traveling and vice versa. We also found that higher values of wave frequency are obtained for relatively thick ferrite films.

Изучены характеристики распространения магнитостатических поверхностных волн в слоистой структуре, которая состоит из ферритовой пластины (железо-иттриевый гранат), полупроводника, "левого" материала и металлической плоскости. В покрытии из "левого" материала как диэлектрическая, так и диамагнитная проницаемость отрицательны в некотором диапазоне частот. Исследованы дисперсионные свойства магнитостатических поверхностных волн. Выявлено, что существование "левых" материалов стимулирует превращение прямых поверхностных волн в обратные и наоборот. Также показано, что более высокие значения частот волн наблюдаются в более толстых поверхностных пленках.

1. Introduction

Magnetostatic surface wave technology is widely used in practical sophisticated devices for direct signal processing, such as bandpass filters, resonators filters, delay lines and oscillators, and for other devices such as isolators and circulators, at microwave frequencies[1]. Magnetostatic surface waves on different magnetic layered structures have been investigated in the Voigt geometry by several researchers [2,3]. Shabat[4] has considered theoretically new strongly nonlinear magnetostatic surface waves for yttrium iron garnet (YIG) substrate and nonlinear dielectric cover. In that analysis [4] the nonlinearity of the dielectric cover is dominant and much stronger than the nonlinearity of YIG. S. Yamada, N.S.Chang et al. [5] have reported the characteristics of magnetostatic surface wave guided by a layered structure consisting of metal, dielectrics semiconductor and YIG . They concluded that the magnetostatic surface waves are amplified when the carrier drift velocity is greater than the phase velocity of the waves.

Recently, there has been great interest in new type of electromagnetic materials called left-handed media or metamaterials [6]. Over 30 years ago, Veselago was the first to consider the left-handed media

(LHM) with simultaneously negative and almost real electric permittivity ε_h and magnetic permeability μ_h in some frequency range [7]. He had emphasized the fact that the intensity of the electric field $\overline{E}$, the magnetic intensity $\overline{H}$ and the wave vector **k** are related by a left- handed rule. This can be easily seen by writing Maxwell's equation for a plane monochromatic wave $\mathbf{k}\ x\mathbf{E} = \frac{\omega\mu_h}{c}\mathbf{H}$ and $\mathbf{k}\ x\mathbf{H} = -\frac{\omega\varepsilon_h}{c}\mathbf{E}$**.** Once ε_h and μ_h are both positive , then $\overline{E}$, $\overline{H}$ and **k** form a right set of vectors [8]. In the case of negative ε_h and μ_h, however, these three vectors form a left set of vectors. One of the distinctive properties of the LH material which has been demonstrated experimentally is their specific frequency dispersion [9]. Many studies have been carried out on waveguide structure containing left handed materials or left handed media as Hamada, Shabat et al. [10] investigated the nonlinear magnetostatic surface waves in a ferrite left handed waveguide structure. Mousa and Shabat [11] have examined the propagation characteristics of nonlinear TE surface waves in a left-handed material and magnetic superlattices(LANS) waveguide structures. Hamada, Fayad and Shabat [12] have discussed the nonlinear surface waves in a left -handed -magnetized ferrite structure. El Astal, Hamada and Shabat[13] studied the characteristics of electromagnetic waves and magnetostatic surface waves in metal-dielectric ferrite left handed waveguide layered structure. Recently, H. J. EL-Khozondar[14] reported results on the electromagnetic surface waves of a ferrite slab bounded by metamaterials. To study the dispersion of the corresponding surface waves, it is necessary to select a particular form of the frequency dependence of the electric permittivity ε_h and magnetic permeability μ_h of the LH medium.

In this paper , we investigate the propagation characteristics of magnetostatic surface waves guided by an optical structure. This structure consists of a ferrite and semiconductor media. They are sandwiched between LHM cover and metal substrate. The interaction between the magnetostatic surface waves and a stream of drifting carriers of drift velocity v_0 in semiconductor is discussed. The magnetic field applied is parallel to the interface and perpendicular to the direction of propagation of the waves. In this communication, we aim to investigate the dispersion characteristics of magnetostatic surface waves propagating in this structure with frequency range at which both ε_h and μ_h is negative in the left-handed material which exists in the metamaterials.

