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Transverse electric surface waves in a plasma medium bounded by magnetic materials

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ABSTRACT

The transverse electric surface waves have been investigated with a plasma medium sandwiched between two ferrite films. The characteristic equations for the field components are derived and a dispersion relation is analytically obtained by using boundary conditions for the tangential field components. Numerical analysis shows the plots of effective wave index with surface wave frequency for different thicknesses and number densities of the plasma medium, and also for the different values of the dielectric constant of the ferrite films.

Introduction

Sandwiched and dielectric slab waveguide structures have been one of the topics of theoretical as well as experimental study in both optical and microwave research. The recent progress in the study of integrated circuits and the antenna systems based on these structures played an important role in the development of communication devices [1–3]. In this context, the properties of electromagnetic (EM) guided and surface waves have been studied extensively by various authors. For example, Xu et al. [4] investigated transverse electric (TE) and transverse magnetic (TM) guided and surface modes in indefinite-medium waveguides. They discussed numerically four distinct cases for the existence conditions of guided modes. More recently, Smirnov and Valovik [5] studied the TE guided waves along a plane dielectric waveguide with Kerr-type nonlinear permittivity. In the presence of nonlinearity, they showed many interesting results for the propagation modes and compared these with the linear modes. In another study, El-Khozondar et al. [6] investigated TE surface waves in a ferrite slab, sandwiched between metamaterials. They numerically analyzed the dispersion characteristics of TE surface waves for the different parameters of metamaterials and the thickness of ferrite slab, etc. Wu [7] studied the TM surface wave in a symmetric planar waveguide consisting of a superconductor sandwiched between nonlinear antiferromagnets. They analyzed phase constant and attenuation constant in the infrared region of frequency as a function of the superconductor's thickness.

Because of the simple geometrical configuration of a slab waveguide structure, different surface and guided modes can be explained by the straightforward mathematical expressions. The propagation characteristics of EM wave transmission in a waveguide structure can be modified by using various types of materials. For the EM wave modes, a lot of research work has been done on waveguide structures in which magnetic and dielectric layers have been frequently used as common materials (e.g. [6–9]). Magnetic materials could not be used before the introduction of ferrites (around 1950) because "skin effect" prevented the wave penetration into interior of the ferromagnetic materials. However, microwaves were able to penetrate into the ferrites and could be influenced by their propagation through the material, making possible a large number of quite novel ferrite components [10]. Since most ferrite components use waveguides or other forms of transmission lines with ferrite material, therefore it is possible to explore simpler types involving ferrite-loaded structures [11]. The waveguide structures fabricated from ferrites are applied as basic elements of different functional devices. In magnetoelectronics and spintronics, these structures may be useful: as waveguides, couplers, delay lines, and filters, etc. The dispersion properties of ferrite devices may be controlled in a broad range due to the possibility of changing the operational frequency and the external magnetic field [12].

The research of plasma-filled structures is motivated by small electronic devices, which are able to operate in the high frequency

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band and are continuously tunable over a broad frequency range. The surface plasma waves have been studied along the boundary between a plasma and dielectric by various authors. For example, Kaliteevski et al. [13] and Moradi [14] investigated the surface wave for TM polarization that propagates parallel to the interface between a thin plasma film and a dielectric medium. In their work, they also showed that there can be no interaction between the transverse and longitudinal waves for TE polarization in the isotropic media. The presence of a plasma medium has strong effects on the dispersion characteristics of the guiding structures. In recent years, a lot of research work has been done on the wave propagation in plasma-filled waveguide structures to study different geometrical and physical parameters etc. (see e.g. [15,16] and references therein).

In the context of electromagnetic field theory, a surface wave can propagate along the boundary between two connected media, and decreases exponentially on both sides of the interface. The exponential decrease depends upon the properties of the two media, such as permittivity and permeability, so that it may be different on both sides of the interface. TE surface wave propagates along the boundary surface of two connected media with opposite signs of permeability, whereas TM wave propagates with opposite signs of permittivity. For both polarizations, the dispersion relation for the surface wave between the wave index and the propagation frequency can be derived [17].

