OPTICAL PROPERTIES OF PHOTONIC METAMATERIALS AND POTENTIAL APPLICATIONS

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Abstract— In this article, we have been studied, optics of single metamaterial and photonic metamateria. Generally single metamaterial is a composite material of negative permittivity and negative permeability or magnetic permeability which was experimentally realised in microwave region. But in my work, I have tried to understand the optics of periodic structure of dielectric and metamaterial i.e. photonic metamaterial for their potential applications. We show that a single layer of photonic metamaterial has a broad reflection property with a modest proportion of tunnelling using dispersion relation values derived from experimental data. The refractive index is close to zero in the range between the electric and magnetic dispersion relation, and negative index materials reflect radiation for all angles of incidence & polarisation with reflectivity of 100. Furthermore, as the angle of incidence increases, the reflecting band doesn't really shift in frequency but actually widens, and some of the wave tunnel approaches zero refractive index. By increasing the spacing between the magnetic & electric plasma frequencies, operational bandwidth can be increased to 100% or more.

Keywords: negative permittivity, negative permeability, magnetic permeability, dispersion relation, polarisation,

I. INTRODUCTION

Metamaterial are artificial structures designed to have properties not available in nature. They relate natural crystals as they are set up from periodically arranged unit cells and side length of each other is ‘a’. Unit cells are not prepared of physical atoms or molecules but it is a small metallic resonator. Veselago in 1968 [1] was proposed Metamaterial regarded by idea of negative-index material. By the help Negative-index materials [2–4] We can construct thin metallic wire split-ring resonators [5,6] Metamaterials have various application like, high-pass, low-pass, and bandpass spatial filters by using metamaterial constructed by Smith et al. [7]. In the indefinite metamaterials the anomalous total reflection phenomenon [8] and the inversion of critical angle and Brewster angle [9] have also been discussed. Metamaterials and plasmonic’s[10] two field have largely developed separately. Metamaterial were prepared at microwave frequencies. The field of plasmonic’s and metamaterials have pro fondly changed the way optics and photonics. The properties of metamaterial are not available in natural material as optical properties radio physical unique electro physical metamaterials are composites with above properties has grown day by day due to their potentialities application. The resonant interaction of electromagnetic wave determined the unusual properties of metamaterials. It spreads via a diverse media containing inclusions. It is produce resonant current excitation by that shaped. Result in new effect along with interferential collective processes the resonant interaction is non-potential. Metamaterials have an electric susceptibility & negative magnetic permeability [11]. An interference phenomenon determines their unusual properties that occur in metamaterials as periodic structures. A fundamental photonic crystal cell's characteristic size is equal to the EM wavelength, whereas the typical size of the resonant inclusions indicated above is substantially smaller [12]. In the 1990s, the analysis of metamaterials with theoreticians, experimentalists, & engineers with backgrounds in optics, radio physics, nanotechnology, and materials science became a major scientific movement. These findings, however, continue to elicit intense disputes at workshop & in publications, where this trend’s backgrounds as well as its underlying principles are explored, infrequently from subjective perspectives. Negative refraction occurs at the contact between two materials a regular substance and a metamaterial is one of the most important properties of metamaterials. L.I. Mandelstam was the author of first; examine the negative consequences in depth in one of his presentations on refraction. In this lecture we also includes the first diagram demonstrating the refracted, vectors of incident and reflected waves, as well as a detailed discussion of how, under negative refraction[13], energy flux travels away from regular substance-metamaterial interface, while phase impinges on it. In an article whose published by D.V. Sivukhinin 1957 in which he studied in dispersion medium propagation of EM waves and demonstrated that with negative dielectric (Ɛ) in a medium and magnetic permeability (μ), The propagation vector of the wave must be oriented toward the interface, i.e., in the opposite group velocity's direction. Negative refraction necessitates negative phase velocity (group velocity related with it). V.L. Ginzburg's & V.N. Agranovich classic monograph addressed the related phenomena at contact with a medium of gyrotropic [14].Many studies have been written about a fundamentally novel application of metamaterials. Let's pretend that any refraction index value, positive or negative, may be manufactured [15].

