

ELECTROMAGNETIC WAVE PROPAGATION THROUGH SINGLE NEGATIVE INDEX MATERIAL

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Due to the potential applications of a negative index material (NIM), the development of the NIM has been occurred at an outstanding place in optics. To understand the optical properties of the single NIM layer, we have studied the propagation of electromagnetic wave through a medium of single NIM layer which is sandwiched between two dielectric materials. By using simple translational matrix method, the optical properties of the structure have calculated in the effect of thickness and plasma frequency of the NIM layer. The zero-refractive index, transmittance and dispersion of the structure are controlled by the thickness and the separation between the electric and magnetic plasma frequencies of NIM layer. The study of the electromagnetic wave propagation through the single negative index material may help to study the unusual behavior of the periodic structure containing NIMs. The study reveals that the single NIM layer can be used to make controlled optical devices (like Omni-directional reflectors) by adjusting the separation between the electric and magnetic plasma frequencies as well as the thickness of the NIM.

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1. Introduction

In 1967, Veselago [1-2], Russian physicist, first formally considered a negative index material (NIM) medium with simultaneously negative the electric permittivity and magnetic permeability at a certain frequency from a theoretical point of view, and concluded that the phase velocity and energy velocity of such media would point in opposite directions. The most fundamental optical effect of the negative refraction is that the bending of light occurs in negative direction when the light crosses the interface between two the materials [3-4]. The principle of negative refraction can be applied to all electromagnetic waves to study the wave propagation. According to Snell's law when an electromagnetic waves traverse the interfaces from a refractive index n_1 to refractive index n_2 , the change in its trajectory can be determined from the ratio of refractive index n_2 / n_1 . For the negative refractive index (NIM), the Snell's law shows that the electromagnetic wave would refract in negative angle due to the value of the ϵ and μ is simultaneously negative i.e. $n = -\sqrt{\epsilon\mu}$.

The numerous investigations have been carried out experimentally and theoretically studies of the NIMs [5-6]. The characters of novel types of micro-structured materials have been demonstrated the property of negative refraction for microwaves frequency range (1.0GHz-10.0GHz) for the arrays of wires [7] and the split-ring resonators (SRRs) [8]. The electric field,

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magnetic field and wave propagation in such materials obey the left-handed rule and are called left-handed materials (LHMs). The perfect lens concept was first suggested by Pendry [9] that a slab of a lossless NIM can provide a perfect image of point source.

Photonic band gap (PBG) materials or photonic crystals (PC) are composed of the periodic structure of two dielectric materials and PC affects the propagation of electromagnetic waves in the same way as the periodic potentials in a semi-conductor crystal affects the electron's motion by allowed and forbidden electronic energy band [10]. Photonic crystals have been also known for some time to exhibit unusual refraction properties, including ultra-refraction, where a beam incident from air is refracted away from the normal, implying a refractive index is less than one [11]. Negative refraction in PCs was first observed experimentally in a 3D-PC [12] and Gralak et al. [13] have studied negative refraction of PC in detail in both the theory and experiment. Negative refraction is exhibited in PCs due to the local curvature of the equifrequency contour (EFC). The group velocity in the EFC is directed away from the normal on the same side as the incident beam. Moreover, if the EFCs are approximately circular, and group velocity is directed radially inwards, then the PC displays negative refraction for all incident angles. For this situation, the concept of an effective refractive index based on the radius of the EFC has been proposed [13]. Many applications of the photonic crystal have been proposed, including the wave guides, perfect mirrors, solar cells and devices for suppression of thermal radiation as well as thermal signature management of military vehicles [14].

Recently Silvestre et al. [15] have studied the role of the dispersion on zero-refractive index bandgaps in periodic multilayers combining ordinary positive index materials and dispersive metamaterials with negative index in certain frequency ranges. The production of zero-average-index bandgaps has been investigated by changing the dispersion models of the metamaterial's constituents. The dispersion relation and associated electric fields of one-dimensional photonic crystal which is composed of alternating layers of right-handed materials (RHMs) and left-handed materials (LHMs) have been investigated for oblique propagation by Dios-Leyva and González-Vasquez [16]. The calculations are performed by assuming that the dielectric permittivity and magnetic permeability are constant in the RHM, whereas both parameters follow a plasmlike dispersion in the LHM. The dispersion curves and associated electric fields are shown to exhibit the interesting features around both the magnetic plasma frequency and the central frequency (ω_0) at which the spatial average of the wave vector component perpendicular to the layers is vanished. The features around magnetic plasma frequency are determined by the occurrence of a strong coupling between the radiation field and the "magnetic plasma" contained in the LHM. The broadband omni-directional reflection properties of single negative index materials have been calculated by using a dispersion relation with parameters taken from experimental data [17]. The reflecting band does not shift in frequency but actually widens with increasing angles of incidence. The operational bandwidth can be found 100% by increasing the separation between the electric and magnetic plasma frequencies. By using the Lorentz and Drude medium models for double-negative slab, Sabah and Uçkun [18] have studied the electromagnetic wave propagation through the frequency-dispersive and lossy double-negative slab embedded between two different semi-infinite media. The reflected, transmitted and loss powers for the frequency-dispersive and lossy double-negative slab are determined using reflection and transmission coefficients for both TE and TM waves.

In this communication, we studied the propagation of electromagnetic wave through a single NIM layer which is sandwiched between two dielectric materials. The optical properties are studied in the effect of thickness, electric plasma and magnetic plasma frequencies of the single NIM layer. The separation between the electric and magnetic plasma frequencies of the NIM is controlled the reflecting and transmitting properties of the structure due to varying the interface effects of the structure and the refractive index of NIM. We have found the interesting results for single negative index materials which can be used to make a good reflector and good transmitter by changing the separation between the electric plasma and magnetic plasma frequencies as well as the thickness of the NIM layer.

2. Theory and formulation

The propagation of electromagnetic wave in a single NIM layer can be described by the study of the amplitudes of electric and magnetic field of composite materials i.e NIM layer. The single NIM layer is sandwiched between two dielectric materials as shown in the figure (1(a)). The translational matrix method is the popular method to solve the amplitude of electromagnetic waves [19-21]. This method is a systematic approach to solve the optical properties of the NIM layer. Let us consider a negative index material (NIM) with refractive index ($n_2 = -\sqrt{\epsilon_2 \mu_2}$) sandwiched between two semi-infinite dielectric media of air and glass. The refractive index distribution is given as below:

$$n(x) = \begin{cases} n_1, & x < 0 & (\text{air}) \\ n_2, & 0 < x < d & (\text{negative index material}) \\ n_3, & d < x & (\text{glass}) \end{cases} \quad (1)$$

The electromagnetic wave incidence in the x-z plane, in plane wave solution of wave equation the electric field defined in the form,

$$E(x,t) = E(x) \exp[i(\omega t - \beta z)] \quad (2)$$

where β is the z component of the propagation wave vector considering that the wave incident from the left side. The electric fields for the three regions (figure (1)) are given as

$$E(x) = \begin{cases} Ae^{-ik_{1x}x} + Be^{ik_{1x}x}, & x < 0 & (3) \\ Ce^{-ik_{2x}x} + De^{ik_{2x}x}, & 0 < x < d & (4) \\ Fe^{-ik_{3x}(x-d)}, & d < x & (5) \end{cases}$$

where A, B, C, D and F are constants and k_{1x} , k_{2x} and k_{3x} are the x-component of the wave vector in three distinct regions (n_1 , n_2 and n_3) respectively. The general wave vectors k_{ix} is defined by

$k_{ix} = [(\frac{n_i \omega}{c})^2 - \beta^2]^{\frac{1}{2}} = (\frac{\omega}{c})n_i \cos \theta_i$ and $\beta = (\frac{\omega}{c})n_i \sin \theta_i$; where $i=1, 2, 3$ and θ_i =ray angle measured from the x-axis. The magnetic field of the corresponding electric field can be defined by the following equation;

$$\vec{H} = \frac{i}{\omega \mu} \vec{\nabla} \times \vec{E} = \frac{i}{\omega \mu} \frac{\partial E}{\partial x} \quad (6)$$

Now applying boundary conditions on the tangential component of the electric field (TE-mode) and tangential component of magnetic field (TM-mode) where there is no coupling between these components in whole medium. The boundary condition at $x = 0$, $x=d$ is applied in equations (3-6), we obtained the reflection and transmission coefficients [19]:

$$t = F/A = \frac{4k_{1x}k_{2x}e^{-ik_{2x}d}}{\frac{1}{\mu_2}(k_{1x} + \frac{k_{2x}}{\mu_2})(\frac{k_{2x}}{\mu_2} + k_{3x}) \left[1 + \frac{(k_{1x} - \frac{k_{2x}}{\mu_2})(\frac{k_{2x}}{\mu_2} - k_{3x})e^{-2ik_{2x}d}}{(k_{1x} + \frac{k_{2x}}{\mu_2})(\frac{k_{2x}}{\mu_2} + k_{3x})} \right]} \quad (7)$$

Similarly for the reflection coefficient:

$$r = B/A = \frac{[(k_{2x} - \mu_2 k_{1x})(k_{2x} + \mu_2 k_{3x}) + (\mu_2 k_{1x} + k_{2x})(\mu_2 k_{3x} - k_{2x})e^{-2ik_{2x}d}]}{[(\mu_2 k_{1x} - k_{2x})(\mu_2 k_{3x} - k_{2x})e^{-2ik_{2x}d} - (\mu_2 k_{1x} + k_{2x})(k_{2x} + \mu_2 k_{3x})]} \quad (8)$$

3. Results and discussion

To study the propagation of electromagnetic wave in the single NIM layer, the simple translational matrix method has been used to calculate optical properties like dispersion relation, reflectance (R), transmittance (T) and absorptance (A) [19, 20]. The negative index material (NIM) or left-handed material (LHM) is a composite materials which contains both negative values of the electric permittivity (ϵ) and magnetic permeability (μ) at certain frequency range.