In the present work, we investigate TE surface waves in a plasma medium, bounded by ferrite films in the presence of an external magnetic field, with negative values of frequency dependent Voigt permeability function $\mu_v(\omega)$ within a certain frequency band. It is seen that TE and TM surface waves are not coupled and studied separately for a system of magneto-plasma films in the Voigt configuration (i.e. a configuration in which magnetic field is parallel to the surface but perpendicular to the propagation direction). However, in the Faraday configuration (i.e. a configuration in which the magnetic field is parallel to the surface and the propagation direction) the surface wave modes are not separated and do not have pure TE and TM wave character because of the coupling between the field components (see e.g. [18,19]). Our proposed work may find some considerable importance in the development of communication devices because of its possible applications in the design and implementation of integrated circuits and the antenna systems, operating at microwave frequencies.

In Section "Geometry of the problem and basic equations", we discuss the geometry of proposed structure and the basic mathematical equations for the field components of plasma medium and ferrite films. Section "Dispersion relation and numerical results" is devoted to derivation and numerical results of the dispersion relation. A brief conclusion of the results is presented in Section "Conclusion".

Geometry of the problem and basic equations

The geometric configuration of the proposed Ferrite/Plasma/Ferrite sandwich structure for the propagation of TE surface waves is shown in Fig. 1. The structure consists of a plasma medium bounded by ferrite films, each of which extends to infinity in the *yz* plane. We consider that the electric and magnetic field components are proportional to $e^{i(kz-\omega t)}$ and are independent of *y* i.e. $\partial/\partial y = 0$, where ω is propagation frequency and $\mathbf{k}$ is propagation vector in the *z* direction. To this sandwich structure, we also apply a static magnetic field $\mathbf{B_o}$ along *y* direction which also results in a uniform intensity $\mathbf{H_o}$ within ferrite films. The electric and magnetic field components for the propagation of TE surface waves along the *z* axis have the following forms:

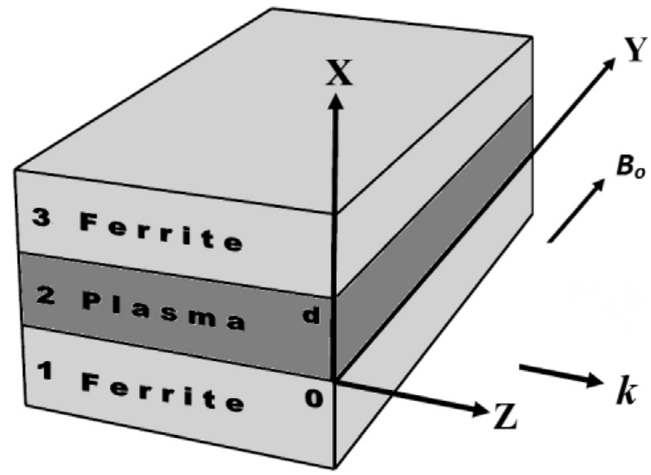

Fig. 1. A schematic representation for the propagation of TE surface waves in a Ferrite/Plasma/Ferrite sandwich structure.

$$E = [0, E_y(\omega, x), 0]e^{i(kz-\omega t)}, \quad H = [H_x(\omega, x), 0, H_z(\omega, x)]e^{i(kz-\omega t)}.$$