Optics of single metamaterial and photonic metamaterial. Generally single metamaterial is a composite material is a composite material of negative permittivity and negative permeability[16] or magnetic permeability which was experimentally realised in microwave region. But in my work, I have tried to understand the optics of periodic structure of dielectric and metamaterial i.e. photonic metamaterial for their potential applications

II. METHOD & METHODOLOGY

Maxwell For Metamaterial

Metamaterial or left handed materials (LHM) are a very interesting and popular subject now. In researching left-handed materials, we consider the situations which are need where magnetic& electric polarizations coexisting and make strange electromagnetic (EM) reactions. Artificial material designed by tinkering with the dielectric constant 'Ɛ' and magnetic permeability 'μ' and also magnetic & electric susceptibilities χ_m & χ_e. It is necessary to consider the interaction between magnetic and electric polarization too, when chiral symmetry is present. For Ɛ<0 and μ<0, allowed a propagating mode by a plane electromagnetic. The dispersion equation is satisfied by a wave in such a medium. $(CK/\omega)^2= \varepsilon\mu$ in the condition of LHM. The dispersion equation appears to be containing a dubious aspect about the right-hand pole structure. In the cases of magnetic (Ɛ=1) or electric (μ=1), corresponding to dipole transitions in electric and magnetic fields, respectively the RHS is a super position of single poles (for response of linear). The separation of magnetic& electric instances happens when the matter system lacks chiral symmetry where the polar and axial vectors are from irreducible representations. In the situation of chiral symmetry, the electric& magnetic changes of matter are virtually indistinguishable. Each transition has the potential to contribute to both Ɛ and μ.

Dispersion and Reflectance, Transmittance and Absorbance

A mathematical method for analysing wave propagation in one-dimensional systems is introduced and discussed. The transfer matrix method is a method that makes use of the transfer matrix. The TMM approach can be applied to study the propagation of quantum particles like electrons, as well as electromagnetic, elastic, & acoustic waves. This method can be simply adapted to any other wave problem after it has been devised for one type of wave. The reflection & transmission amplitudes can be simply specified and analysed using the transfer matrix approach. We'll look at both travelling and stationary (bound) waves. Once the TMM for a one potential has been determined, it may be simply extended to calculate TMM for identical potential-N analytically. Travelling waves produce pass bands as the number of potentials grows, but bound wave or standing produce gap in spectrum of energy of the system. In addition to estimating transmission& reflection properties of un-arrangement random systems, the transfer matrix formalism is particularly useful. By measuring the transmission (t) and reflection 'r' amplitudes, we can derive information about sample's physical property. Here we discuss about the relation of dispersion.

The relation of dispersion is,

$$E = E(q) \tag{1}$$

The physical properties of e- in the region outside sample are determined by the dispersion relation. These areas are known as leads. And here we discuss about the transmission and reflection respectively. We calculate transmitted wave ($\Psi_L^-(x)$ from the linear relation between outgoing and incoming waves is given by

$$\Psi_L^-(x=0) = S_{12}\Psi_L^-(x=l) \qquad (2.)$$

&reflected wave $\Psi_L^+(x+l)$ is given by

$$\Psi_R^+(x=l) = S_{22}\Psi_R^-(x=l) \qquad (3)$$

S_{12} the transmittance amplitude (t) & S_{22} is called reflection amplitude (r);

$$r = S_{22},\ t = S_{12} \qquad (4)$$

At last, in the terms of reflection& transmission amplitudes, the scattering matrix S can be written as follows:

$$\mathbf{S}=\begin{pmatrix} r' & t \\ t' & r \end{pmatrix} \qquad (5)$$

The transmissions (reflection) coefficient is defined as the likelihood of a particle being transferred (reflected),

$$R = |r|^2 \& \quad T = |t|^2 \qquad (6)$$

Symmetry properties of scattering matrix using

$$|r| = |r'| \text{ and } |t| = |t'| \qquad (7)$$

The transfer matrix can be written in a more symmetric form as follows:

$$\mathbf{M} = \begin{pmatrix} (t')^{*-1} & rt^{-1} \\ -t^{-1}r' & t^{-1} \end{pmatrix} \qquad (8)$$