The dielectric permittivity (ϵ) and magnetic permeability (μ) are given by $\epsilon = 1 - \frac{\omega_{ep}^2}{\omega(\omega + i\gamma)}$

and $\mu = 1 - \frac{F\omega_{mp}^2}{\omega(\omega + i\gamma)}$, where ω_{ep} =electric plasma frequency, ω_{mp} =magnetic plasma frequency and

γ =attenuation of the dispersive medium [3]. The electric permittivity (ϵ) and magnetic permeability (μ) of the NIM become negative when the incident frequency is less than plasma frequencies. The figure (1(b)) shows the electric permittivity, magnetic permeability and refractive index of the NIM layer with electric plasma frequency ($\omega_{ep}=15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp} = 1.0 \times 10^{15}$ Hz), attenuation ($\gamma=0.05 \times \omega_{ep}$) and $F=1$. The considered structure of the single NIM layer is sandwiched between two homogeneous and isotropic layers. In isotropic material, the vectors \vec{S} and \vec{K} are parallel to each other and $\epsilon\mu > 0$, is known as right handed material (RHM) or ordinary materials (OM).

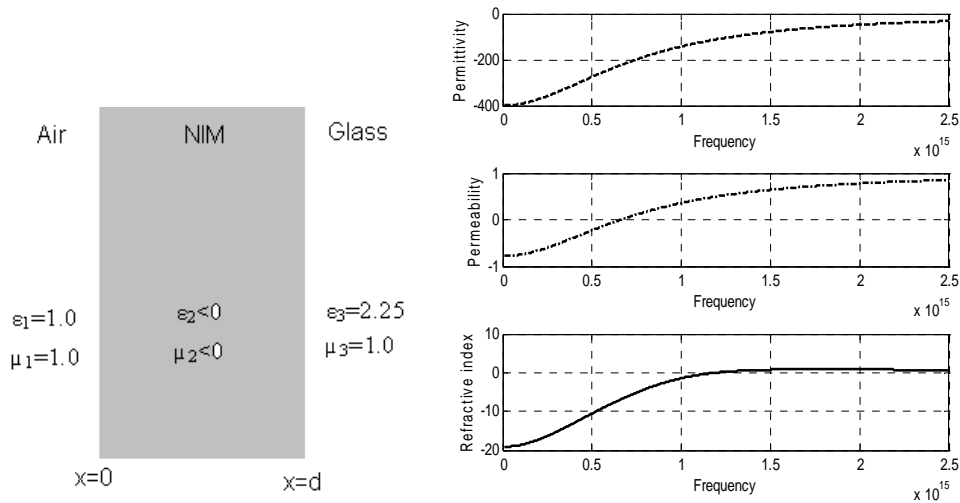


Fig. 1. (a) Thin single NIM layer sandwiched between two media with dielectric constant $n=1.0$ (air) (b) Optical constants of NIM layer with electric plasma frequency ($\omega_{ep}=15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp} = 1.0 \times 10^{15}$ Hz), attenuation ($\gamma=0.05 \times \omega_{ep}$).

The figure (2) shows the dispersion relation, transmittance, reflectance and absorption at the single NIM layer with the glass substrate i.e. $n_3=1.5$. The optical constant of the negative index material is taken with the effect of the electric plasma frequency ($\omega_{ep}=10 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp}=1 \times 10^{15}$ Hz) and attenuation ($\gamma=0.05 \times \omega_{ep}$). The thickness of the single NIM layer is 100nm. The dispersion relation is totally matched with reflectance of the structure. The reflectance is observed 0.82 at the range of frequency 0.47×10^{16} to 1.12×10^{16} Hz and the transmittance is continuously increased above the frequency 1.12×10^{16} Hz. Similarly calculation has been performed with increased the electric plasma frequency i.e. $\omega_{ep}=15 \times 10^{15}$ Hz. The optical properties of the structure containing NIM layer with increased electric plasma frequency ($\omega_{ep}=15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp} = 1.0 \times 10^{15}$ Hz) and attenuation ($\gamma=0.05 \times \omega_{ep}$) are shown in the figure (3). On comparing the figures (2) and (3), we have found that the dispersion