Field components for the plasma medium

We assume that a plasma medium with thickness *d* occupies region 2 ($0 \le x \le d$), bounded by ferrite films with region 1 ($x < 0$) and region 3 ($d < x$) of the space, as shown by coordinate system used in Fig. 1. Using time dependent perturbations, following linearized equations of continuity, momentum transfer, and Maxwell's equations can be used to express plasma like medium in the absence of an equilibrium electric field E_o and electron drift velocity V_o [20]:

$$i\omega p = n_o m\, v_{th}^2 \nabla \cdot \mathbf{V}, \tag{1}$$

$$n_o m(-i\omega \mathbf{V} + v\mathbf{V}) = -e n_o(\mathbf{E} + \mathbf{V} \times \mathbf{B_o}) - \nabla p, \tag{2}$$

$$\nabla \times \mathbf{H} = -e n_o \mathbf{V} - i\omega\varepsilon_o \mathbf{E}, \tag{3}$$

$$\nabla \times \mathbf{E} = i\omega\mu_o \mathbf{H}, \tag{4}$$

where p, n_o, m, $\mathbf{V}$, e, v and $v_{th} = (\gamma' \mathrm{KT}/\mathrm{m})^{1/2}$ are the pressure, number density, mass, velocity, charge, collision frequency, and thermal velocity of the electron, respectively, whereas γ', K and T are ratio of specific heats, the Boltzmann constant, and the temperature of the plasma medium. Eq. (4) yields the following form with the help of Eqs. (1)–(3):

$$\nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} = \frac{\omega^2}{c^2}\left[\left(1 - \frac{\omega_p^2}{\omega^2 + i\omega v}\right)\mathbf{E} - \left(\frac{\omega_p^2}{\omega^2 + i\omega v}\right)\mathbf{V} \times \mathbf{B_o} + \left(\frac{v_{th}^2}{\omega^2 + i\omega v}\right)\nabla(\nabla \cdot \mathbf{E})\right]. \tag{5}$$

Here ω_p is the electron plasma frequency and is given by $\omega_p = (e^2 n_o/\varepsilon_o m)^{1/2}$.

In our model, the external magnetic field $\mathbf{B} = B_o\hat{j}$ is parallel to the electric field fluctuation $\mathbf{E} = E_y\hat{j}$ and perpendicular to the wave propagation direction $\mathbf{k} = k_z\hat{k}$. Since $\mathbf{E} = E_y\hat{j}$, we need only the component v_y i.e. $\mathbf{V} = v_y\hat{j}$. This geometry for $TE(H_x, E_y, H_z)$ surface wave may be approximated by incidence of microwaves on the narrow dimension of plasma medium in the waveguide structure. Therefore, $\nabla\mathbf{E} = (\hat{i}\partial/\partial x + \hat{k}\partial/\partial z)(E_y\hat{j}) = 0$ and $\mathbf{V} \times \mathbf{B}_o = 0$. Thus above equation reduces to

$$\frac{d^2E_y}{dx^2} - k^2E_y + \frac{\omega^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\,\upsilon}\right)E_y = 0,$$

or

$$\frac{d^2E_y}{dx^2} - k_p^2E_y = 0, \tag{6}$$

where $k_p^2 = k^2 - k_o^2\varepsilon_p$ and $k_o^2 = \omega^2/c^2$. The dielectric constant ε_p of the plasma medium is given by

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\,\upsilon}, \tag{7}$$

For Eq. (6), we can write the following solution:

$$E_{y2} = A\cosh(k_px) + B\sinh(k_px), \tag{8}$$

here we use subscript '2' which refers to region 2 i.e. the plasma medium. By using Eq. (4), the corresponding magnetic field components are obtained as

$$H_{x2} = \frac{-k}{\omega\mu_o}[A\cosh(k_px) + B\sinh(k_px)], \tag{9}$$

$$H_{z2} = \frac{-ik_p}{\omega\mu_o}[A\sinh(k_px) + B\cosh(k_px)]. \tag{10}$$

Field components for the ferrite films

In the sandwich structure, ferrite films occupy regions 1 and 3. For these two regions the Maxwell's field equations can be written as

$$\nabla \times \mathbf{H} = -i\omega\,\varepsilon_o\,\varepsilon_f\,\mathbf{E}, \tag{11}$$

$$\nabla \times \mathbf{E} = i\omega\mu_o\,\bar{\mu}\mathbf{H}, \tag{12}$$

where ε_f is the dielectric constant of ferrite material and $\bar{\mu}$ is the Polder permeability tensor [21,22], given by