2. The dispersion relation

The structure geometry of the problem considered here is shown in Fig.(1). The structure consists of the ferrite yttrium iron garnet film(YIG), which occupies the region $0 \le y \le a$ and a semiconductor film which occupies the region $a \le y \le a + b$. They are bounded by LHM cover of the space $y \ge a + b$, and the metal substrate of the space $y \le 0$. We present the dispersion equation for transverse electric (TE) waves propagating in the x direction with a propagation wave constant in the form $\exp[i(kx - 2\pi ft)]$, where k is the propagation constant, and f is the operating frequency. The magnetic permeability tensor of the gyromagnetic ferrite film is given by [1-4]:

$$\mu_f(\omega) = \mu_0 \begin{bmatrix} \mu_1 & i\mu_2 & 0 \\ -i\mu_2 & \mu_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Where $\mu_1 = \mu_B[1 + f_0 f_m / f_0^2 - f^2]$, $\quad \mu_2 = \mu_B f\ f_m / f_0^2 - f^2$. The tensors are called the usual Polder tensor elements, with $f_0 = (1/2\pi)\gamma\mu_0 H_0$ and $f_m = (1/2\pi)\gamma\mu_0 M_0$, H_0 is the applied magnetic field, M_0 is the dc saturation magnetization, μ_B is the background optical magnon permeability and γ is the gyromagnetic ratio. The ferrite has also a dielectric constant ε_f.

The dielectric function of semiconductor is expressed by [15] as: $\varepsilon_s = \varepsilon_0\varepsilon_B - \sigma k_i v_0/\omega^2 - i\sigma(\omega - k_r v_0)/\omega^2$

ε_B represents the dielectric constant of semiconductor, $k_i = Im\ k_x$ and k_r is real k_x σ is conductivity, where $\sigma = n_0\mu_m$ [15], n_0 is carrier density, v_0 is the carrier drift velocity in the semiconductor and μ_m is mobility.

From Maxwell's equations we can obtain electric and magnetic field components in three regions under the following assumptions [15]:

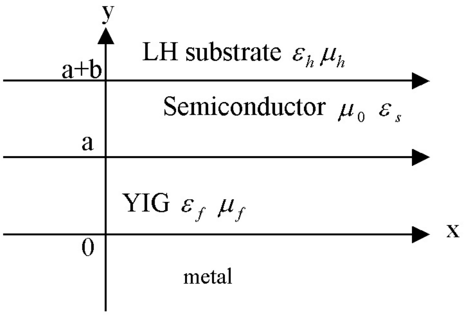


Fig. 1. Magnetostatic surface waves waveguide composed of ferrite film, semiconductor film and coordinate system

(1) The magnetostatic approximation $\nabla x H = 0$ is employed in the ferrite film.

(2) Collision dominance in semiconductor film.

(3) The metal plate is assumed to be a perfect conductor. The electric and magnetic field vectors for TE waves propagating along x-axis with angular frequency ω and wave number k_x are defined as:

$$E = [0\ ,\ 0,\ E_z(\omega\ ,y)\ ]\ \exp i\,(k_x\ x - \omega\ t)\,, \tag{2a}$$

$$H = [H_x(\omega\ ,y)\ ,\ H_y(\omega\ ,y),\ 0]\ \exp i\,(k_x\ x - \omega t)\,. \tag{2b}$$

The wave equation in each media is obtained from Maxwell's equations in three layers :

a - In LH cover. Both a negative dielectric permittivity and permeability are written as [10-14]:

$$\varepsilon_h(\omega) = 1 - \frac{\omega_p^2}{\omega^2},\ \mu_h(\omega)\ = 1 - \frac{F\,\omega^2}{\omega^2 - \omega_0^2} \tag{3}$$

with plasma frequency ω_p and resonance frequency ω_0.

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

$$\frac{\partial^2 E_z}{\partial\, y^2}\ -\ k_0^2(n_x^2 - \varepsilon_h\mu_h)\, E_z = 0, \tag{4}$$

Where $n_x = k_x/k_0$, $k_0 = \omega/c$, $c = 1/(\varepsilon_0\mu_0)^{1/2}$, ε_0 and μ_0 are the dielectric permittivity and magnetic permeability of free space respectively.

The exact solution of Eq(4) has the form:

$$E_z\,(y) = C\,e^{-k_3 y},\quad H_x = (-1/i\omega\mu_0\mu_h)\frac{\partial E_z^l}{\partial y}, \tag{5}$$

where $k_3 = k_0\sqrt{n_x^2 - \varepsilon_h\mu_h}$ is decay constant of the waves in LH cover. C is an amplitude coefficient which can be determined by the boundary conditions.

b - In semiconductor film.

