Enhancement of Photonic Band Gap in One-Dimensional Plasma-Dielectric Ternary Photonic Crystal

Girijesh Narayan Pandey*, Narendra Kumar, Asish Kumar***, Khem B. Thapa**** and Sonu Kaliramna*****
Department of Applied Physics, Amity Institute of Applied Sciences, Amity University, Uttar Pradesh, Noida 201313, India
***Email:** gnpandey2009@gmail.com

Abstract: *We theoretically design a multilayer structure of hyperbolic meta-material based on plasma photonic crystal which is composed of traditional dielectric and plasma materials. The reflection, transmission and absorption spectra of the multilayer ternary periodic structure at normal incidence have been investigated using transfer matrix method. We have analyzed that the reflection, the transmission and the absorption are highly affected with the variable parameters of optical constants. Such a structure shows a similar good absorptive nature up to normalized frequency 2.25, while above this frequency, it exhibits multiple broadband electromagnetic wave tunneling. The calculated results reveal an innovative idea in designing some optical devices using such hyperbolic meta-material based photonic crystal with wideband tunneling.*

***Keywords*:** Hyperbolic meta-material, Microwave, Transfer matrix method (TMM), Filling fraction, Broadband tunneling, Normalized frequency

Introduction

As we know that photonic crystals (PCs) are artificial dielectric, metallic or plasma nanostructures composed of two or more media in which the dielectric constant varies periodically in space. The novel idea of the periodic nano-structure of photonic band gap material was theoretically proposed by Yablonovitch, and was experimentally observed by John in the same year. The photonic band gaps (PBGs) are the unique features of the PCs, where electromagnetic wave doesn't propagate in the periodic structure [1-7]. Hyperbolic meta-materials (HMM), an anisotropic medium, exhibit a hyperbolic shape of the dispersion relation, which has been investigated in terahertz (THz), visible and near infrared frequency regions. Hyperbolic meta-materials have a variety of potential applications including negative refractive index, optical waveguide, and imaging hyper lens. The absorption of hyperbolic meta-materials has been studied in the last several years.

A novel implementation of hyperbolic meta-materials at the far infrared frequency is composed of stacked grapheme sheets separated by thin dielectric layers, which shows that the graphene based hyperbolic meta-material can be worked as a super absorber for near fields. Hyperbolic meta-materials have clear potentials of enhancing the decay rate of emitters near its surface and also for designing efficient and innovative absorbers. The wideband transmission feature of the hyperbolic meta-material structure can be employed in designing various optical devices [8-12].

Theoretical Model and Methodology

We analyze the optical wave propagation in a stacked structure of hyperbolic meta-material photonic crystal (HMMPC) as shown in Fig.1 by well known transfer matrix method (TMM) [13]. The incident angle of electromagnetic wave is Θ_o; A and B are the normal dielectric materials, and C is hyperbolic meta-material consisting of plasma and dielectric. For our multilayer design, we use effective medium theory to study the electromagnetic wave propagation in hyperbolic meta-material, which is an anisotropic medium with uniaxial dielectric tensor components and all other characteristics are as given in ref. [14].

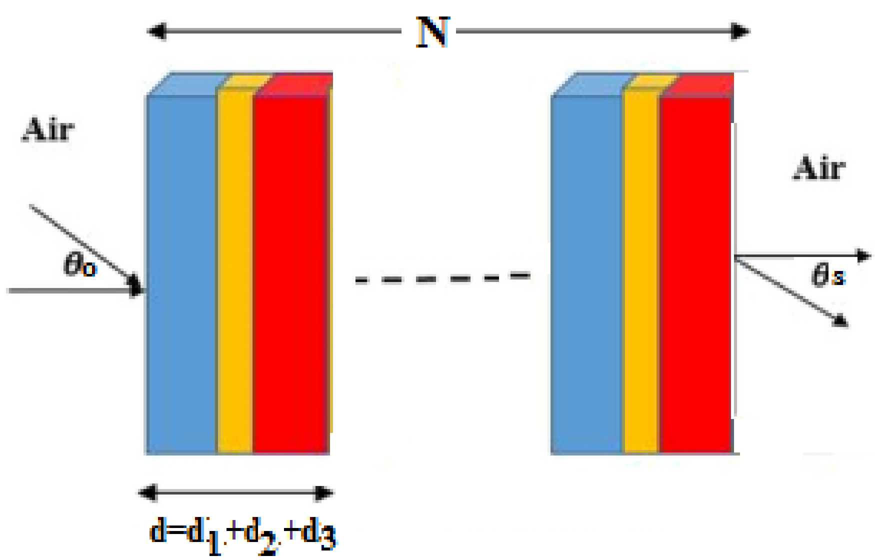

Fig.1: A one-dimensional ternary periodic structure.

The characteristic matrix for a layer is

$$M_i = \begin{bmatrix} \cos\gamma_i & -\frac{i}{p_i}\sin\gamma_i \\ -ip_i\sin\gamma_i & \cos\gamma_i \end{bmatrix} \quad (1)$$

where $\gamma_i = (\omega/c)n_i d_i \cos\Theta_i$, c is the speed of light in vacuum, Θ_i is the ray angle inside ith layer with a refractive index as $n_i = (\varepsilon_i \mu_i)^{\frac{1}{2}}$; $p_i = \sqrt{\frac{\mu_i}{\varepsilon_i}}\cos\theta_i$ *for TM waves*; $\cos\theta_i = \left(1 - \frac{n_o^2 \sin^2\theta_o}{n_i^2}\right)$ in which n_0 is the refractive index of air where the incident wave tends to enter the layered media. The reflection, transmission and absorption properties of the one-dimensional hyperbolic meta-material photonic crystal are investigated with the help of total matrix given as

$$M(Nd) = \left(\prod_{i=1}^{3} M_i\right)^N = \begin{pmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2} \end{pmatrix} \tag{2}$$

Hence, the reflection and transmission coefficients of the 1D HMM PC is calculated by

$$t = \frac{2p_0}{(M_{11} + M_{12}/p_0 + M_{21}p_0 + M_{22})} \tag{3a}$$

$$r = \frac{(M_{11} + M_{12}/p_0 - M_{21}p_0 - M_{22})}{(M_{11} + M_{12}/p_0 + M_{21}p_0 + M_{22})} \tag{3b}$$

The reflectance R, transmittance T and absorbance spectra of the one-dimensional meta-photonic PC is given by [13]

$$T = \left(\frac{p_s}{p_0}\right)|t|^2 ; \tag{4a}$$

$$R = |r|^2 ; \tag{4b}$$

and $A = 1 - R - T$ (4c)

Results and Discussion

First, we study the reflection, transmission and absorption of the conventional plasma photonic crystal. We consider the composition parameters for these: $\varepsilon_A=40$, $d_A=1.3$ *mm*, $\varepsilon_B=2.2$, $d_B=2.9mm$, $\mu_A=\mu_B=1$, $\Theta o=0^0$, $N=10$, respectively. We introduce the hyperbolic meta-material as the third layer with $\varepsilon_D=1, \mu_D=1, d_D=1.8$, $d_{HM}=2mm$, $f=0.9$, $d_C=0.2mm$, , $\omega_p= 28.4$ GHz, $\mu_C=1$, respectively; and ε_C, is given in [14], using the relation: $\varepsilon_\perp = \frac{d_m\varepsilon_m + d_p\varepsilon_p}{d_m + d_p}$; $\varepsilon_\parallel = \frac{\varepsilon_m\varepsilon_p(d_m + d_p)}{\varepsilon_m d_p + \varepsilon_p d_m}$, where d_m, d_p are the thicknesses of meta-material and plasma. We have theoretically studied the reflection, transmission and absorption spectra of the ternary periodic structure of dielectric material and plasma photonic crystal at a normal incident angle for transverse magnetic (TM) polarization.

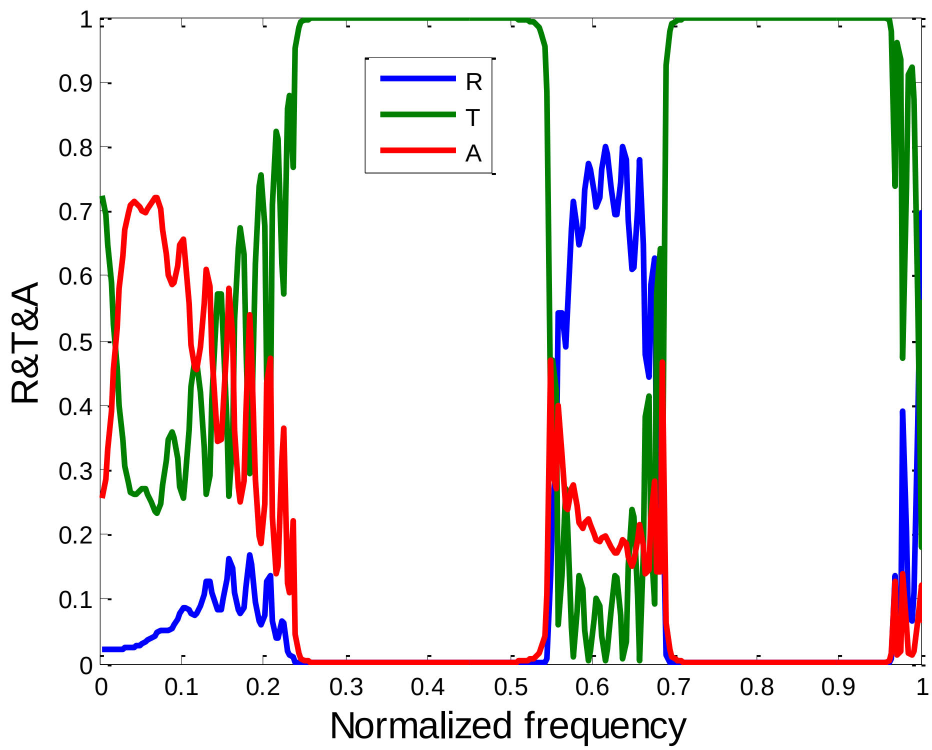

Fig. 2: *The reflection, transmission and absorption spectra of the one-dimensional ternary periodic structure.*