$$\bar{\mu} = \begin{pmatrix} \mu_{xx} & 0 & i\mu_{zx} \\ 0 & \mu_{yy} & 0 \\ -i\mu_{zx} & 0 & \mu_{xx} \end{pmatrix}, \tag{13}$$

where

$$\mu_{xx} = \left(1 + \frac{\omega_o\,\omega_m}{\omega_o^2 - \omega^2}\right)\mu_B, \quad \mu_{zx} = \left(\frac{\omega\,\omega_m}{\omega_o^2 - \omega^2}\right)\mu_B, \quad \mu_{yy} = \mu_B.$$

Here μ_{xx}, μ_{zx}, and μ_{yy} are the elements of Polder tensor, μ_B is the background optical magnon permeability, whereas ω_o and ω_m are given by $\omega_o = \mu_o\gamma H_o$, $\omega_m = \mu_o\gamma M_o$ [21,23]. Here M_o is the static magnetization, and H_o the uniform intensity within ferrite films resulting from the applied static magnetic field B_o. Analysis of ferrite waveguides is complex because of the anisotropy of the ferrite materials. Thus, for convenience, some details of the analytical solution of the transversely magnetized ferrite films are presented here.

For the $TE(H_x, E_y, H_z)$ surface wave, Eq. (13) together with Eqs. (11) and (12) give the following forms:

$$\frac{\partial H_z}{\partial x} - ikH_x = i\omega\varepsilon_f\,\varepsilon_o\,E_y, \tag{14}$$

$$-kE_y = \omega\mu_o\mu_{xx}H_x + i\omega\mu_o\mu_{zx}H_z, \tag{15}$$

$$\frac{\partial E_y}{\partial x} = \omega\mu_o\mu_{zx}H_x + i\omega\mu_o\mu_{xx}H_z, \tag{16}$$

using Eq. (14) in (15) and (16), we have the following pair of equations

$$-k\frac{\partial E_y}{\partial x} = i\omega\mu_o\mu_{xx}\frac{\partial H_x}{\partial x} - k\omega\mu_o\mu_{zx}H_x - k_o^2\,\varepsilon_f\,\mu_{zx}E_y, \tag{17}$$

$$\frac{\partial^2 E_y}{\partial x^2} = \omega\mu_o\mu_{zx}\frac{\partial H_x}{\partial x} - k\omega\mu_o\mu_{xx}H_x - k_o^2\,\varepsilon_f\,\mu_{xx}E_y, \tag{18}$$

combining these equations, we get

$$\frac{\partial^2 E_y}{\partial x^2} = -k\frac{\mu_{zx}}{\mu_{xx}}\frac{\partial E_y}{\partial x} - k\omega\mu_o\mu_v H_x - k_o^2\,\varepsilon_f\,\mu_v E_y, \tag{19}$$

where $\mu_v = (\mu_{xx}^2 - \mu_{zx}^2)/\mu_{xx}$ is the frequency dependent Voigt permeability [21,22]. Now eliminating H_z from (15) and (16), we have

$$\frac{\mu_{zx}}{\mu_{xx}}\frac{\partial E_y}{\partial x} = -kE_y - \omega\mu_o\mu_v H_x, \tag{20}$$

substituting this equation in (19), we get the wave equation in E_y as

$$\frac{d^2E_y}{dx^2} - k_f^2E_y = 0, \tag{21}$$

where $k_f^2 = k^2 - k_o^2\varepsilon_f\mu_v$. We write the solution of above equation in the following form:

$$E_y = C\,e^{k_f x} + D\,e^{-k_f x}. \tag{22}$$

For region 1, the following TE field components E_{y1} , H_{x1} , and H_{z1}, for the ferrite film at $x < 0$ are obtained from (22), (15) and (16), and here we assume that the field penetration length in ferrite film is much shorter than its thickness:

$$E_{y1} = C\,e^{k_f x}, \tag{23}$$

$$H_{x1} = \frac{-1}{\omega\mu_o\mu_{xx}\,\mu_v}(k\mu_{xx} + k_f\mu_{zx})\,C\,e^{k_f x}, \tag{24}$$

$$H_{z1} = \frac{-i}{\omega\mu_o\mu_{xx}\,\mu_v}(k\mu_{zx} + k_f\mu_{xx})\,C\,e^{k_f x}, \tag{25}$$