relation, transmittance, reflectance and absorption of the structure are increased with increasing the separation between the electric and magnetic plasma frequency when the attenuation is constant. Due to plasmonic response of the NIM, the position of the lower frequency is found to be fixed but the position of the higher frequency moves to the high frequency. Now we have repeated the calculation with the increased electric plasma frequency ($\omega_{ep}=20\times 10^{15}\text{Hz}$) and magnetic plasma frequency ($\omega_{mp}=1.0\times 10^{15}\text{Hz}$) i.e. $\Delta\omega=19\times 10^{15}\text{Hz}$. The dispersion relation and reflectance of the structure are found broaden which is depicted in the figure (4). From the study of these figures, we concluded that the optical properties are increased due to increasing the separation between the electric and magnetic plasma frequencies. The figures (2), (3) and (4) show that the single NIM layer can be made as a good reflector with increased electric plasma frequency when the magnetic plasma frequency, thickness and attenuation are constant. The optical properties of the structure containing single NIM layer are controlled by changing electric plasma frequency.

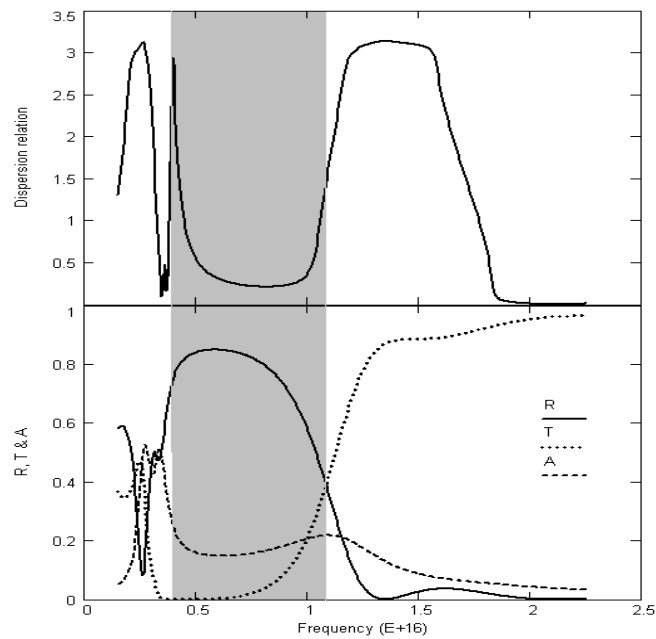


Fig. 2. Dispersion relation, R, T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep}=10\times 10^{15}\text{Hz}$), magnetic plasma frequency ($\omega_{mp}=1.0\times 10^{15}\text{Hz}$), attenuation ($\gamma=0.05\times\omega_{ep}$) and thickness 100nm.

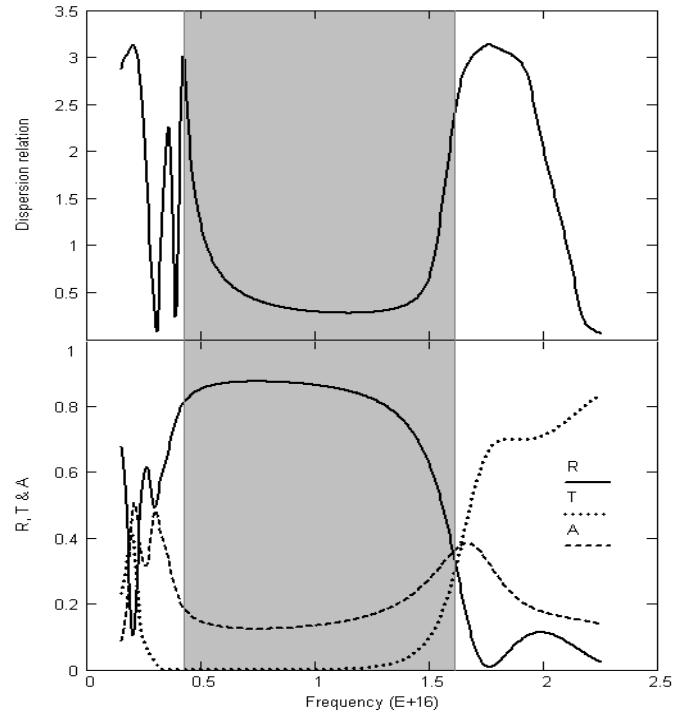


Fig. 3. Dispersion relation, R , T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep} = 15 \times 10^{15} \text{ Hz}$), magnetic plasma frequency ($\omega_{mp} = 1.0 \times 10^{15} \text{ Hz}$), attenuation ($\gamma = 0.05 \times \omega_{ep}$) and thickness 100nm.