The Maxwell's equations can be written as:

$$\nabla \times \overline{E} = i\,\omega\,\mu_o\overline{H}$$

$$\nabla \times \overline{H} = -i\omega\ \varepsilon_s\,\overline{E} \tag{6}$$

The wave equation is:

$$\frac{\partial^2 E_z}{\partial\, y^2}\ +\ \left(\frac{\omega^2}{c^2}\ \varepsilon_s\ -\ k_x^2\right)\ E_z\ = 0 \tag{7}$$

An appropriate solution for Eq.(7) is given by [16]

$$E_z\,(y) = A_1\, e^{k_1 y} + A_2 e^{-k_1 y}, \quad H_x = (-1/i\omega\mu_0)\frac{\partial E_z}{\partial y} \tag{8}$$

where $k_1 = k_0\sqrt{n_x^2 - \varepsilon_s}$.

b - In ferrite film.

The curl Maxwell's equations are:

$$\begin{gathered} \frac{\partial E_z}{\partial y} = i\omega\mu_o(\mu_1 H_x + i\mu_2 H_y), \\ k_x E_z = -\omega\,\mu_o(-i\mu_2\, H_x + \,\mu_1\, H_y), \\ ik_x H_y - \frac{\partial\, H_x}{\partial y} = 0. \end{gathered} \tag{9}$$

By these equations, the wave equation is:

$$\frac{\partial^2\, E_z}{\partial\, y^2} - k_x^2 E_z = 0. \tag{10}$$

The solution of Eq.(10), corresponding to a surface wave localized in the layer $0 \le y \le a$, is given by:

$$E_z\,(y) = B_1\, e^{k_2 y} + B_2 e^{-k_2 y}, \tag{11}$$

B_1, B_2 are amplitude coefficients, they can be determined by the boundary conditions where $k_2 = sk_x$ is magnetostatic wave number of the x direction, $s = \pm 1$, for ± 1 x where $s = 1$ stands for the propagation of the waves in the forward direction , and $s = -1$ stands for the propagation of the waves in the backward direction. From these equations, the magnetic field H_x is written as:

$$H_x = \frac{(k_x\mu_2 - k_2\mu_1)B_1 e^{k_2 y} + (k_x\mu_2 + k_2\mu_1)B_2 e^{-k_2 y}}{i\omega\mu_0(\mu_2^2 - \mu_1^2)}. \tag{12}$$

The boundary conditions at all interfaces requires that both H_x and E_z components are continuous but for the electric field in metal which is zero $E_z(metal) = 0$ at $y = 0$ because the metal is a perfect conductor of $\sigma \to \infty$ and $k_i \to \infty$.

As a result of applying the previous boundary conditions, the dispersion equation is then:

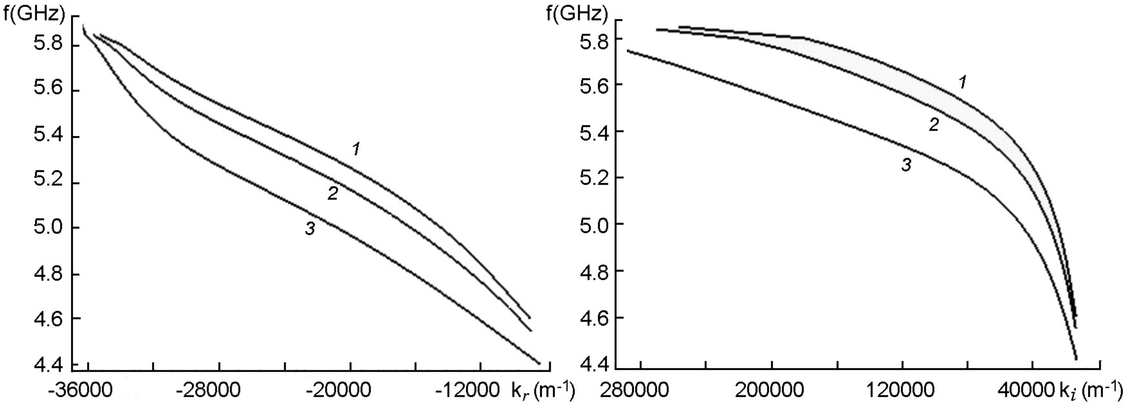
$$\frac{k_3}{k_1\mu_h} = \frac{(k_1 - W)e^{-k_1(a+b)} - (k_1 + W)e^{-k_1(a-b)}}{(k_1 - W)e^{-k_1(a+b)} + (k_1 + W)e^{-k_1(a-b)}}, \tag{13}$$