Similarly, we can obtain the TE field components for the ferrite film at $x > d$ for region 3 as

$$E_{y3} = D\,e^{-k_f x}, \tag{26}$$

$$H_{x3} = \frac{-1}{\omega\mu_o\mu_{xx}\,\mu_v}(k\mu_{xx} - k_f\mu_{zx})\,D\,e^{-k_f x}, \tag{27}$$

$$H_{z3} = \frac{-i}{\omega\mu_o\mu_{xx}\,\mu_v}(k\mu_{zx} - k_f\mu_{xx})\,D\,e^{-k_f x}. \tag{28}$$

Dispersion relation and numerical results

In this section, dispersion relation of TE surface waves for the Ferrite/Plasma/Ferrite sandwich structure is obtained by applying the boundary conditions for continuity of tangential components of electric and magnetic fields at the two interfaces $x = 0$ and $x = d$. In this connection, we can match Eqs. (8), (23) and (10), (25) at $x = 0$ and Eqs. (8), (26) and (10), (28) at $x = d$ in the following manner:

$$E_{y2}|_{x=0} = E_{y1}|_{x=0}, \quad H_{z2}|_{x=0} = H_{z1}|_{x=0},$$

and

$$E_{y2}|_{x=d} = E_{y3}|_{x=d}, \quad H_{z2}|_{x=d} = H_{z3}|_{x=d},$$

After skipping some mathematical details, we can obtain the following dispersion relation:

$$\tanh(k_p\,d) = \frac{2k_f\,k_p\,\mu_v\,\mu_{xx}^2}{(k^2\,\mu_{zx}^2 - k_f^2\,\mu_{xx}^2) - k_p^2\,\mu_{xx}^2\mu_v^2}. \tag{29}$$

For the numerical analysis, a convenient form of relationship between the effective wave index β and the propagation frequency ω can be written by using expressions of k_p and k_f as indicated in Eqs. (6) and (21). Thus, Eq. (29) yields

$$\tanh\left\{\frac{\omega d}{c}(\beta^2-\varepsilon_p)^{1/2}\right\}=\frac{2\mu_{xx}^2\mu_v(\beta^2-\varepsilon_p)^{1/2}(\beta^2-\varepsilon_f\mu_v)^{1/2}}{\{\beta^2\mu_{zx}^2-\mu_{xx}^2(\beta^2-\varepsilon_f\mu_v)\}-\mu_{xx}^2\mu_v^2(\beta^2-\varepsilon_p)}. \tag{30}$$

The values of ε_p, μ_{xx}, μ_{zx}, and μ_v, have been indicated in Eqs. (7), (13), and (19). Using Eq. (30), we can numerically illustrate the effective wave index β versus propagation frequency ω for different values of the thickness d of the plasma medium. The effects of variation in the number density n_o of the plasma medium and the dielectric constant ε_f of the ferrite films have also been observed. The parameter values chosen for the ferrite film are $\omega_m = 3.08\times10^{10}$Hz, $\omega_o = 0.343\times\omega_m$Hz, $\mu_B = 1$ and $\varepsilon_f = 14$ [6]. Since TE waves are associated with H_x and H_z, therefore they depend upon the frequency dependent μ_{xx} and μ_{zx} components of the Voigt permeability function given by $\mu_v = (\mu_{xx}^2-\mu_{zx}^2)/\mu_{xx}$, as indicated in expression (19). For the case of TE surface waves in Voigt propagation geometry as depicted in Fig. 1, the function μ_v has been plotted in Fig. 2 against the propagation frequency ω [21–23]. For $\mu_v<0$ in a frequency range from $\omega_1 = [\omega_o(\omega_o+\omega_m)]^{1/2}\approx 2.1\times10^{10}$Hz to $\omega_2=\omega_o+\omega_m\approx4.5\times10^{10}$Hz i.e. to the right of singularity, the interfaces can support TE surface wave (where ω_1 is the resonance frequency). For a plasma medium, we have assumed that $(v/\omega)<<1$. Here, we choose typical values of electron number density n_o for an over-dense plasma regime with $\varepsilon_p = 1-(e^2n_o/\varepsilon_o m)/\omega^2 = 1-\omega_p^2/\omega^2<0$ when $\omega<\omega_p$. This over-dense plasma regime has significant importance in different areas of theoretical and experimental studies [24].