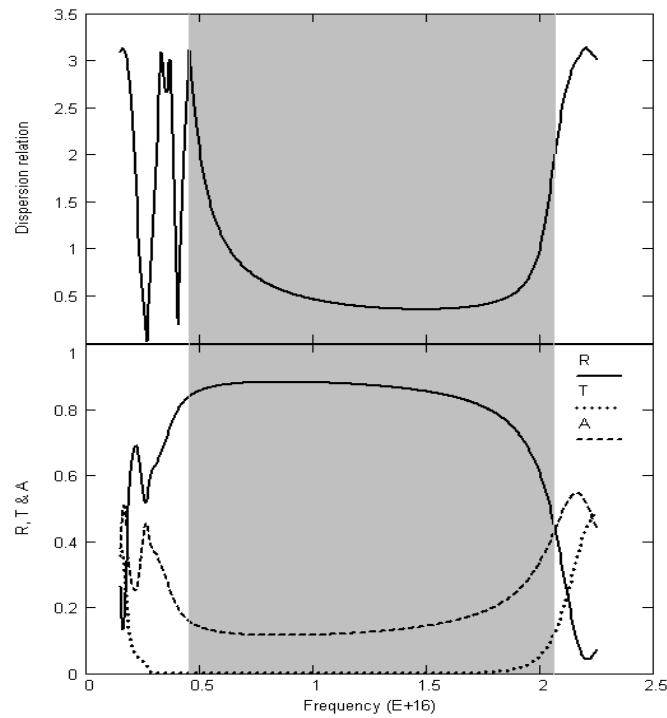


Fig. 4. Dispersion relation, R , T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep} = 20 \times 10^{15} \text{ Hz}$), magnetic plasma frequency ($\omega_{mp} = 1.0 \times 10^{15} \text{ Hz}$), attenuation ($\gamma = 0.05 \times \omega_{ep}$) and thickness 100nm.

Now the optical properties of the structure are calculated which vary with the magnetic plasma frequency i.e. 0.1×10^{15} Hz and the electric plasma frequency is to be fixed i.e. 15×10^{15} Hz. The optical properties of the NIM layer for 100 nm thickness having electric plasma frequency ($\omega_{ep} = 15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp} = 0.1 \times 10^{15}$ Hz) attenuation ($\gamma = 0.05 \times \omega_{ep}$) are calculated as shown in the figure (5). The optical properties of the considered structure are found same as for the single Ag layer, discussed Ref. [20]. The transmittance behavior of the single NIM layer is similar to the Ag metallic layer when the magnetic plasma frequency of the NIM is decreasing ten times to the initial value. Similar calculations have been adopted for the structure having the electric plasma frequency ($\omega_{ep} = 15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp} = 3.9 \times 10^{15}$ Hz), attenuation ($\gamma = 0.05 \times \omega_{ep}$) of the negative index material with thickness 100 nm, shown in figure (6). When the separation between the electric and magnetic plasma frequencies differ from $\Delta\omega = 11.1 \times 10^{15}$ Hz. the unusual behavior of the optical properties at the frequency 1.5×10^{16} Hz are obtained. The reflectance becomes zero near at the frequency 1.5×10^{16} Hz. On the other hand the transmittance and absorption of the structure become zero and 0.95% respectively at the frequency 1.5×10^{16} Hz due to effects of magnetic plasma frequency. Below the frequency (1.5×10^{16} Hz) the R, T and A of the structure are found with same values as discussed earlier in the figure (5).

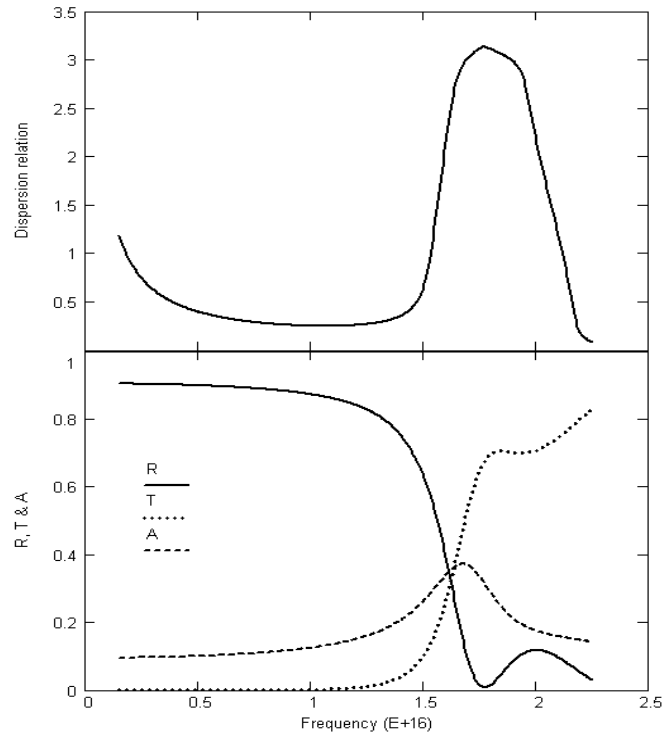


Fig. 5. Dispersion relation, R, T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep} = 15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp} = 0.1 \times 10^{15}$ Hz), attenuation ($\gamma = 0.05 \times \omega_{ep}$) and thickness 100 nm.