Transmission Coefficient

Transmission coefficient $T=|t|^2$ can be calculated using the scattering matrix S and the transfer matrix, respectively.

$$T = |t|^2 = |S_{12}|^2 = \frac{1}{|M_{22}|^2} \qquad (9)$$

Expression usage for M_{22} we found T is equal to,

$$T = \frac{1}{1+\frac{1}{4}[\left[\frac{k}{k\prime}-\frac{k\prime}{k}\right]^2 \sin^2 2k\prime a} \qquad (10)$$

Transmission coefficient T can also be calculated.

$$T = \frac{1}{1+\left|\frac{r}{t}\right|^2} = \frac{1}{1+|M_{12}|^2} \qquad (11)$$

Formula (9) applies to both positive and negative as long as E > V0.

III. RESULTS AND DISCUSSION

The photonic metamaterials are the periodic structure of the dielectric and metamaterials. The electromagnetic wave (EMW) propagation inside the photonic materials is due to the wave propagation vector ‘k’. The ‘k’ is dependent upon the refractive index of material called optical density of the materials. So, the refractive index and reflectance of the materials are considered in the study. From Maxwell equation, the refractive index (n) defined by the following relation,

$$n^2 = \varepsilon\mu \qquad (12)$$

Refractive index of material is dependent upon the electric permittivity and magnetic permeability which is given for the SSR materials as;

$$\varepsilon(\omega) = 1 - \frac{(\omega_{ep}^2-\omega_{eo}^2)}{(\omega^2-\omega_{eo}^2+i\gamma\omega)} \qquad (13)$$

$$\mu(\omega) = 1 - \frac{(\omega_{mp}^2-\omega_{mo}^2)}{(\omega^2-\omega_{mo}^2+i\gamma\omega)} \qquad (14)$$

Where ω_{ep} is electric plasma frequency, ω_{eo} is electric resonance frequency, ω_{mp} is magnetic plasma frequency, ω_{mo} is magnetic resonance frequency & γ is loss of the material. This parameter is taken from reference [20] i.e.

$$\omega_{eo} = 2\pi \times 10.3\ GHz$$

$$\omega_{mp} = 2\pi \times 10.95\ GHz$$

$$\omega_{eo} = 2\pi \times 10.05\ GHz$$

$$\gamma = 2\pi \times 10\ MHz$$

Using these parameters, we have studied the optical density as well as the reflectance of the single materials and repeated the paper of Bloemer et al. [21].

1 Single Metamaterials

1.1 Refractive Index of single metamaterials

To study the optical constant of single metamaterial, we have taken $\omega_{eo} = 2\pi\times10.3$ GHz, $\omega_{ep} = 2\pi\times12.8$ GHz, $\omega_{mo} = 2\pi\times10.05$ GHz, $\omega_{mp} = 2\pi\times10.95$ GHz, $\gamma = 2\pi\times10$ MHz, $\omega_0 = 2\pi\times10$ GHz. The real refractive index andextinction coefficient are shown in the Fig.1.The Fig. has three parts of refractive index (I) positive index at high frequency range, (ii) zero index in the 1.1-1.3 frequency range and (iii) negative index range below the 1.1 frequency range.

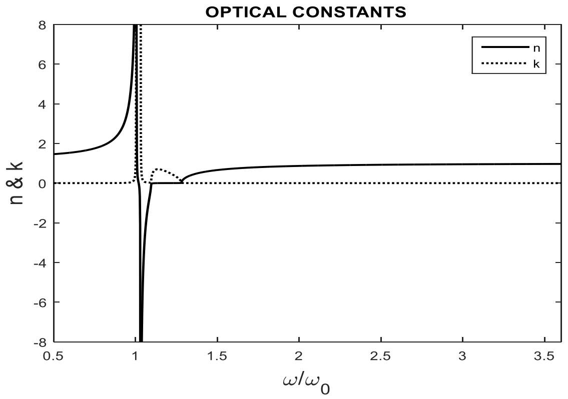

Fig 1: Optical constant of single metamaterial of index 'n' and extinction coefficient 'K' versus ω/ω_0 with $\omega_{eo} = 2\pi\times10.3$ GHz, $\omega_{ep} = 2\pi\times12.8$ GHz, $\omega_{mo} = 2\pi\times10.05$ GHz, $\omega_{mp} = 2\pi\times10.95$ GHz, $\gamma = 2\pi\times10$ MHz, $\omega_0 = 2\pi\times10$ GHz, [20]

