NUMERICAL STUDY OF NEGATIVE-REFRACTIVE INDEX FERRITE WAVEGUIDE

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ABSTRACT

Consider a magnetized ferrite-wire waveguide structure situated between two half free spaces. Ferrites to provide negative permeability and wire arrays to provide negative permittivity. The structure form left-handed material (LHM) with negative refractive index. The transmission of electromagnetic waves through the structure is investigated theoretically. Maxwell's equations are used to determine the electric and magnetic fields of the incident waves at each layer. Snell's law is applied and the boundary conditions are imposed at each layer interface to calculate the reflected and transmitted powers of the structure. Numerical results are illustrated to show the effect of frequency, applied magnetic fields, angle of incidence and LHM thickness on the mentioned powers. The analyzed results show that the transmission is very good when the permeability and permittivity of the structure are both simultaneously negative. The frequency band corresponding to this transmission can be tuned by changing the applied magnetic fields. The obtained results are in agreement with the law of conservation of energy.

Key words: Applied magnetic fields, Electromagnetic waves, ferromagnetic material, frequency, Reflected power, transmitted power.

INTRODUCTION

Metamaterials (sometimes termed left-handed materials (LHMs)) are materials whose permittivity ε and permeability μ are both negative and consequently have negative index of refraction. These materials are artificial and theoretically discussed first by Veselago [1] over 40 years ago. The first realization of such materials, consisting of split-ring resenators (SRRs) and continuous wires, was first introduced by Pendry [2, 3]. Regular materials are materials whose ε and μ are both positive and termed right handed materials (RHMs).

Magnetized ferrite is an additional alternative to SRR to provide negative permeability. Consequently, a LHM can be achieved by inserting a periodic continuous wires into the ferrite material [4-7]. ε and μ of this LHM have tuna-

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ble properties by changing the applied bias magnetic fields and both exhibit negative values at certain frequency band. Y. He et al [8] have studied the role of ferrites in negative index metamaterials. M. Augustine et al [9] have formulated a theoretical analysis of ferrite-superconductor layered structures. H. Zhao et al [10] have studied a magnetotunable left-handed material consisting of yttrium iron garnet slab and metallic wires. R. X. Wu. [11] has shown the effect of negative refraction index in periodic metal-ferrite film composite. F. J. Rachford et al [12] have performed simulations of ferrite-dielectric-wire composite negative index materials. Q. X. Chu et al [13] have shown a novel left-handed metamaterial with wire array in a ferrite-filled rectangular waveguide.

In this paper we consider a magnetized ferrite-wire structure inserted in vacuum. A plane polarized wave is obliquely incident on it. ε and μ of the structure can easily be tuned by changing the applied magnetic fields and negative refractive index of it is achieved at a certain frequency band to make the structure LHM. Maxwell's equations are used to determine the electric and magnetic fields in each region. Then , Snell's law is applied and the boundary conditions of the fields are imposed at each interface to obtain a number of equations with unknown parameters. The equations are solved for the unknown parameters to calculate the reflection and transmission coefficients. These coefficients are used to determine the reflected and transmitted powers of the structure. The effect of many parameters like frequency, applied magnetic fields and angle of incidence etc. on the mentioned powers is studied in detail. It is demonstrated that, if both ε and μ of the ferrite-wire structure are both positive and both negative, then the electromagnetic waves can propagate through it. On the other hand if either ε or μ of the structure is negative, the incident radiation will be reflected and no transmission of the waves will be through the structure. Moreover the frequency band of zero or nonzero transmission of the waves can be tuned by changing the applied magnetic fields due to the tenability of ε and μ of the structure. To check the validity of the performed computations the law of conservation of energy given by [14 , 15] is satisfied for all examples.

THEORY

Consider a rectangular ferrite-wire waveguide structure located between two half free spaces and a dc applied magnetic field acts on it along the X axis [4, 5]. A plane polarized wave is incident on the plane y = 0 at angle θ relative to the normal to the boundary (fig. 1). The effective permeability of the ferrite is given by [4, 5]:

$$\mu_f = \frac{\eta^2 - \mathrm{K}^2}{\eta} \tag{1}$$

Where $\eta = 1 + \dfrac{\omega_m(\omega_o - i\alpha\omega)}{(\omega_o - i\alpha\omega)^2 - \omega^2}$, $\mathrm{K} = \dfrac{\omega_m \omega}{(\omega_o - i\alpha\omega)^2 - \omega^2}$, $\omega_o = \gamma B$, $\omega_m = \gamma M$

γ is the gyromagnetic ratio, B is the intensity of the applied magnetic field, M is the saturation magnetization, ω is the angular frequency and i = $\sqrt{-1}$.