where $W = \frac{k_x\mu_2 - k_2\mu_1(1/\tan ch(k_2 a))}{(\mu_2^2 - \mu_1^2)}$

3. Numerical results and discussion

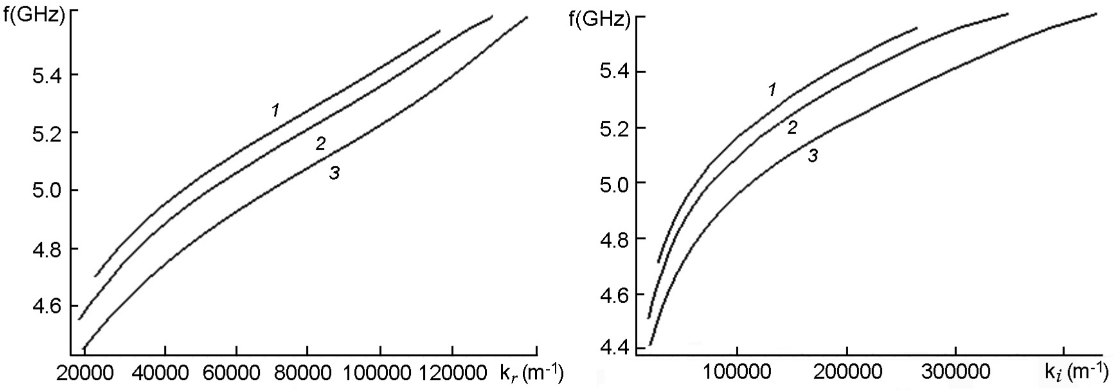
In the present work, the numerical calculations for a LH cover, ferrite, and semiconductor, are taken with the following parameters: $\omega_p/2\pi$ = 10GHz, $\omega_0/2\pi$ = 4GHz, and $F = 0.56$ [9], the applied field, $\mu_0 H_0 = 0.15\ T$, $\mu_0 M_0 = 0.175\,\mathrm{T}$ $\mu_B = 1$, $\varepsilon_f = 1$, $\gamma = 1.97 \times 10^{11}$ rad/sec. T and $\varepsilon_B = 15.68$, $n_0 = 10^{21}/m^3$, $\mu_m = 22\,m^2$/V.s for semiconductor film[15].

The dispersion equation (13) has been solved to compute the frequency versus the effective wave number for different values of the ferrite film thickness (a). We have solved Eq.(13) in the form of a complex wave number $k_x = k_r + ik_i$. We consider two interaction cases between the magnetostatic surface waves and a stream of drifting carriers in semiconductor as: (1) $s = 1$ and $v_0 = 1 \times 10^6$ m/s, (2) $s = -1$ and $v_0 = -2 \times 10^5$ m/s.



a) b)

Fig. 2. Dispersion curves of magnetostatic surface waves for $\epsilon_h < 0$, $\mu_h < 0$, for (*1*) $a = 1.2 \times 10^{-5}$ m, (*2*) $a = 1 \times 10^{-5}$ m and (*3*) $a = 0.7 \times 10^{-5}$ m. The curves are labeled with values of $b = 1 \times 10^{-6}$ m, $s = 1$, $v_0 = 1 \times 10^6$ m/s, $n_0 = 10^{21}\mathrm{m}^2$, $\mu_m = 2\mathrm{m}^2$/V.s and $\gamma = 1.97 \times 10^{11}$ rad /T.s.



a) b)

Fig. 3. Dispersion curves of magnetostatic surface waves for $\epsilon_h < 0$, $\mu_h < 0$, for(*1*) $a = 1.2 \times 10^{-5}$ m, (*2*) $a = 1 \times 10^{-5}$ m and (*3*) $a = 0.7 \times 10^{-}5$ m. The curves are labeled with values of $b = 1 \times 10^{-6}$ m, $s = -1$ and $v_0 = -2 \times 10^5$m/s .

