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# