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Reflection, Transmission and Absorption Spectra of 1D Periodic Structure Containing Hyperbolic Metamaterial

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Abstract
In this work, the optical properties of one dimensional (1D) multilayer structure of traditional dielectric and hyperbolic meta-material are theoretically calculated. Hyperbolic meta-material is the composite of dielectric and plasma material. The reflection, transmission and absorption spectra of the multilayer 1D ternary periodic structure at normal incident have been calculated using transfer matrix method (TMM). We have theoretically analyzed the reflection, the transmission and the absorption spectra against frequency are affected with the variation variable parameters of optical constant of the material. The calculated results reveals that an innovative idea to design the tunable filter, optical window, optical logic gate, broadband reflector and absorption-based devices.

Keywords- Photonic crystals, Dielectrics, Hyperbolic material, Optical switch, Filter.

1. Introduction

By altering the dielectric constant, a periodic structure of dielectric materials known as Photonic Crystals (PC) regulates the propagation of electromagnetic waves. Yablonovitch (1987) and John (1987) originally hypothesized the photonic band gap (PBG) of the PC in 1987. This is because the PC's periodicity is caused by wave resonance. A PBG is dependent on various factors such as the incident wave frequency range, number of stacks, filling percentage, and index of refraction (Joannopolos et al., 2007). The special abilities of PBG periodic structures to control electromagnetic waves make them useful in a wide range of applications. These materials have potential applications in science and technology, especially in the field of optical device development. 1D periodic structure, or layered media with one-directional material periodicity, is the most basic type of PC and can be readily fabricated using thin-film technology. 1D periodic structure is used in many optical and photonic devices, omni-directional filters, broadband reflectors, microwave absorbers, tunable filters, and optoelectronic devices (Fink et al., 1998; Krauss and Richard, 1999; Sakoda, 2004; Busch et al., 2007; Kumar et al., 2018; Kumar et al., 2019).

Anisotropic media having a hyperbolic form dispersion that can affect frequencies ranging from terahertz to near infrared are known as hyperbolic materials. These incredibly high dispersion materials have enormous potential applications in the fields of meta-material, absorption, optical switches, waveguide in the optical domain, cloaking, and hyper lenses for imaging (Smith and Shurig, 2003; Iorsh et al., 2013; Sreekanth et al., 2013). A recently developed hyperbolic material consisting of graphene and stacked sheets of a thin dielectric layer is being investigated as an ultra-high absorber in the near field region (Guclu et al., 2012; Zhang et al., 2013). Hyperbolic materials exhibit both metallic and dielectric properties. Hyperbolic material exhibits dielectric behavior with fewer free electrons and high transmission, whereas metallic behavior is characterized by strong reflectance and absorption because of many free electrons paralleling wave propagation.

As a result, hyperbolic materials can be classified into two categories: dielectric type II behavior and metallic type I behavior. Epsilon nearly zero (ENZ) and epsilon nearly pole (ENP) are two significant properties of the wave projection. Additionally, they are divided into two categories: ENZ and ENP. When free electrons are moving during wave propagation, ENZ is always present. When there is no free electron in motion, ENP occurs (Alu et al., 2007; Silverinha and Engheta, 2007; Ferrari et al., 2015; Shekhar et al., 2014; Korobekin et al., 2010). Because of the changeable characteristics and strong absorption spectra of hyperbolic materials, researchers are concentrating on absorption-based optical devices. They are utilizing graphene and dielectric-based 1DPS to develop and fabricate these devices while examining the differences between various materials (Kumar et al., 2020; Kumar et al., 2024).

2. Theoretical Model and Methodology

We have theoretically calculated the stacked of 1D ternary periodic structure of artificial dielectric (A), traditional dielectric (B) and composite layer of hyperbolic meta-material (C) i.e. the composite layer of plasma and dielectric material. The reflection, transmission and absorption spectra of 1D ternary periodic structure analyzed using simple and well-known transfer matrix method (TMM) (Yeh, 1988). For the composite meta-material layer, we use effective medium theory (EMT) to study the behavior of electromagnetic wave propagation in hyperbolic meta-material that is an anisotropic medium with uniaxial dielectric tensor components. We use the TMM to analyze the behavior of electromagnetic wave propagation in periodic structure.

The characteristic matrix for considered periodic structure,

$$M_i = \begin{bmatrix} \cos\gamma_i & -\frac{i}{p_i}\sin\gamma_i \\ -ip_i\sin\gamma_i & \cos\gamma_i \end{bmatrix}$$

where, $\gamma_i = \frac{\omega}{c} n_i d_i \cos\theta_i$, c is the speed of light in vacuum, $\theta_i$is the ray angle inside layer i^{th} with a refractive index as $n_i = \sqrt{\varepsilon_i \mu_i}$ $p_i = \sqrt{\frac{\varepsilon_i}{\mu_i}}\cos\theta_i$ and $\cos\theta_i = \sqrt{1 - \frac{n_0 \sin^2\theta_0}{n_i^2}}$ in which n_0 is the refractive index of air where the incidence wave tends to enter the layer/material.

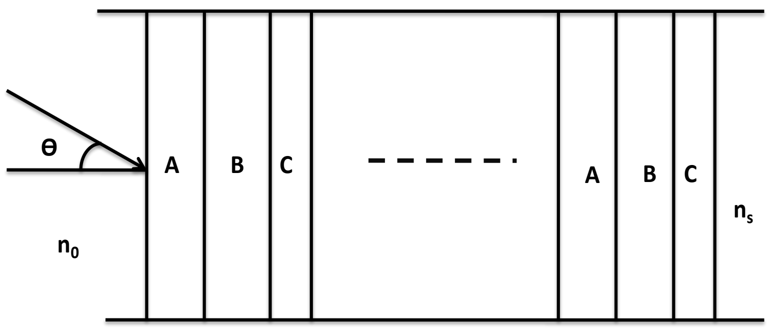

Figure 1. Schematic diagram of 1D ternary dielectric and hyperbolic material based periodic structure.

The reflection, transmission and absorption properties of the 1D ternary periodic structure of artificial dielectric, traditional dielectric and hyperbolic meta-material are investigated. The transfer matrix is given as $M(d) = \begin{pmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2} \end{pmatrix}$ & total matrix is given as $M = (M_A M_B M_C)^{10}$.

The reflection and transmission coefficient of the 1D ternary periodic structures calculated by,

$$t = \frac{2p_0}{\left(M_{11} + \frac{M_{12}}{p_0} + M_{21}p_0 + M_{22}\right)} \qquad \& \qquad r = \frac{\left(M_{11} + \frac{M_{12}}{p_0} - M_{21}p_0 - M_{22}\right)}{\left(M_{11} + \frac{M_{12}}{p_0} + M_{21}p_0 + M_{22}\right)}$$

The reflection, transmission and absorption spectra of the 1D meta-photonic crystal containing dielectric and hyperbolic meta-material is given by $T = \left(\frac{p_s}{p_0}\right)|t|^2$, $R = |r|^2$ and $A = 1 - R - T$ (Iorsh et al., 2013).

3. Results and Discussion

Firstly, we have theoretically studied the reflection, transmission and absorption of 1D ternary periodic structure containing artificial dielectric, traditional dielectric and hyperbolic meta-material using TMM. We consider the parameters for artificial dielectric and traditional dielectrics are:$\varepsilon_A = 40$, $d_A = 1.3mm$, $\varepsilon_B = 2.2$, $d_B = 2.9mm$, $\mu_A = \mu_B = 1$, $\theta = 0^0$, $N = 10$, respectively. We added the hyperbolic meta-material that is the composite of dielectric and plasma material. The parameters for dielectric and plasma are followed as: $\varepsilon_D = 1$, $\mu_D = 1$, $d_D = 1.8mm$, $d_{HM} = 2mm$, $d_C = 0.2mm$, $\omega_p = 28.4GHz$, $\varepsilon_C = 1 - \frac{\omega_p{}^2}{\omega^2 + i\gamma}$, $\mu_C = 1$ respectively.

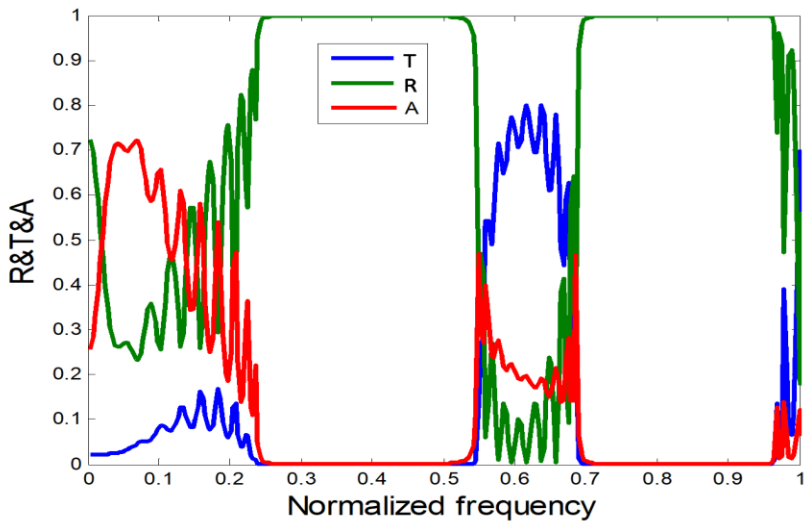

Figure 2. Shows the reflection, transmission and absorption spectra of 1D ternary periodic structure.

The reflection, transmission and absorption spectra of 1D ternary periodic structure of dielectric material and plasma photonic crystal at a normal incident angle for transverse magnetic (TM) polarization. We investigate the reflection, transmission and absorption against normalized frequency at lower and higher frequency range of dielectric and plasma materials. The reflection, transmission and absorption spectra analyzed and obtained structure shows multiband formation after incident electromagnetic wave in considered periodic structure. The multiband range occurs in 0.25-0.52 and 0.70-0.95, respectively as shown in **Figure 2**. Reflection, transmission and absorption spectra show the unique behavior corresponds to the frequency. Reflection, transmission and absorption behavior shows when electromagnetic wave interact with periodic structure some part of light reflected, transmitted and absorbed at the interface and formed frequency band called photonic band gap. Reflection, transmission spectra against frequency shows the unique behavior as tunable filter. In this article, absorption spectra against frequency shows unique behavior at lower and higher frequency range shows the optical switch and absorption devices. These calculated results proposed an innovative idea to design the tunable filter, optical window, optical logic gate, broadband reflector and absorption-based devices as shown in **Figure 2**.

4. Conclusion

The reflection, transmission and absorption spectra of 1D ternary periodic structure of traditional dielectric and hyperbolic material at normal incidence using well known transfer matrix method is theoretically analyzed. The theoretically calculated results show the multiband formation in the frequency range 0.25-0.52 and 0.70-0.95, respectively. The reflection transmission and absorption against normalized frequency shows the broadband reflector, tunable filter and optical switches, respectively corresponds to normalized frequency. These calculated results proposed an innovative idea to design the broadband reflector, tunable filter and optical switches.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

AI Disclosure

The author(s) declare that no assistance is taken from generative AI to write this article.

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