In Fig. 3, we plot the effective wave index β versus propagation frequency ω, for different thicknesses d of the plasma medium as indicated by continuous, dashed, and dotted lines, i.e. $d = 10\times10^{-4}$m, $d=5\times10^{-4}$m, and $d = 1\times10^{-4}$m, respectively, with $n_o = 10^{21}\text{m}^{-3}$. It is observed that for each thickness d, there are two regions of propagation for TE wave around a gap (or non-propagation region) within the frequency band from 2.1×10^{10}Hz to 4.5×10^{10}Hz. We notice that for the values of effective wave index $\beta\le2$, the propagation gap increases as thickness decreases.

At higher frequencies, the upper region of propagation shows nearly a uniform value of wave index i.e. $\beta\approx2$ for all thicknesses, whereas at larger values of wave index, the lower region of propagation shows a uniform value of the wave frequency i.e.

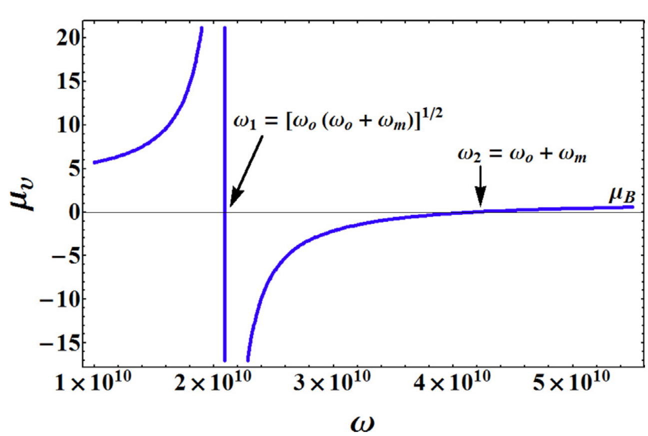

Fig. 2. Voigt permeability μ_v as a function of propagation frequency ω.

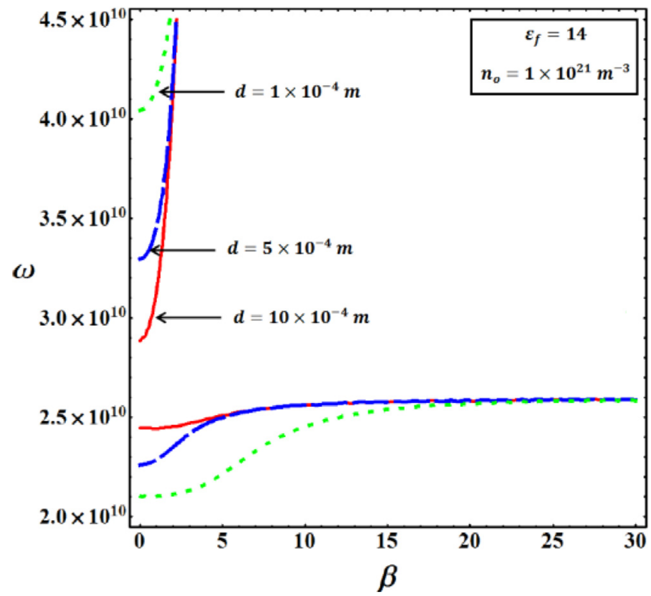

Fig. 3. Effective wave index β versus propagation frequency ω for different thicknesses of the plasma medium.

