Analysis of multichannel reflectors using one-dimensional photonic crystal with symmetric and asymmetric micro-plasma defects

ALOK KUMAR PANDEY[1], GIRIJESH NARAYAN PANDEY[2,*], NARENDRA KUMAR[3], KHEM BAHADUR THAPA[4], J. P. PANDEY[1]
[1]*Department of Physics, M.L.K. P.G. College, Balrampur 271201, Uttar Pradesh, India*
[2]*Department of Applied Physics, Amity Institute of Applied Sciences, Amity University, Noida 201301, Uttar Pradesh, India*
[3]*Department of Physics, SLAS, Mody University of Science and Technology, Lakshmangarh 332311, Sikar, Rajasthan, India*
[4]*Department of Physics, School of Physical and Decision Sciences, Babasaheb Bhimrao Ambedkar University, Vidya Vihar, Raibarely Road, Lucknow 226025, Uttar Pradesh, India*

In the present communication, the transmittance of electromagnetic waves in a 1D photonic crystal, with introduction of a defect layer of micro-plasma inside the regular structure of photonic crystal, has been theoretically studied. A periodic media with alternate thin layers of air and SiO_2 dielectric materials are considered in the two forms of PC as $(AB)^N$ and $(BA)^N$. The transmittances and the photonic band structures are calculated using transfer matrix method and Bloch's function. The transmittance spectra of these PCs along with asymmetrically and symmetrically introduced micro-plasma defects are studied for varying thickness of micro-plasma. In this analysis, we focus our attention to the zero-transmittance or bandgap regions. The zero-transmittances of the defected PC structures of the air and SiO_2 composites are found with the multichannel reflector behavior by introducing a micro-plasma defect layer with its assigned thickness in several considered cases. It is demonstrated that such idea for a defected PC can be employed in design of the multichannel filters and other PC-based devices.

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1. Introduction

Photonic crystals (PCs) offer some special and interesting characteristics and hence are emerged as a thrust area in optical engineering and solid state physics [1, 2] and have achieved a phenomenal growth in recent decades. PCs are periodically structured electromagnetic media, with a periodic variation of dielectric constant and can stop propagation of certain frequency ranges, known as photonic bandgaps (PBGs). The nomenclature of PC having dusty plasma and discharged micro-plasma is plasma photonic crystal [3, 4]. These classes of materials have wide applications, such as, in the inhibition of spontaneous emission, low-loss wave guide, narrow-band filters, frequency converters, strong field enhancement related to the group velocity, and propagation mode near the band edge [5-7]. The plasma photonic crystals in one-, two- and three- dimensional periodic arrangements of dynamically controlled micro-plasma posse an important role in changing the refraction characteristics of electromagnetic (EM) waves. Kiskinen *et al.* [8] have theoretically studied dusty plasma crystals and reported PBGs for the first time. The dusty plasma characteristics are owing to its dynamic structure and general phenomenology. Hojo *et al.* [9-11] have theoretically studied the dispersion relation and reflection-less transmission of electromagnetic wave in one-dimensional photonic crystal (1DPC), where the dispersion relation is obtained by solving a Maxwell's equations using a method analogous to Kronig-Penney's model. Marklund *et al.* [12, 13] studied the quantum electrodynamical effect in dusty plasma. They have predicted a new non-linear electromagnetic wave mode in magnetized dusty plasma, which is due to the interaction of an intense circularly polarized EM wave with dusty plasma, in which quantum electrodynamical photon-photon scattering is taken into account. Shiveshwari [14, 15] studied the propagation of electromagnetic waves in 1D plasma-air photonic crystal with finite and infinite periodic structure. Ojha *et al.* [16-19] have already studied the reflection properties of plasma dielectric photonic crystal for making omnidirectional reflector with effect of variation of plasma width and plasma density. Omni-directional reflector can be obtained by increasing the plasma density for given thickness of the plasma layers

In this paper, we analyze the optical properties of a one-dimensional photonic crystal (1DPC) containing air and SiO_2 with introduced plasma defect for asymmetric and symmetric arrangements using transfer matrix method (TMM). We introduce plasma defect in $(BA)^5D(BA)^5$ and $(AB)^5D(AB)^5$ structures. We focus our attention to the zero-transmittance regions. Here, we obtain multichannel reflection modes, for a particular thickness of plasma defect due to the presence of defect plasma inside the periodic structure of the air and SiO_2 materials in the asymmetric and symmetric arrangements which may be used in designing the multichannel filter [20-21].