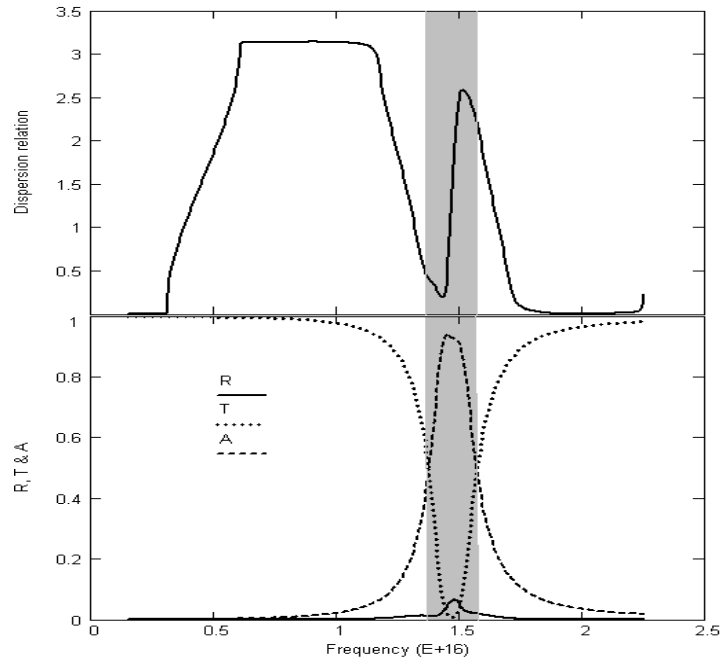


Fig. 6. Dispersion relation, R , T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep}=15\times 10^{15}\text{Hz}$), magnetic plasma frequency ($\omega_{mp}=3.9\times 10^{15}\text{Hz}$), attenuation ($\gamma=0.05\times\omega_{ep}$) and thickness 100nm.

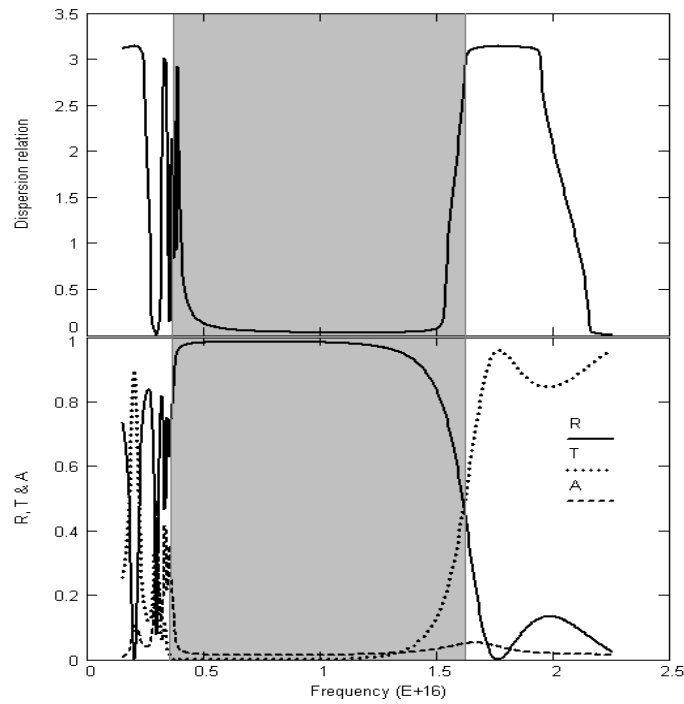


Fig. 7. Dispersion relation, R , T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep}=15\times 10^{15}\text{Hz}$), magnetic plasma frequency ($\omega_{mp}=1.0\times 10^{15}\text{Hz}$), attenuation ($\gamma=0.005\times\omega_{ep}$) and thickness 100nm.