$\omega = 2.5\times10^{10}$Hz for all thicknesses. In this analysis, the upper region of propagation shows an unphysical region for $\beta>2$. Thus we see that for the larger values of effective wave index β, the lower region of propagation becomes independent of the given values of the thicknesses d at frequency $\omega = 2.5\times10^{10}$Hz, whereas for the higher values of propagation frequency ω, the upper region of propagation seems to be independent of the thicknesses at $\beta\approx2$. This also shows that propagation characteristics are sensitive to the thicknesses of the plasma medium within certain intermediate ranges of the effective wave index and frequency, etc.

Fig. 4 shows a plot of effective wave index β versus propagation frequency ω for different number densities n_o of the plasma medium as indicated by continuous, dashed and dotted lines, i.e. $n_o = 10^{21}\text{m}^{-3}$, $n_o = 3\times10^{21}\text{m}^{-3}$ and $n_o = 6\times10^{21}\text{m}^{-3}$, respectively, with $d = 5\times10^{-4}$m. We notice that, at some higher number densities $n_o = 3\times10^{21}\text{m}^{-3}$ and $n_o = 6\times10^{21}\text{m}^{-3}$, the lower region of propagation moves upwards with negative slope at smaller values of β. Since the slope of a dispersion curve gives us the group velocity, therefore a negative slope indicates that the direction of group velocity is anti-parallel to the phase velocity. This type of a backward wave propagation shows that our proposed structure acts as a negative-index material [25] in the lower region of propagation at smaller values of β. The upper region of propagation shows almost a similar trend as discussed in Fig. 3. We also observe that the propagation gap decreases as number density increases. Thus, our dispersion curves are also sensitive to the number density n_o or dielectric constant ε_p of the plasma medium, since $\varepsilon_p = 1-(e^2n_o/\varepsilon_o m)/\omega^2$.

Fig. 5 shows a plot of β versus ω for different values of dielectric constant ε_f of the ferrite films as indicated by continuous, dashed and dotted lines i.e. $\varepsilon_f = 14$, $\varepsilon_f = 2.3$, and $\varepsilon_f = 1$, respectively, with $n_o = 10^{21}\text{m}^{-3}$ and $d = 5\times10^{-4}$m. We observe that for a particular range of dielectric constant of the ferrite films i.e. $\varepsilon_f < 2.3$, the lower region of propagation moves upwards with negative slope at smaller values of β, whereas upper region of propagation shows almost a similar trend as discussed in the above two cases. Since Figs. 4 and 5 show similar trends of negative slope, therefore our proposed structure has also shown some flexibility either in the number density of plasma medium or in the dielectric constant of the ferrite films.

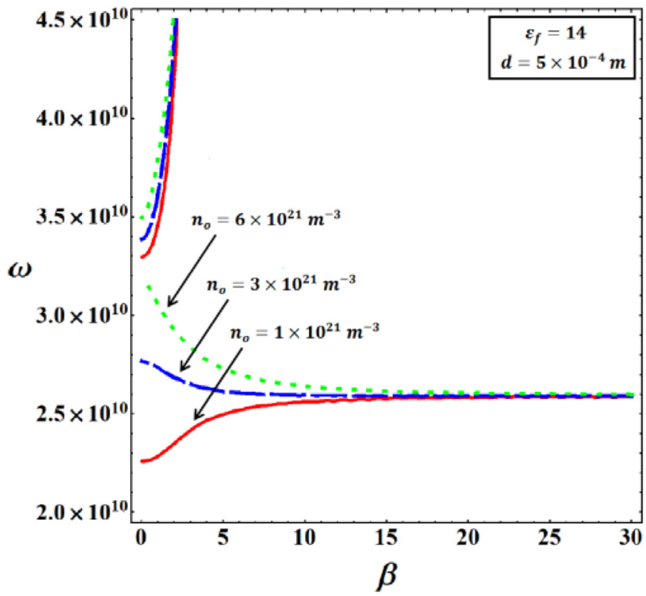

Fig. 4. Effective wave index β versus propagation frequency ω for different values of number densities.