The effective permittivity of the structure is considered to be [4, 5]:

$$\varepsilon_f = \varepsilon_r - \frac{\sigma_{eff}}{\omega\varepsilon_o[i + (1.57\times10^{-6}\,\omega\sigma_{eff})(3.18\mu_o + .413\mu_f)]} \tag{2}$$

Where ε_o and μ_o are the permittivity and permeability of free space respectively, ε_r is the relative permittivity of ferrite material and σ_{eff} is the effective conductivity of wire arrays.

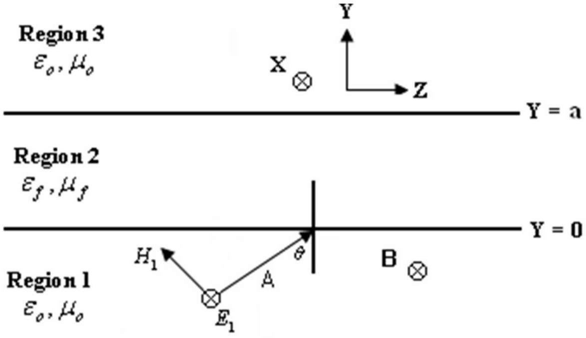


Fig. 1 – Oblique incidence of electromagnetic wave on a ferrite-wire structure embedded in vacuum

The transverse components of the electric and magnetic fields in each region of *Fig.1* are [9, 16]:

Region 1:

$$E_{1x} = \left(Ae^{ik_{oy}y} + Be^{-ik_{oy}y}\right)e^{i(k_{oz}z-\omega t)} \tag{3}$$

$$H_{1z} = \frac{1}{\mu_o\omega}\left[\left(-Ak_{oy}e^{ik_{oy}y} + Bk_{oy}e^{-ik_{oy}y}\right)\right]e^{i(k_{oz}z-\omega t)} \tag{4}$$

Region 2:

$$E_{2x} = \left(Ce^{ik_{fy}y} + De^{-ik_{fy}y}\right)e^{i\left(k_{fz}z-\omega t\right)} \tag{5}$$

$$H_{2z} = \frac{1}{\omega}\left[\left(Ck_c e^{ik_{fy}y} + Dk_b e^{-ik_{fy}y}\right)\right]e^{i(k_{fz}z-\omega t)} \tag{6}$$

With:

$$k_c = \frac{k_{fz}}{\mu_v} - \frac{k_{fy}}{\mu_f},\ k_b = \frac{k_{fz}}{\mu_v} + \frac{k_{fy}}{\mu_f},\ \mu_v = \frac{\eta^2 - \mathrm{K}^2}{i\mathrm{K}} \tag{7}$$

Region 3:

$$E_{3x} = Fe^{ik_{oy}y}e^{i(k_{oz}z-\omega t)} \tag{8}$$

$$H_{3z} = \frac{1}{\mu_o\omega}\left(-Fk_{oy}e^{ik_{oy}y}\right)e^{i(k_{oz}z-\omega t)} \tag{9}$$

Where A, B, C, D, F are the amplitudes of the forward and backward traveling waves. $k_o = \omega/c$ is the free space wave vector, $k_f = n_f\omega/c$ is the wave vector inside the slab and $n_f = \sqrt{\frac{\varepsilon_f\mu_f}{\varepsilon_o\mu_o}}$ is the refractive index of it.

$$k_{oz} = k_{fz} = k_o \sin\theta \text{ (Snell's Law)} \tag{10}$$

$$k_{oy} = \frac{\omega}{c}\sqrt{1-\sin^2\theta},\ k_{fy} = \frac{\omega}{c}\sqrt{n_f{}^2 - \sin^2\theta} \tag{11}$$

Matching the boundary conditions for the transverse field components at each layer interface, that is at y=0, $E_{1x} = E_{2x}$ and $H_{1z} = H_{2z}$, at y=a $E_{2x} = E_{3x}$ and $H_{2z} = H_{3z}$. This yields the following equations [16]:

$$A+B=C+D \tag{12}$$

$$\frac{k_{oy}}{\mu_o}(-A+B) = Ck_c + Dk_b \tag{13}$$

$$Ce^{ik_{fy}a} + De^{-ik_{fy}a} = Fe^{ik_{oy}a} \tag{14}$$

$$Ck_c e^{ik_{fy}a} + Dk_b e^{-ik_{fy}a} = -\frac{k_{oy}}{\mu_o}Fe^{ik_{oy}a} \tag{15}$$

Letting A=1 and solving these four equations for the unknown parameters enables us to calculate the reflection and transmission coefficients B and F [16]. The reflected and transmitted powers are defined as [16]:

$$R = BB^* \tag{16}$$

$$T = FF^* \tag{17}$$

Where B^* _ and F^* _ are the complex conjugate of B and F respectively.