2. Mathematical modeling

A very conventional simple method of mathematical modeling is the transfer matrix method (TMM). We consider a periodic arrangement of multilayer structure with refractive indices n_1 and n_2, each with thicknesses d_1 and d_2 respectively. Here, we choose the refractive indices of the periodic materials 1.0 (A-material) for air and 1.46 for SiO_2 (B-material) as shown in Fig. 1. We determine the transmittances of the considered structure for asymmetric and symmetric arrangements with defect plasma as shown in Fig. 2. We have also compared these results with pure periodic structure $(AB)^5(AB)^5$ (i.e. $(AB)^{10}$) of the air and SiO_2 materials using the transfer matrix technique.

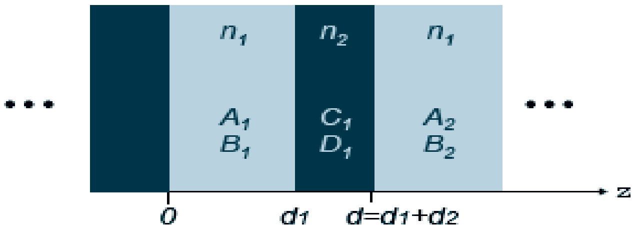

Fig. 1. A 1DPC with a periodic arrangement of multilayer structure with refractive indices n_1 and n_2

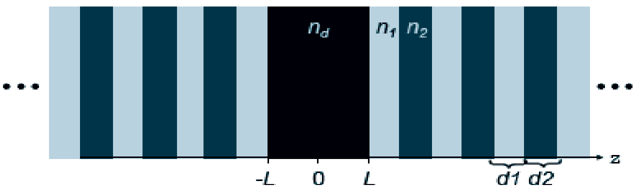

Fig. 2. A defect layer with index n_d surrounded with infinite layers in the left and right directions as defected PC

Here, a periodic multilayer structure is considered with refractive indices n_1 and n_2, each with thicknesses d_1 and d_2 respectively. Here, we choose the refractive indices of the periodic materials 1.0 (A-material) for air and 1.46 for SiO_2 (B-material) as shown in Fig. 1. We determine the transmittances of the considered structure for asymmetric and symmetric arrangements with defect plasma as shown in Fig. 2. We have also compared these results with pure periodic structure $(AB)^5(AB)^5$ (i.e. $(AB)^{10}$) of the air and SiO_2 materials using the transfer matrix technique.

Let the plane EM waves are propagating to the right and the left through different layers, where for index n_1, the amplitudes are A_1 and B_1 respectively, and for layer with index n_2 the amplitudes are $C_1$and D_1, respectively. Hence electric field in term of wave vector along z-axis for layer with index $n_{1,}$ can be expressed as

$$E(z) = A_1 e^{ik_1 z} + B_1 e^{-ik_1 z} \qquad (1)$$

Similarly the electric field in term of wave vector along z-axis for layer with index n_2 can be represented as

$$E(z) = C_1 e^{ik_2(z-d_1)z} + D_1 e^{-ik_1(z-d_1)} \qquad (2)$$

The parameter k_1 and k_2 are called the wave vectors, and can be expressed as $k_1 = \omega n_1$ and $k_2 = \omega n_2$. At the interface between layers ($z = d_1$), the solution and its derivative should be continuous. This gives a relation between plane waves amplitudes as

$$\begin{bmatrix} C_1 \\ D1 \end{bmatrix} = M_{12} \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} \qquad (3)$$

and also at z = d, using the continuity of the plane waves and their derivatives at interface between the layers with index n_2 and n_1, we get

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = M_{21} \begin{bmatrix} C_1 \\ D_1 \end{bmatrix} \qquad (4)$$

where the matrix M_{21} is the same as M_{12} where the indices are exchanged. Using the above two matrix equations, we have

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = M \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} \qquad (5a)$$

where $M = M_{21}M_{12}$, where matrix elements are given by

$$M_{11} = e^{ik_1 d_1}\left[\cos k_2 d_2 + \frac{1}{2} i\left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right)\sin k_2 d_2\right],$$

$$M_{12} = e^{-ik_1 d_1}\left[\frac{1}{2} i\left(\frac{k_2}{k_1} - \frac{k_1}{k_2}\right)\sin k_2 d_2\right],$$

$$M_{21} = e^{ik_1 d_1}\left[\frac{1}{2} i\left(\frac{k_2}{k_1} - \frac{k_1}{k_2}\right)\sin k_2 d_2\right] = \overline{M_{12}}$$

$$M_{22} = e^{-ik_1 d_1}\left[\cos k_2 d_2 - \frac{1}{2} i\left(\frac{k_2}{k_1} + \frac{k_1}{k_2}\right)\sin k_2 d_2\right] = \overline{M_{11}} \qquad (5b)$$

The matrix M shall be called as the transfer matrix of one unit cell of the structure. Using the TMM, we can show the relation between the wave amplitudes existing in the left and right exteriors as follows:

$$\begin{bmatrix} t \\ 0 \end{bmatrix} = M \begin{bmatrix} 1 \\ r \end{bmatrix} \qquad (6)$$

where t represent the transmission and r represents the reflection coefficients, for the EM wave through the periodic layered homogenous media with N unit cells, can be expressed as

$$r = \left(\frac{b_0}{a_0} \right)_{b_N = 0} = \frac{M_{21}}{M_{11}} \qquad (7)$$

$$t = \left(\frac{a_N}{a_0} \right)_{b_N = 0} = \frac{1}{M_{11}} \qquad (8)$$

where transmittance is defined as

$$T = |t|^2 \qquad (9)$$

Thus, we can plot transmittance versus normalized frequency curves using equation (9) to obtain the complete photonic bandgap regions or zero-transmittance regions.

3. Results and discussion

In the present study, we analyze the optical features exhibited by a 1DPC containing air and SiO_2 with plasma layer defect by using transfer matrix method. The refractive indices of the periodic materials are 1.0 (A-material) for air and 1.46 for SiO_2 (B-material), with thicknesses 0.125 mm and 0.086 mm, respectively. We determine the transmittance from the chosen periodic structure for asymmetrically and symmetrically introduced plasma layer defects. Thereafter, we compare these results with pure periodic structure $(AB)^5(AB)^5$, i.e., $(AB)^{10}$) as well as $(BA)^5(BA)^5$, i.e. $(BA)^{10}$). Fig. 3 to 5 show the transmittance versus normalized frequency curves for pure periodic structure i.e. $(air/SiO_2)^N$ along with asymmetry defect periodic structure, i.e., $(air/SiO_2)^{N/2}$/ plasma/ $(air/SiO_2)^{N/2}$ and symmetry defect periodic structure, i.e., $(air/SiO_2)^{N/2}$/plasma/$(SiO_2/air)^{N/2}$ for different thicknesses of plasma. Next Fig. 6 to 9 show the transmittance versus normalized frequency curves for pure periodic structure $(SiO_2/air)^N$ along with asymmetry defect periodic structure, i.e., $(SiO_2/air)^{N/2}$/plasma/$(SiO_2/air)^{N/2}$ and symmetry defect periodic structure, i.e,. $(SiO_2/air)^{N/2}$/ plasma/$(air/SiO_2)^{N/2}$ for different thicknesses of plasma. In these figures, the transmittance versus normalized frequency plots for without defect are mentioned as in part (a), with defect for asymmetric as in part (b), and symmetric as in part (c) arrangements as shown in Figs. 3 to 5 for $(AB)^{10}$, and 6 to 9 for $(BA)^{10}$ respectively.