The calculation has been done by Bloemer et al [21] for calculating the ominidirectional reflection behaviour of single metamaterial due to zero refractive index. They have calculated the refractive index using with following data with $\omega_{eo} = 2\pi\times10.3$ GHz, $\omega_{ep} = 2\pi\times12.8$ GHz, $\omega_{mo} = 2\pi\times10.05$ GHz, $\omega_{mp} = 2\pi\times10.95$ GHz, $\gamma = 2\pi\times10$ MHz, $\omega_0 = 2\pi\times10$ GHz,. Such single metamaterial has negative, positive as well as zero values of refractive indices. The zero refractive index of the single metamaterial has unique behaviour for TE and TM modes of the incident waves. But we are interested to reflectance of single metamaterial for semi-infinite material of substrate of the single metamaterial for the zero refractive index material.

The effective parameters of the refractive indices are ω_{ep} is electric plasma frequency; ω_{em} is magnetic plasma frequency and γ is loss of material. For low loss of the material we had taken the constant γ in our calculation as in the reference [21]. It means the optical density or refractive index is variable with ω_{ep} and ω_{em}, so we increase the value of electric plasma frequency with other parameters same. The figure 2 shows the refractive index (n) & extinction coefficient of single metamaterial with parameters $\omega_{eo} = 2\pi\times10.3$ GHz, $\omega_{ep} = 2\pi\times12.8$ GHz, $\omega_{mo} = 2\pi\times10.05$ GHz, $\omega_{mp} = 2\pi\times10.95$ GHz, $\gamma = 2\pi\times10$ MHz, $\omega_0 = 2\pi\times10$ GHz. It is depicted from figure 2 that now changing the value of ω_{ep} the region of negative refractive index get suppressed and the region of zero refractive index has widen from $\omega= 1.1\times\omega_0$ to $\omega = 2.43$ X ω_0 The wider the spectral region, the greater the difference between magnetic & electric plasma frequency.

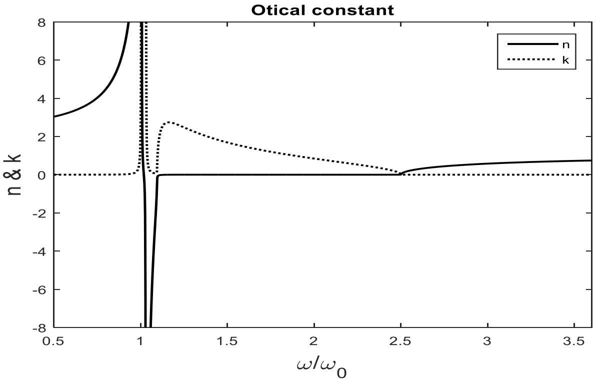

Fig 2: Optical constant of single metamaterial of index ‘n’ and extinction coefficient ‘K’ versus ω/ω_0 with $\omega_{eo} = 2\pi\times10.3$ GHz, $\omega_{ep} = 2\pi\times12.8$ GHz, $\omega_{mo} = 2\pi\times10.05$ GHz, $\omega_{mp} = 2\pi\times10.95$ GHz, $\gamma = 2\pi\times10$ MHz, $\omega_0 = 2\pi\times10$ GHz [20]

1.2 Optics of single metamaterials

In reference [21] the zero refractive index has found complete reflection band gap for both modes, TE and TM. So they are called it broad band ominidirectional reflector. Now we are calculated the reflectance of the single metamaterial with substrate which are shown in figure (3) for TE and TM modes.

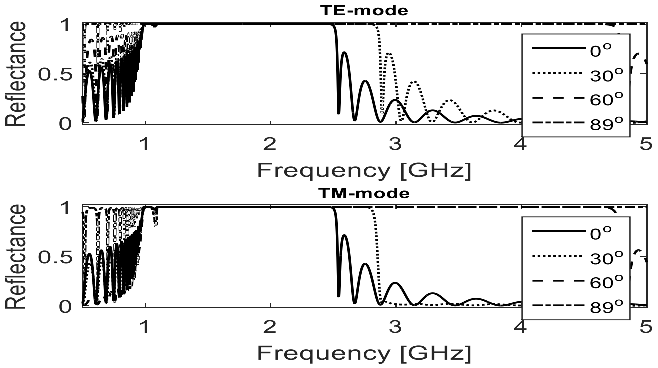

Fig 3: Reflection versus ω/ω_0 of single metamaterial with substrate for TE and TM polarized wave

The reflectance of single metamaterial is calculated when single metamaterial is placed between (n=1) and (n=1.51) in TE mode for different value of incident angles. These calculation are matched with reference [21] which shows that the reflectance of the single metamaterial are obtained in the frequency range $\omega = 1.1 \text{ X } \omega_0$ to $\omega = 1.28 \text{ X } \omega_0$.

1.3 3-D Diagram 3-D diagram of the reflectance for TE and TM mode, which is denoted the reflection versus frequency of single metamaterial with substrate for TE and TM polarized wave.

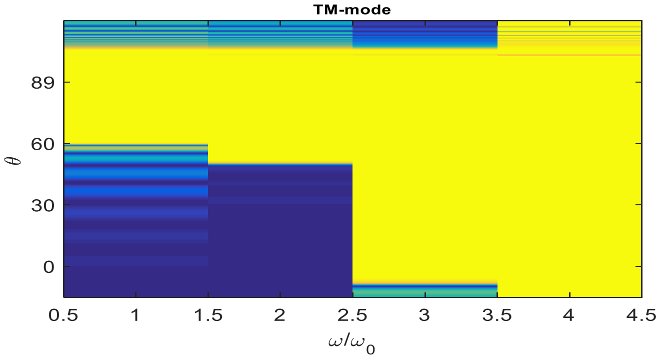

Fig 4:3-D diagram θ versus ω/ω_0 for TM mode

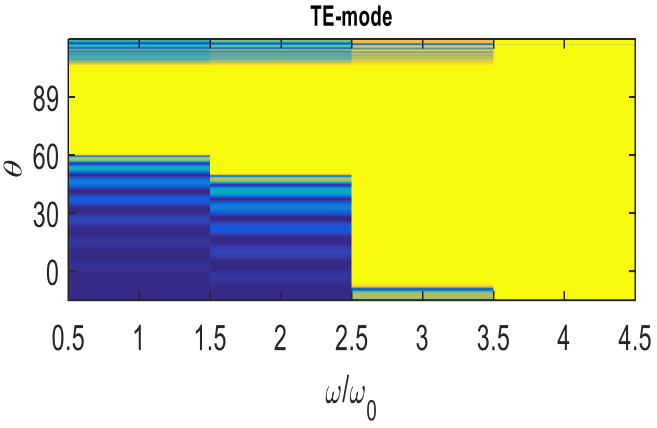

Fig -5:3-D diagram θ versus ω/ω_0 for TE mode

I conclude that the single metamaterial has the zero index gaps which have large reflectance obtained for TE and TM modes. Now, I am interested to study the optical properties of the periodic stricture containing metamaterial and dielectric materials.

In our calculation, we have considered that the single metamaterial is located in a substrate of SiO_2 $n = 1.51$ & calculate reflectance of semi finite material. Broadband ominidirectional reflection from single metamaterial has been calculated by Bloemer et al. [21] using characteristics matrix method. Now we study the refractive index of the single metamaterial with varying incident frequency which is shown in Fig 1.

2 Photonic Metamaterial

2.1 Refractive Index of Metal

Now I have taken same refractive index for metamaterials as discussed earlier in the previous section i.e. optical constant of metamaterials. And thickness is $d_1 = 12$ & $d_2 = 6$. The refractive index of the metamaterial is shown in the Fig.6. The refractive index of dielectric is 1.51. And thickness is $d_1 = 12$ & $d_2 = 6$ By using the TMM method as discussed in previous chapter, the reflectance of the photonic metamaterials can be calculated,

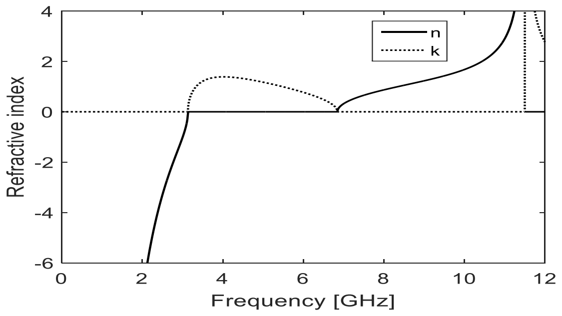

Figure 6: The refractive index of metal, refractive index n & k versus frequency ω/ω_0

2.2 Optics of Photonic Metamaterial

The transmittance properties of the photonic metamaterials are shown in the Fig. 7. The calculated results have found that the periodic structures of the dielectric and metamaterials i.e. photonic metamaterials have the following properties:

- There are three type of band gap found,
  - Zero- gap due to zero refractive.
  - Bragg's gap due to PIM.
  - Mixed gap of zero and Bragg gap.

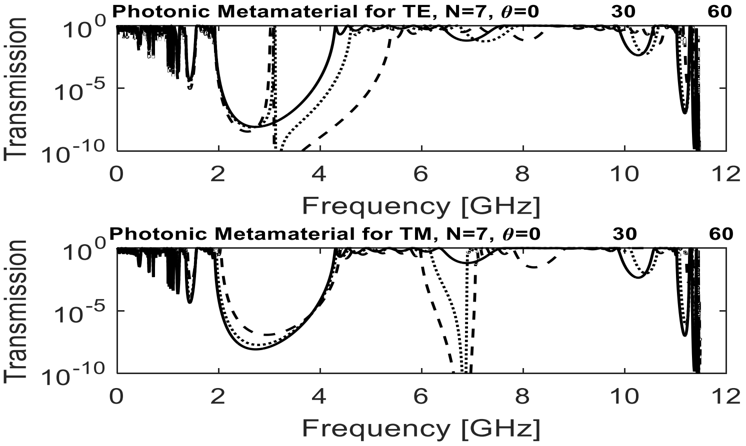

Fig 7: Transmission versus ω/ω_0 of photonic metamaterial with substrate for TE and TM polarized wave

From above results, I have concluded that:

- Zero gap of photonic metamaterial may be used as an ominidirectional reflector for TE and TM mode.
- Photonic metamaterial may be used as zero gaps, Bragg's gaps as well as mixed gaps for quantum computing.

V. CONCLUSION

We show that a single layer of photonic metamaterial has a broad reflection property with a modest proportion of tunnelling using dispersion relation values derived from experimental data [20]. The refractive index is close to zero in the range between the electric and magnetic plasma frequencies, and negative index materials reflect radiation for all angles of incidence & polarisation with reflectivities of 100 percent. Furthermore, as the angle of incidence increases, the reflecting band doesn't really shift in frequency but actually widens, and some of the wave tunnel approaches zero refractive index. By increasing the spacing between the magnetic & electric plasma frequencies, operational bandwidth can be increased to 100% or more.

In the region between magnetic& electric plasma frequencies, one layer of single metamaterial provides broadband reflecting capabilities. At optical frequencies, optical constant of single metamaterials is similar to that of actual metals. However, because the real part of index of refraction is virtually zero, metallic single metamaterials have better reflecting qualities than regular metals. The numerous uses for single metamaterials in general, and metallic single metamaterials in particular, such as hollow core waveguides and extremely efficient back reflectors for same light fixtures, provide extra motivation to create these novel metamaterials.

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