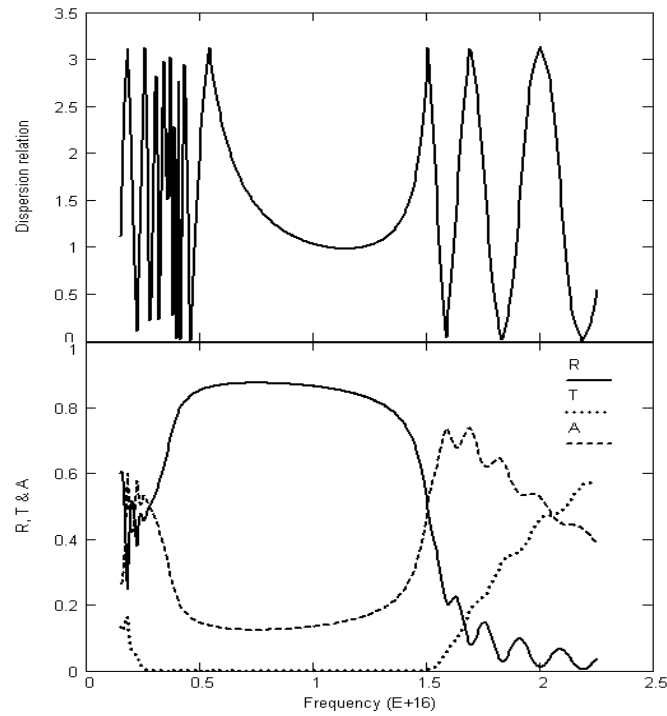


Fig. 8. Dispersion relation, R , T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep}=15\times 10^{15}\text{Hz}$), magnetic plasma frequency ($\omega_{mp}=1.0\times 10^{15}\text{Hz}$), attenuation ($\gamma=0.05\times\omega_{ep}$) and thickness 320nm.

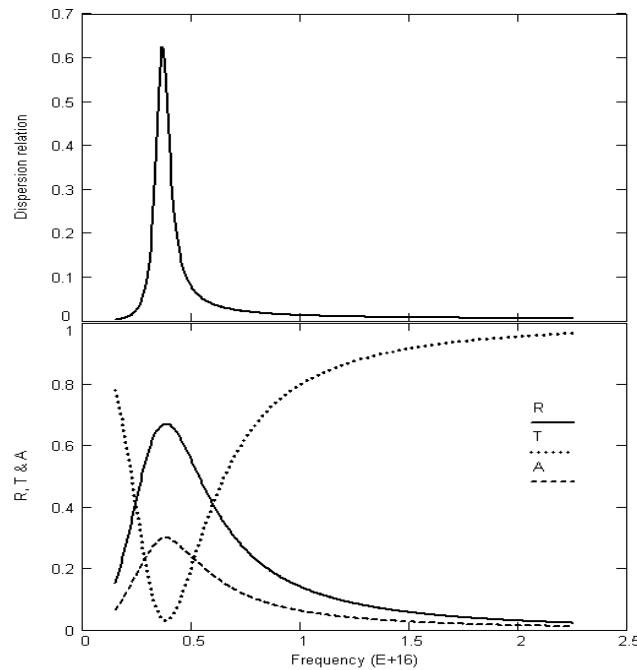


Fig. 9. Dispersion relation, R , T and A versus frequency for the NIM layer with electric plasma frequency ($\omega_{ep}=15\times 10^{15}\text{Hz}$), magnetic plasma frequency ($\omega_{mp}=1.0\times 10^{15}\text{Hz}$), attenuation ($\gamma=0.05\times\omega_{ep}$) and thickness 10nm.

The figure (7) shows the dispersion relation, R , T and A for the structure containing negative index material with the electric plasma frequency ($\omega_{ep}=15\times 10^{15}\text{Hz}$), magnetic plasma frequency ($\omega_{mp}=1.0\times 10^{15}\text{Hz}$) at 100nm thickness but the attenuation is reduced ($\gamma=0.005\times\omega_{ep}$). On decreasing the attenuation of the negative index material, the reflectance of the structure found

100% at the frequency range of 0.45×10^{16} Hz to 1.60×10^{16} Hz. Again we have studied optical properties of the NIM layer with the effect of the thickness of the NIM i.e. 320nm; when the electric plasma frequency ($\omega_{ep}=15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp}=1.0 \times 10^{15}$ Hz) and attenuation ($\gamma=0.05 \times \omega_{ep}$) and glass substrate ($n=1.5$) is considered, shown in figure 8. It is observed that the reflectance and absorption of the structure are found 0.85 and 0.18 respectively at the frequency range 0.30×10^{16} Hz to 1.5×10^{16} Hz. However the transmittance is nearly zero at the frequency range of 0.30×10^{16} Hz to 1.5×10^{16} Hz. Similar calculation has been done for the structure of the thickness 10nm of NIM layer having the electric plasma frequency ($\omega_{ep}=15 \times 10^{15}$ Hz), magnetic plasma frequency ($\omega_{mp}=1.0 \times 10^{15}$ Hz) and attenuation ($\gamma=0.05 \times \omega_{ep}$), as shown in figure (9). The reflectance of such single NIM layer is found 0.65 at the lower frequency 4.0×10^{15} Hz. The transmittance is found approximately zero, but the absorption of the negative index material show about 0.35 of the incident beam at the same frequency. From study the figures (5), (8) and (9), the abnormal and unusual behaviors of the optical properties of the structure are found due to the variation of the thickness of NIM.