NUMERICAL RESULTS

In this section the reflected and transmitted powers of the structure are calculated numerically as a function of frequency, angle of incidence, applied magnetic fields and thickness of ferrite. In our method we have used the parameters as in [17]: M = 4398 G, $\gamma = 2.8$ MHz/Oe, $\alpha = .006$, $\varepsilon_r = 4$. Three values of B are selected to be B = 500 Oe , 750 Oe, and 1000 Oe. The central frequency is selected to be 8.6 GHz. This frequency is chosen such that ε_f and μ_f are both simultaneously negative for all values of the applied magnetic fields. The slab thickness is assumed to be one half-wavelength long at the central frequency.

$\mu_f(\omega)$ with real part Re (μ_f) and $\varepsilon_f(\omega)$ with real Re (ε_f) are plotted as a function of frequency ω in *fig. 2* for three values of the applied magnetic fields (B = 500 Oe, B = 750 Oe, B = 1000 Oe). As shown from the figure the frequency ranges in which Re (μ_f) and Re (ε_f) are negative can be changed with the applied magnetic field [8]. In the case of B = 500 Oe, μ_f and ε_f are both negative in the frequency range of (6.4 GHz – 10.8 GHz) and consequently the ferrite-wire structure exhibits negative refractive index (i. e. LHM) in that range. For B = 750 Oe and B = 1000 Oe the ferrite-wire structure exhibits LHM in. the frequency ranges of (7.2 GHz – 11 GHz) and (8.2 GHz – 11.2 GHz) respectively.

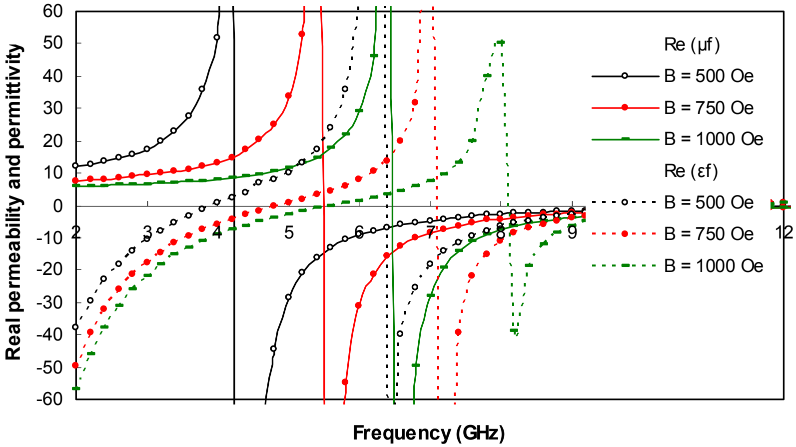
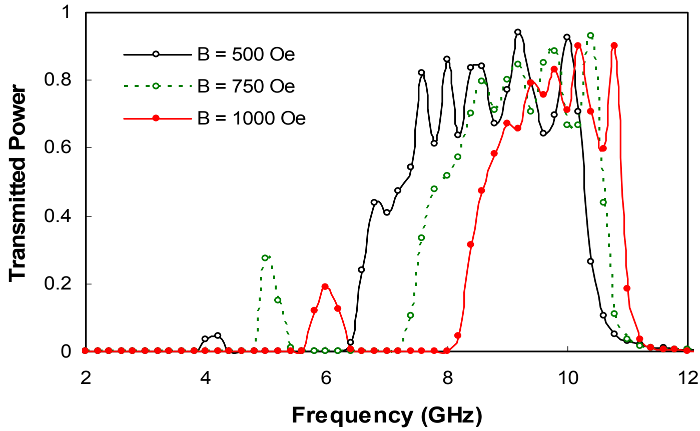
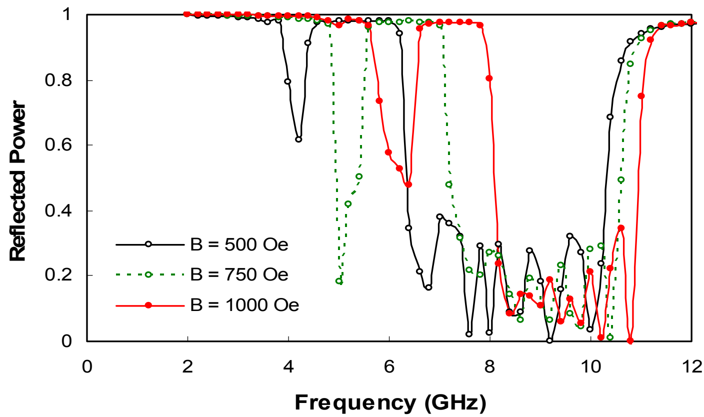