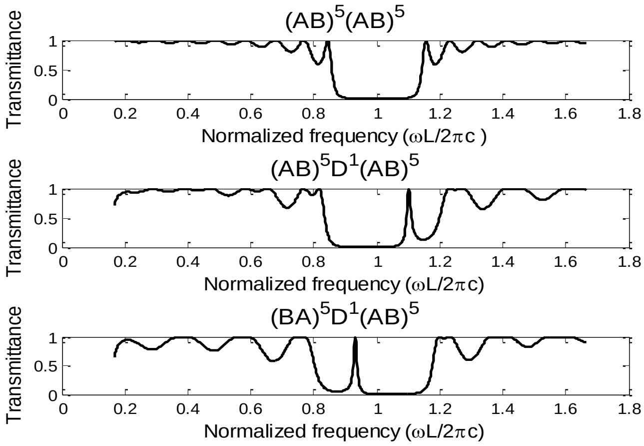

Fig. 3. Transmittance versus normalized frequency plots for: d_d=0.05 mm (plasma), d_a=0.125 mm (n=1 for air) and d_b=0.086 mm (n=1.46 for SiO_2)

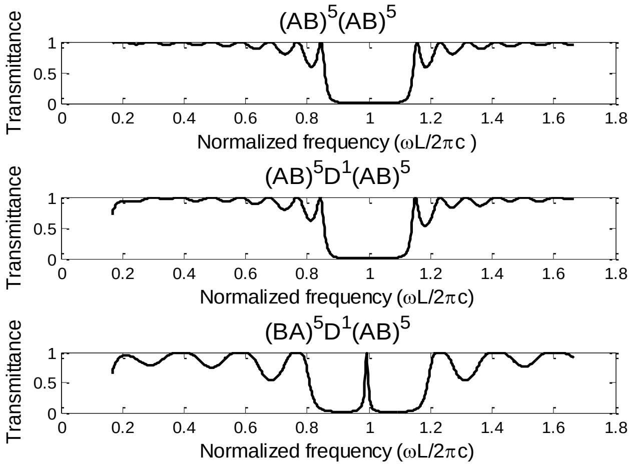

Fig. 4. Transmittance versus normalized frequency plots for: d_d=0.005mm (plasma), da=0.125mm (n=1 for air) and db=0.086mm (n=1.46 for SiO_2)

We concentrate on photonic bandgaps or zero-transmittance regions, where the zero transmittance regions are the bandgaps. Referring Fig. 3 (a), the transmittance of one-dimensional photonic crystal without defect gives a large bandgap form for normalized frequency range 0.87 to 1.12. Here, the transmittance of 1DPC shows the asymmetric and symmetric defect modes inside the bandgap due to plasma as the defect material. The asymmetric defect plasma PC exhibits larger bandgap in comparison to without or normal photonic crystal of the air/SiO_2 materials. The central band splits in two components for symmetric structure. If we decrease the plasma thickness, the bandgaps where the bands with transmittance zero, for $(AB)^5(AB)^5$, are shifted toward left for asymmetric case and splits completely in two parts for the symmetric structure as depicted in Fig. 4. Thus, on decreasing the plasma thickness from 0.5 mm to 0.005

mm, the transmittance versus normalized frequency plots gives an enhanced bandgap with splitting in symmetric case. On the other hand, if we increase the plasma thickness up to the value of 2.5 mm, the PBGs split into multichannel reflectors with five defect modes and hence can used as multichannel filters as shown in part b and c of Fig. 5. In this figure, the transmittance for defect plasma photonic crystal for symmetric arrangement offers five defect modes having enlarged bandgap range 0.80 to 1.18 and these are shifted towards to lower frequency range compared to asymmetric arrangement with plasma defect.

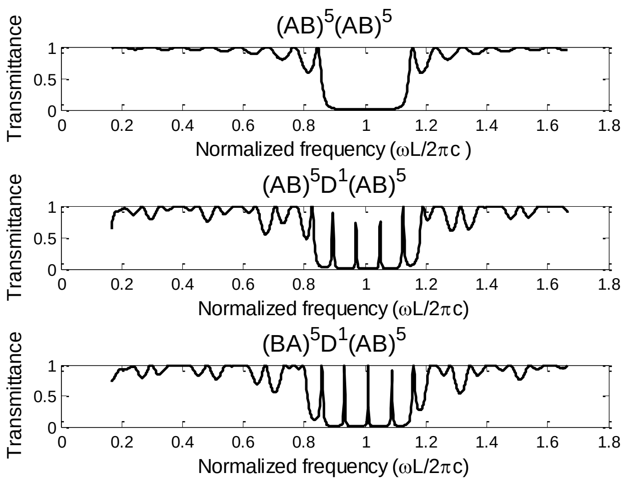

Fig. 5. Transmittance versus normalized frequency plots for: d_d=2.5mm (plasma), d_a=0.125mm (n=1 for air) and d_b=0.086mm (n=1.46 for SiO_2)

Moreover, for $(BA)^5(BA)^5$, Figs. 6-9 show that the bandgap range is obtained from 0.82 to 1.18 with two defect modes inside the bandgap. The zero-transmitted band is splitted in two components for asymmetric and symmetric defects and with decrease in the defect thickness; the bandgaps are shifted toward right for asymmetric case and splits completely in two parts for the symmetric structure. Thus, if we decrease the plasma thickness from 0.5 mm to 0.005 mm, the transmittance versus normalized frequency plots give a reduced bandgap with splitting in symmetric case as shown in Figs. 7 to 8. On the other hand, if we increase the plasma thickness up to 0.5 mm, the bandgap is splitted into multichannel reflector as shown in part b and c of Fig. 9. This type of the arrangement may use to multichannel filter having abroad bandgap.

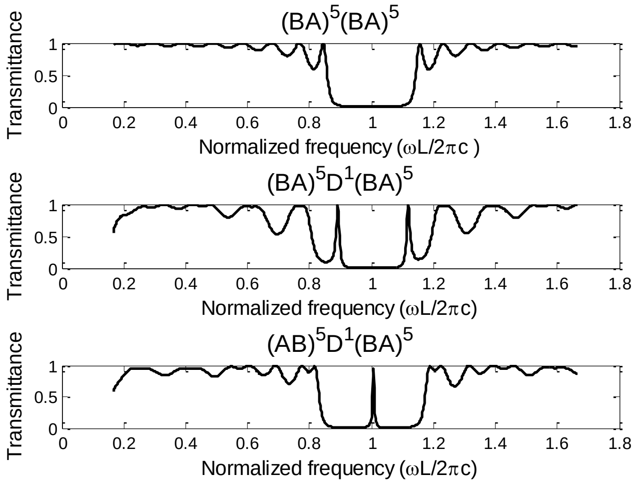

Fig. 6. Transmittance versus normalized frequency plots for: d_d=0.5mm (plasma), d_a= 0.086mm (n=1.46 for SiO_2) and d_b=0.125mm (n=1 for air)

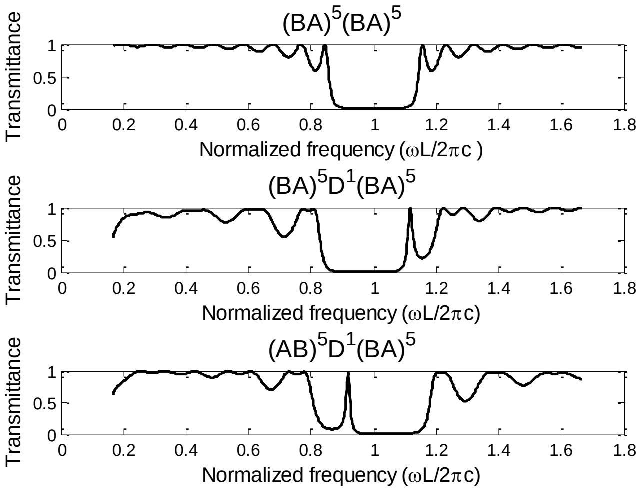

Fig. 7. Transmittance versus normalized frequency plots for: d_d=0.05mm (plasma), d_a= 0.086mm (n=1.46 for SiO_2) and d_b=0.125mm (n=1 for air)