We investigate the reflection, transmission and absorption against normalized frequency in the frequency range 0 to 1.0 with variable parameters of dielectric and plasma materials. The reflection, transmission and absorption spectra analyzed and obtained structure shows multiband formation of complete transmittance for the electromagnetic wave propagation through the considered periodic structure.

Comparing our result with those obtained by others [15, 16], the ternary structure is found with similar behavior of good absorptive nature up to normalized frequency 2.25. Above this normalized frequency, we obtain two broadbands with high transmission with negligible reflectance and absorbance in the normalized frequency ranges 2.25 to 5.15 and 6.9 to 9.65, respectively. Such kind of broadband electromagnetic wave tunneling are the new insights of this particular structure. These calculated results propose an innovative idea to design the tunable filter, optical window, optical logic gate, and high transmission-based devices.

References:

E. Yablonovitch, “Inhibited spontaneous emission in solid-state physics and electronics,” Phys. Rev. Lett. 58, 2059 (1987).

S.John, “Strong localization of photons in certain disordered dielectric super lattices”, Phys. Rev. Lett. 58, 2486 (1987).

J. D. Joannopolos, Johnson, R. D. Meade and J. N. Winn, Photonic crystals: Molding the flow of light, Princeton, NJ, USA: Princeton Univ. Press (2007).

A. Kumar and K. B. Thapa, Study of optical property of defect mode in one dimensional double negative photonic crystal with plasma, Adv. Sci. Eng. Med. 10, 1-5 (2018).

A. Kumar, P. P. Singh and K. B. Thapa, A new idea for broadband reflector and tunable multi-channel filter of one dimensional symmetric photonic crystal with magnetized cold plasma defects, AIP Conference Proceedings 1953, 060043 (2018).

A. Kumar, N. Kumar and K. B. Thapa, Tunable broadband reflector and tunable narrowband filter of a dielectric and magnetized cold plasma photonic crystal, Eur. Phys. J. Plus, 133, 250 (2018).

A. Kumar, K. B. Thapa and S. P. Ojha, A tunable broadband filter of ternary photonic crystal containing plasma and superconducting material, Indian J. Phys., 1-8 2018.

D. R. Smith and D. Schuring,” Electromagnetic wave propagation in media with indefinite permittivity and permeability tensors,” Phy. Rev. Lett. 90, 077405, (2003).

I. V. Iorsh, I. SMukhin, I.V. Shadrivov, P.A. Belov, and Y.S. Kivshar,”Hyperbolic metamaterial based on multilayer graphene structures,” Phys. Rev. B 87, 075416 (2013)

M. A. K. Othman, C. Guclu, and F. Capolino,”Graphene based tunable hyperbolic metamaterials and enhanced near-field absorption,” Opt. Express 21,7614 (2014).

Asish Kumar, Khem B. Thapa and Anil K. Yadav, Enhancement of absorption property of one-dimensional ternary periodic structure containing plasma based hyperbolic material for the application of microwave devices, J. MagnMagn. Mater, 93, 165371, 2019.

Asish Kumar, N. Kumar, GN Pandey, D Singh and K. B. Thapa, Metamaterial-plasma based hyperbolic material for sensor, detector and switching application at microwave region, Journal of Physics: Condensed Matter, 32, 1-12, 2020.

P. Yeh,“Optical Waves in Layered Media”, John Wiley and Amp; Sons, New York, (1988).

Z. Jiao, R. Ning, Y. Xu, and J. Bao,” Tunable angle absorption of hyperbolic meta-material based plasma photonic crystals,” Phys. Plasma 23, 063301 (2016).

F Wu, K Lyu, S Hu, M Yao, S Xiao, Ultra-large omnidirectional photonic band gaps in one-dimensional ternary photonic crystals composed of plasma, dielectric and hyperbolic metamaterial, Optical Materials 111, 110680 (2021).

F Wu, G Lu, Z Guo, H Jiang, C Xue, M Zheng, Ultra-large omnidirectional photonic band gaps one-dimensional photonic crystals containing hyperbolic metamaterials, Physical Review Applied 10, 064022 (2018).