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Design of Cold Plasma Based Ternary Photonic Crystal for Microwave Applications

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Abstract: In this paper, we propose a Silicon/Plasma/Air ternary 1D photonic crystal, whose transmission and reflection properties have been studied. We draw the transmittance and reflectance versus frequency spectra in microwave region (GHz) for RHP Plasma based ternary PC by changing the angle of incidence for a fixed value of unit cells, magnetic field, layer thickness, collision frequency, and electron density. It is observed that with increase in angle of incidence, there is increase in photonic bandgap obtained in low and high frequency regions. With increase in angle, the photonic bandgaps shift towards higher frequencies. At angle 89° there are multiple sharp peaks of transmission are obtained. By comparing this ternary PC with a binary silicon/plasma PC, it is observed that this proposed PC has higher number of bands for smaller angles which makes them a good candidate for making multi-channel tunable filters, and for higher angle it behaves like broadband reflector. The proposed structure may also be a good candidate for many applications in making other microwave devices.

Keywords: ternary, silicon, cold plasma, transmittance, oblique

1. Introduction

In recent decades, photonic crystal (PC) has been a field of investigation to control the optical properties of materials viz. to unprecedented control of light in certain regions, to prohibit its propagation or to allow it to propagate only in certain directions and at certain frequencies [1-2]. A lot of studies have been made for binary PC with and without defects and also the investigation is shifted toward ternary PC which have many applications in the field of optical communication and optical Engineering [2]. The researchers have been using the dispersive media to get the

tunable PCs, such as semiconductor, plasma, superconductor, etc. based PCs emerged as recent interest globally due to offering reduction of damping in the electromagnetic waves [3-8].

The plasma photonic crystals (PPCs) are artificially periodic array composed of alternating thin unmagnetized or magnetized plasmas and dielectric materials or vacuum [2, 9]. It has a photonic band gap that is controllable by means of plasma parameters. In 1DPPC, the magnetized cold plasma has an additional parameter such as gyro-effective frequency in presence of external magnetic field that depends on external magnetic field of magnetized cold plasma. There are two types of polarization configurations namely right-hand and left-hand polarizations, there have positive and negative values of the gyro-effective frequency, respectively [10-13]. Plasma has various future applications in the field of power production and cold plasma is cool enough to support a multitude of chemical reactions [2, 12]. Kumar *et al.* reported the variation in photonic band structures (PBSs) as a function of angle of incidence, magnetic field strength, electron density, and thickness variations [14]. Abadla *et al.* [15] proposed ternary PCs that can offer better performance over the binary ones. In more recent, ternary structures with new chosen materials are under investigation for novel and efficient kind of tuning of the PBGs [16-17].

Motivated by their numerous advantages of ternary PC, we decided to work on plasma based Ternary PC. Here, we proposed a Silicon/Plasma/Air ternary 1D photonic crystal, whose transmission and reflection properties have been studied. We compare this ternary PC characteristics with a binary silicon/plasma PC, it is shown that such a ternary PC has higher number of bands for smaller angles which makes them a good candidate for making multi channel tunable filters [18] and for higher angle it behaves like broadband reflector.

2. Theoretical modeling:

The transmittance and reflectance are theoretically calculated by well-known transfer matrix method (TMM) [19-20]. The semiconductor, plasma and air layers are periodically arranged along the z-direction as shown in Figure 1. The ternary periodic structure unit cell is made with three layers of silicon, RHP of cold plasma and air, in which layer thickness are taken as d_1 , d_2 and d_3 respectively. The thickness of unit cell

is $d_1+d_2+d_3=d$, which is known as lattice constant. The refractive indices of Silicon, RHP of cold plasma and air is n_1 , n_2 and n_3 respectively; and the number of unit cells is N .

Fig.1: Schematic representation of the 1D Ternary PPC in the presence of externally applied static magnetic field B along the direction of $+z$ axis under RHP configuration.

The transmittance spectra are determined on the characteristic matrix method, which is easy and most effective to analyze the transmission properties of PCs. The total characteristic matrix for N -period for the structure $(ABC)^N$ is expressed as

$$M(Nd) = \begin{pmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2} \end{pmatrix} \quad (1)$$

The characteristic matrix for k^{th} layer at incident angle θ_i is given as

$$M_k = \begin{bmatrix} \cos \beta_k & -\frac{i}{p_i} \sin \beta_k \\ -i p_k \sin \alpha_k & \cos \beta_k \end{bmatrix} \quad (2)$$

where $\beta_k = \frac{\omega}{c} n_k d_k \cos \theta_k$, c is the speed of light in vacuum, θ_k is the ray angle inside the k^{th} layer ($k = 1, 2$ and 3 ; viz. A, B and C materials), the refractive index of the material $n_k = \sqrt{\mu_k \epsilon_k}$, $p_k = \sqrt{\frac{\epsilon_k}{\mu_k}} \cos \theta_k$ and $\cos(\theta_k) = \sqrt{1 - \frac{n_0^2 \sin^2 \theta_i}{n_k^2}}$, in which the refractive index of air is $n_0 = n_1 = n_3$ and the wave is incident angle at the surface is θ_i from air. Here, M_A, M_B and M_C are the characteristic matrices for the three layers A, B and C, viz. Si, RHP plasma and air, respectively given by equation (2).

The transmission coefficient of the ternary 1DPPC of the form (ABC)^N is expressed as,

$$t = \frac{2\alpha_0}{(M_{1,1}+M_{1,2}\alpha_s)\alpha_0 + (M_{2,1}+M_{2,2}\alpha_s)} \quad (3)$$

where $\alpha_0 = n_0 \cos \theta_0$ and $\alpha_s = n_s \cos \theta_s$; n_s is the refractive index of the substrate. Here, we have taken $n_0 = n_s = 1.0$ for the free space or air. Hence, the transmittance (T) for 1D periodic structure is given by

$$T = \frac{\alpha_s}{\alpha_0} |t|^2 \quad (4)$$

The cold plasma complex permittivity is a function frequency (ω) and in static magnetic field (B) can be expressed as

$$\varepsilon = 1 - \frac{\omega_{pe}^2}{\omega^2 (1 - i \frac{\zeta}{\omega} \mu \frac{\omega_{le}}{\omega})} \quad (5)$$

where gyro-frequency is $\omega_{le} = \frac{eB}{m}$, the -ve sign of ω_{le} indicates the positive magnetic field and is called the right-hand polarization (RHP). Here, ζ is the effective collision frequency, and plasma frequency is $\omega_{pe} = \sqrt{\frac{n_e e^2}{m \varepsilon_0}}$ with m , n_e , ε_0 , B and e are the electronic mass, electron density, permittivity in free-space, external magnetic field and the electronic charge, respectively.

3. Results and Discussion

In this work, we have calculated transmittance and reflectance for ternary plasma based photonic crystal. The parameters such as magnetic field (B), electron density (n_e), effective collision frequency (γ) and lattice period (N) are kept constant. In this analysis we have chosen, refractive index of silicon and air as $n_1=3.46$ and $n_3=1$ respectively; magnetic field $B=1.5$ T, electron density $n_e=8 \times 10^{17} \text{ m}^{-3}$, collision frequency $\zeta=2\pi \times 10^7 \text{ Hz}$, $d_1=d_2=d_3=10$ mm, lattice period $N=10$.

The transmittance as well as reflectance spectra versus frequency are plotted using TMM by considering it as absorption less media. In this only angle of incidence

at the interface is changed and all other parameters like collision frequency, electron density and thickness of layers are kept constant. The transmittance/reflectance spectra in various cases of incident angles are depicted in Figures 2-5.

Fig 2: Transmittance and Reflectance versus frequency spectra with (i) $\theta=0^\circ$ and (ii) $\theta=15^\circ$.

In these graphs, it is observed that, for $d_1+d_2+d_3=30\text{mm}$ and $B=1.5\text{ T}$ and changing the angle of incidence from 0° to 15° ; the number of photonic band gaps decreases and the bands shifts towards right and thickness of bandgaps increases.

Fig 3: Transmittance and Reflectance versus frequency spectra with (i) $\theta=30^\circ$ and (ii) $\theta=45^\circ$.

Changing angle of incidence from 30° to 45° , the and keeping other parameters constant, the number of photonic bandgaps obtained are two. Their thickness increases as the angle of incidence is increased and the bandgaps shifts towards right.

Fig 4: Transmittance and Reflectance versus frequency spectra with (i) $\theta = 60^\circ$ and (ii) $\theta = 75^\circ$.

Fig 5: Transmittance and Reflectance versus frequency spectra with $\theta = 89^\circ$.

Varying the angle of incidence to 60° and 75° it is again observed that there is

a shifting in photonic bandgaps towards right and there is increase in their thickness. At angle 89° photonic bandgaps completely disappear and only sharp transmission peaks are obtained. This property of this proposed PC makes it have good capabilities to be a good multichannel filter for smaller angles and for higher angles it can offer novel idea in designing broadband reflectors and optical mirrors in the microwave region.

For the comparison between the proposed ternary PPC and a binary PC, Silicon/Plasma Binary PC is considered under a constant magnetic field. For this binary PC the transmittance and reflectance are calculated. Fig 6-7 shows the transmittance and reflectance versus frequency graphs for different angle of incidences. Here, magnetic field $B=1.5$ T, electron density $n_e=8 \times 10^{17} \text{ m}^{-3}$, collision frequency $\gamma=2\pi \times 10^7 \text{ Hz}$, $d_1=d_2=10$ mm, lattice period $N=10$ is kept constant and changing the angle of incidence on surface. The refractive index of silicon is taken as $n_1=3.46$.

Fig 6: Transmittance and Reflectance versus frequency spectra with (i) $\theta=0^\circ$ and (ii) $\theta=30^\circ$.

In these graphs, it is observed that for changing angle of incidence from $0^\circ, 30^\circ$ and

60° and keeping other parameters such as refractive index, electron density, collision frequency as constant. The number of photonic bandgaps are two and they shift towards right as angle increases and their thickness also increases.

Fig 7: Transmittance and Reflectance versus frequency spectra for (i) $\theta=60^\circ$ and (ii) $\theta=89^\circ$.

For angle of incidence 89°, there are no photonic bandgaps obtained but there are multiple transmission bands present.

By comparing both ternary and binary PPC, it concluded that for lower angle of incidence, ternary PPC has higher number of photonic bandgaps than binary plasma PPC which gives ternary PPC more applications in making multichannel filters. For higher angles the changes in transmission and reflection spectrum of TE wave in 1D ternary and binary PPC behave in similar manner for different angles.

4. Conclusion

In this work, a ternary plasma based photonic crystal is presented on Silicon/Plasma/Air layers. We made the study of transmittance property of the Plasma based ternary photonic crystal by using transfer matrix method (TMM) by keeping the parameters such as magnetic field (B), electron density (n_e), effective collision frequency (γ) and lattice period (N) constant and only changing the angle of incidence on the surface.

By plotting the graph between transmittance and reflectance versus frequency in the microwave region (GHz), it has been observed that with the increase in angle of incidence, there is increase in photonic bandgap width obtained in low and high frequency regions. With increase in angle, the photonic bandgaps shift towards higher frequencies. At angle 89° multiple sharp peaks of transmissions are obtained and the bandwidth of bandgaps is increasing. It is proposed that such ternary PC can be utilized in making multichannel tunable filter and for higher angle it behaves like broadband reflector.

Comparing this ternary PC with a binary Si/Plasma PC it can be clearly observed that the number of photonic bandgaps obtained in ternary PC are higher for smaller angles and have lesser number of transmission peaks associated with photonic bandgaps which makes them better candidate for making multichannel filters. The proposed structure is a good candidate for many applications including multichannel tunable filters and other devices in different frequency regions as compared with binary PC or PC with defect. Thus, this analysis of ternary PPC can be further employed for making modeling of ternary PC by introducing defects. This study can also be useful for designing similar microwave devices.

Author Declarations

*Ethics approval and consent to participate:	Yes
*Consent for publication:	Yes
* Availability of data and materials:	Not Applicable
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* Authors' contributions	first 60%, rest equally from second and third
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* Authors' information (optional).	
* Disclosure of potential conflicts of interest	Not Applicable
* Research involving Human Participants and/or Animals	Not Applicable
* Informed consent	Not Applicable

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