Fig.(2.a) shows that for this set of parameters, the frequency range in which both ε_h and μ_h are negative is from 4 GHz to 6 GHz. In this range, and when $s = 1$ and $v_0 = 1 \times 10^6$ m/s, the computed dispersion curves (f versus k_r) for different values of ferrite film thickness show that the waves propagate in the backward wave direction. Fig. 2(b) illustrates (f versus k_i) for different values of ferrite film thickness. Also magnetostatic waves turn their direction from forward to backward. This forward behavior of waves has been obtained by Yamada and Chang in the absence of (LHM) [15].

We notice that both the wave phase velocity $v_p = \frac{\omega}{k_x}$ and the wave group velocity $v_g = \frac{\partial\omega}{\partial k_x}$ dispersions are affected by the thickness of the ferrite film(a) where v_p decreases to positive values and v_g decreases to negative values by decreasing the YIG thickness (a) this means that the cover behaves as a left handed medium. Figs.(3a,b) display examples of dispersion curves for different values of the ferrite film thickness at $s = -1$ (backward traveling) and $v_0 = -2 \times 10^5$ m/s. We see that waves change from backward traveling direction to forward traveling one. A strong shift is also observed to higher values of f as a is increased.

Figs.(4a,b) also illustrate the dispersion curves for different values of carrier drift velocity v_0. On

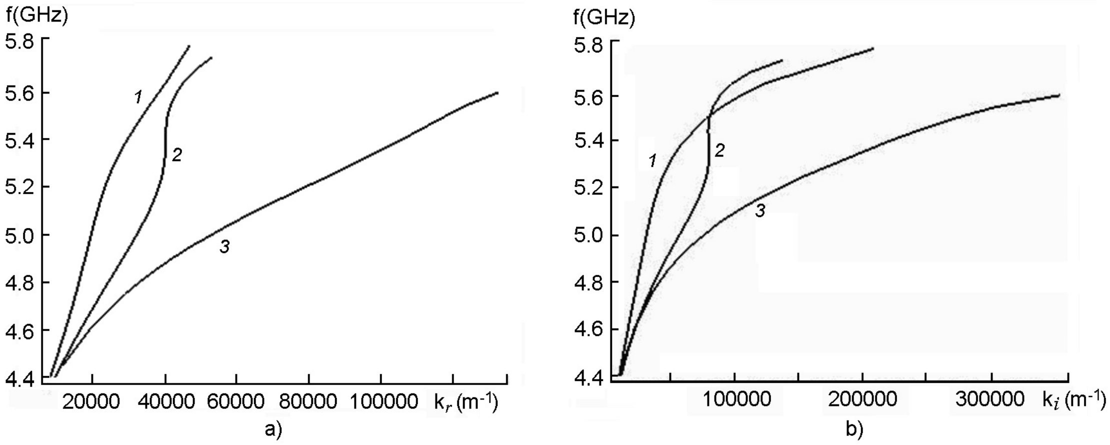


Fig. 4. Computed dispersion curves for (*1*) $v_0 = -7\times10^5$ m/s, (*2*) $v_0 = -5\times10^5$ m/s, (*3*) $v_0 = -2\times10^5$ m/s, $s=-1$, $a = 1\times10^{-5}$ m and $b = 1\times10^{-6}$ m.

increasing v_0 to the values (-2×10^5 m/s and -7×10^5 m/s), the wave phase velocity v_p increases sharply in the forward direction.

4. Conclusion

In this communications, we investigate for the first time the propagation characteristics of the surface waves in a waveguide structure containing nearly artificial left- handed materials, semiconductor and ferrite. The obtained results show many interesting features which may be used in design future microwave-photonic devices, we believe these results could be useful and important for a deeper understanding of the propagation.

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Характеристики магнітостатичних поверхневих хвиль у хвильоводній структурі метаматеріал-ферит-напівпровідник

Х.М.Муса, М. Ель-Абадла, М.М.Шабат

Досліджено характеристики проходження мегнетостатичних поверхневих хвиль у шаруватій структурі, що складається з феритової пластини (залізо-ітрієвий гранат, YIG), напівпровідника, "лівого"матеріалу (LHM) та металевої пластини. У покритті з "лівого"матеріалу як діелектрична, так і діамагнітна проникність є від'ємними у певному діапазоні частот. Досліджено дисперсійні властивості магнітостатичних поверхневих хвиль. Виявлено, що існування "лівих"матеріалів стимулює перетворення прямих поверхневих хвиль у зворотні та навпаки. Також показано, що більш високі значення частот хвиль отримуються у більш товстих феритових плівках.