Fig. 2 – Calculated effective permeability and permittivity under different applied magnetic fields B = 500 Oe, B = 750 Oe and B = 1000 Oe

The transmitted and reflected powers as a function of frequency are calculated in *fig. 3*. for $\theta = 30^\circ$ and a = $\lambda/2$. The frequency is changed between 2 GHz and 12 GHz, because the simultaneously negative values of Re (μ_f) and Re (ε_f) under the three values of B can be realized in this range. In this example it can be seen that, if both μ_f and ε_f are both positive and both negative, the transmission is very good and the electromagnetic wave can propagate through the ferrite-wire structure. This is because the propagation constant of the waves in the structure are real ($k_f^{\;2} = \frac{\omega^2}{c^2}\varepsilon_f \mu_f$). If either μ_f or ε_f is negative, the propagation constant is imaginary and then the incident radiation will be reflected and no transmission of the waves will be through the structure. The symmetry of nonzero transmission shifts in frequency to the right side when the applied field increased. This is due to the tunability of the LHM which arises from the variation of the applied magnetic fields.



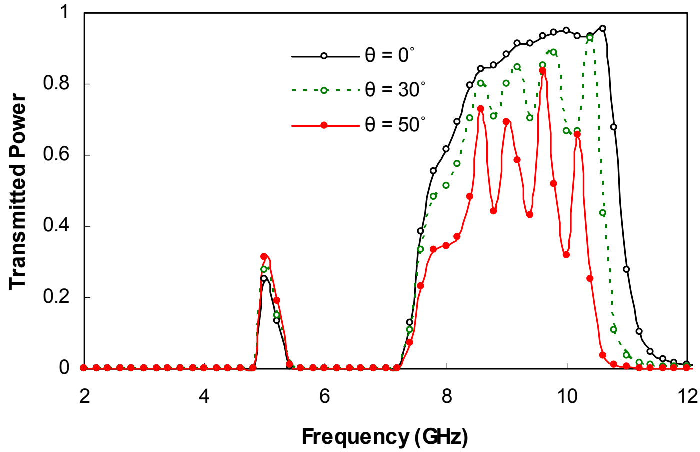
(a)



(b)

Fig. 3 – The transmitted and reflected powers against frequency when the applied magnetic field changes B = 500 Oe, B = 750 Oe and B = 1000 Oe

Figure 4 shows the transmitted and reflected powers as a function of frequency when the incidence angle changes (θ = 0˚, θ = 30˚, θ = 50˚) for B = 500 Oe. The frequency range and thickness of ferrite is the same as in the last example. It can be seen that the transmitted power is decreasing while the reflected power increasing with the angle of incidence. Moreover they show oscillatory behavior for θ = 30˚ and 50˚ while they show nearly no ripples for θ = 0˚.



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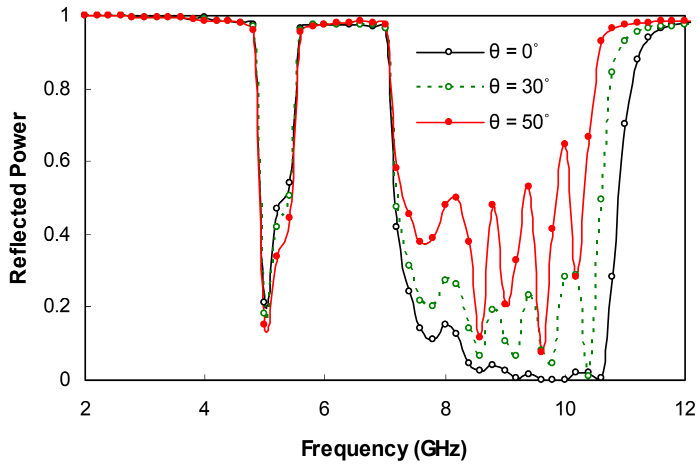

(b)

Fig. 4 – The transmitted and reflected powers as a function of frequency for three values of the angle of incidence θ = 0˚, θ = 30˚, θ = 50˚.