4. Conclusions

We have investigated that the single NIM layer has shown their good reflectivity and transitivity properties at the certain range of the frequency due to the separation between the electric and magnetic plasma frequencies as well as the thickness of the NIM. The transmittance and reflectance of the NIM layer are similar to the Ag metal with low magnetic plasma frequency [20]. However, the reflectivity properties of the NIM layer are superior to ordinary Ag metal because of the refractive index of the NIM is found nearly zero or less than one. Such single NIM layer may be used as a good reflector, transmitter and absorber devices by adjusting the electric plasma frequency, magnetic plasma frequency and also thickness of NIM layer. The study of the electromagnetic wave propagation in the single negative index material may help to study the unusual behavior of the periodic structure containing negative index and dielectric materials. The widen transmittance and reflectance of the single NIM layer at the frequency range may be used to make omni-directional reflectors and perfect lens having the refractive index of the NIM near to zero or less than zero (i.e. negative).

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References

- [1] V. G. Veselago, *Sov. Phys- Usp.* **10**, 509 (1968)
- [2] V. G. Veselago, L. Braginsky, V. Schklover, C. Hafner, *J. Comput. Theor. Nanosci.* **3**, 1 (2006)
- [3] R.A. Shelby, D.R. Smith, S.C. Nemat-Nasser, S. Schultz, *Appl. Phys. Lett.* **78**, 489 (2001); S.A. Ramakrishna, *Phys. Rev. Lett.* **68**, 449 (2005)
- [4] N. Wongkasem, A. Akyurtlu, K. A. Marx, *Progress In Electromagnetics Research, PIER* **63**, 295 (2006)
- [5] R.A. Shelby, D.R. Smith, S. Schultz, *Science* **292**, 77 (2001); I. Awai, I. Matsuda, M. Hotta, A. Sanada, H. Kubo, *Journal of the European Ceramic Society* **26**, 1811(2006)
- [6] J.A. Kong., *Progress In Electromagnetics Research, PIER* **35**, 1 (2002); Kyoung-Youm Kim, *Opt. Lett.* **30**, 430 (2005)
- [7] D.R. Smith, W. Padilla, D.C. Vier, S.C. Nemat-Nasser, S. Schultz, *Phys. Rev. Lett.* **84**, 4184 (2000)

- [8] A. Ishimaru, S. Jaruwatanadilok, and Y. Kuga, Progress In Electromagnetics Research, PIER **51**, 139 (2005)
- [9] J.B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000)
- [10] K. B. Thapa, S. K. Singh, S. P. Ojha, Int. J. Infrared Millimeter Waves **27**, 1257 (2006)
- [11] J. P. Dowling, J. Mod. Opt. **41**, 345 (1994); S. Enoch, G. Tayeb, D. Maystre, Opt. Comm. **161**, 171 (1994)
- [12] H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, S. Kawakami, Phys. Rev. B **58**, R10096 (1998)
- [13] B. Gralak, S. Enoch, and G. Tayeb, J. Opt. Soc. Am. A **17**, 1012 (2000)
- [14] A. Mekis, J.C. Chen, I. Kurland, S. Fan, P.R. Villeneuve, J.D. Joannopoulos, Phys. Rev. Lett. **77**, 3788 (1996)
- [15] E. Silvestre, R. A. Depine, María L. Martínez-Ricci, J. A. Monsoriu, J. Opt. Soc. Am. B **26**, 581 (2009)
- [16] M. de Dios-Leyva and O. E. González-Vasquez, Phys. Rev. B **77**, 125102 (2008)
- [17] M. Bloemer, G. D'Aguanno, and M. Scalora, Appl. Phys. Lett. **87**, 261921, (2005)
- [18] C. Sabah and S. Uçkun, Opto-electronics Rev., **15**, 133 (2007)
- [19] M. Born and E. Wolf, Principles of Optics (Oxford: Pergamon, 1989)
- [20] P. Yeh, Optical Waves in Layered Media (John Wiley & Sons, 1984)
- [21] M. Bloemer, G. D'Aguanno, M. Scalora, Appl. Phys. Lett. **87**, 261921 (2005)