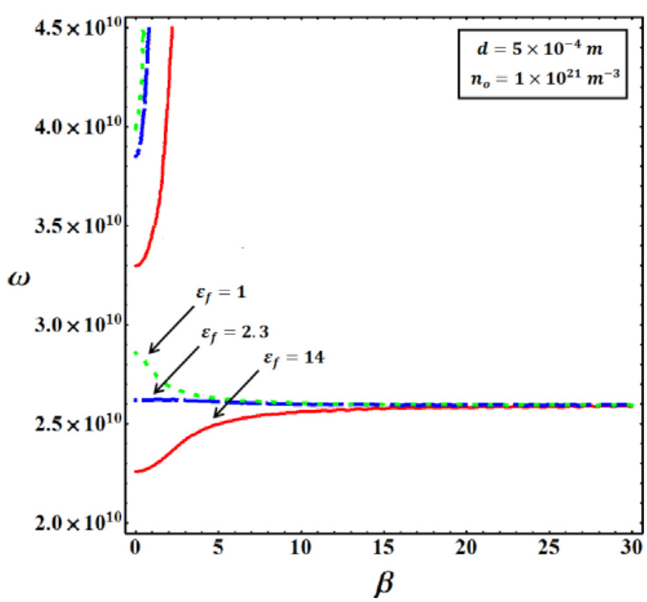

Fig. 5. Effective wave index β versus propagation frequency ω for different values of dielectric constant of ferrite.

From the view point of possible applications to waveguides, we have presented an analysis of TE surface waves in a Ferrite/Plasma/Ferrite sandwich structure in the presence of an external magnetic field with $\mu_v(\omega) < 0$ and $\varepsilon_f > 0$ for a certain range of frequency ω. Recently, some of the work on waveguide and sandwich structures has also been reported on artificially made left-handed materials (LHMs) with $\mu(\omega) < 0$ and $\varepsilon(\omega) < 0$ i.e. the materials for which the permittivity $\varepsilon(\omega)$ and permeability $\mu(\omega)$ have negative values simultaneously in a certain frequency range (see for example [6,8]). However, artificial materials, in which only one parameter $\mu(\omega) < 0$ or $\varepsilon(\omega)$ has negative value in a given frequency range, may also offer interesting possibilities in the development of future devices and components. Such single negative (SNG) materials may conceptually be made more easily than double negative LHMs. Our proposed work may offer an exciting effort to further explore the possibility of using ferrite materials for future applications [26,27].

Conclusion

We have presented an analysis of TE surface waves for a plasma medium sandwiched between two ferrite films. In order to numerically illustrate the effective wave index versus propagation frequency, our analysis has been carried out in the frequency range where Voigt permeability function has negative values. Within this specific frequency band, it has been observed that for each thickness, there are two propagation regions around a gap. For smaller values of effective wave index, the propagation gap increases as thickness decreases. It is also observed that for the larger values of effective wave index, the lower region of propagation becomes independent of the thicknesses at some constant value of the frequency, whereas for the higher values of frequencies, the upper region of propagation seems to be independent of the thicknesses at some constant value of the effective wave index. These specific propagation characteristics of the band-gap effects may have useful advantages over the other models and can be applied to the variety of communication devices.

Our proposed structure is also sensitive to the number density of the plasma medium and the dielectric constant of the ferrite films. It is noticed that the band-gap effects are maintained when we change the values of these two parameters separately. In both cases, the lower region of propagation has similar characteristics and shows negative slopes or negative group velocities like the negative-index materials. Thus, the present structure is flexible for these parameters due to similarities between the propagation characteristics. However, if the geometry of the proposed structure is properly designed, then it is more convenient to control number density of the plasma medium than the dielectric constant of the ferrite films.

Competing interests

The authors declare that they have no competing interests regarding the publication of this paper.

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