Figure 5 represents the transmitted and reflected powers versus the ferrite thickness for three values of the applied magnetic fields, 30˚ angle of incidence and 8.6 GHz frequency of the incident waves. The slab thickness is changed from zero mm to λ/2 (17.44 mm). It can be observed that the reflected power shows oscillatory behavior with thickness for all values of the applied magnetic fields. The transmitted power shows the same behavior but slightly decreasing with thickness for B = 500 Oe and 750 Oe and considerably decreasing with thickness for B = 1000 Oe.

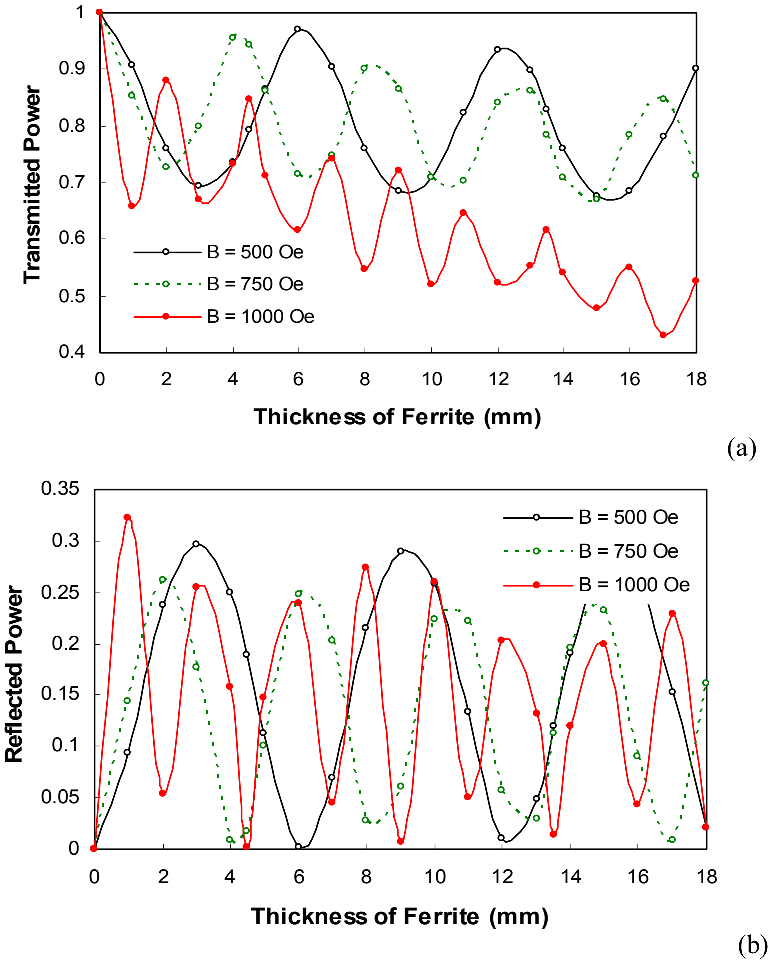

Fig. 5 – The transmitted and reflected powers versus ferrite thickness for three values of applied magnetic fields B = 500 Oe, B = 750 Oe and B = 1000 Oe

CONCLUSIONS

Reflection and transmission of electromagnetic waves by a magnetized ferrite-wire structure inserted in vacuum are analyzed numerically. Total reflection of the waves by the structure is obtained due to the difference in signs between μ and ε of the structure. Transmission of radiations through the structure is realized when μ and ε of the structure are both negative or both positive. The frequency band of reflection and transmission of the waves by the structure can be tuned by changing the applied magnetic field due to the tunability of μ and ε. Thus we can say that the variation of the applied magnetic field changes the reflection and transmission of the waves by the structure. Numerical examples are already presented to illustrate the paper idea and to prove the validity of the obtained results. Moreover the conservation of energy is satisfied throughout the performed computations for all examples. The discussed problem is useful for applications which require controlling of reflected and transmitted powers like antenna radome, microwave, millimeter wave and optical devices.

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