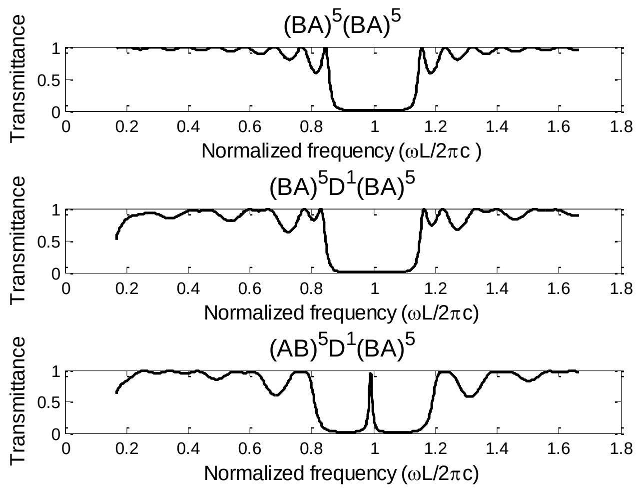

Fig. 8. Transmittance versus normalized frequency plots for: d_d=0.005mm (plasma), d_a= 0.086mm (n=1.46 for SiO_2) and d_b=0.125mm (n=1 for air)

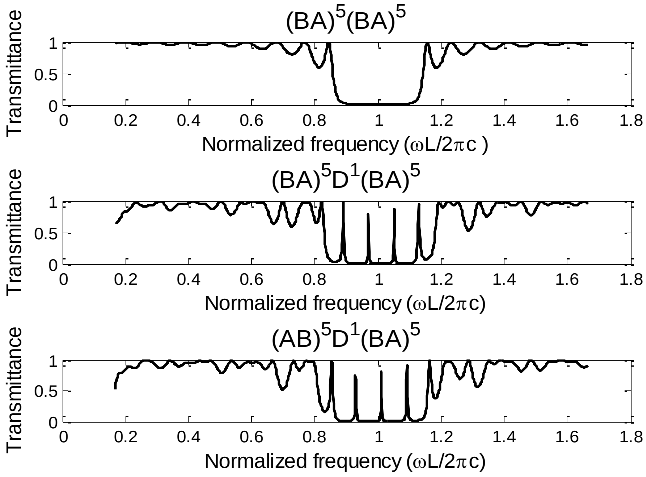

Fig. 9. Transmittance versus normalized frequency plots for: d_d=2.5 mm (plasma), d_a= 0.086 mm (n=1.46 for SiO_2) and d_b=0.125 mm (n=1 for air)

Thus, we can demonstrate the 1-D photonic crystal with plasma defect in asymmetric and symmetric modes can tune the photonic bandgap positions and widths along with the number of bands. If we decrease the plasma thickness, the bandgap behavior shows reverse effect in $(BA)^5D(BA)^5$ in comparison to $(AB)^5D(AB)^5$, where we see that in the symmetric mode the zero-transmittance has been spllited into two parts. If we increase the plasma thickness keeping all parameters same, we find multichannel reflecting behaviors in asymmetric and symmetric modes for these two structures. Thus, we infer that the transmittance of the defect plasma in asymmetric and symmetric arrangement photonic crystals may be used as a multichannel filter in telecommunication and designing PC-based optical devices.

4. Conclusion

We analyzed the transmittance characteristics of the normal and photonic crystal with plasma defect in asymmetric and symmetric arrangements, and we focused our attention to the zero-transmittance or bandgap region in different cases of the study. The defective plasma photonic crystal with asymmetric and symmetric arrangements have been found to offer a large bandgap with a defect mode of the transmittance as compared to the without defect. Besides this, the bandgap of the asymmetric arrangement gives slightly larger bandgap as compared to the bandgap of the symmetric arrangement, and asymmetric structure is splitted into two components. The central band frequency and bandwidth can be tuned by changing the plasma thickness. If we increase the plasma thickness up to 2.5 mm, a multiple high reflections are obtained that might have some technological applications in designing multichannel filters. The zero-transmittance of the asymmetric and symmetric arrangements is shifted towards the higher and lower frequency, respectively. Such a tunable PC can be highly useful in designing multichannel reflectors and gives an innovative idea for designing other PC-based optical components and devices.

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*Corresponding author: gnpandey@amity.edu, jppandeymlk@gmail.com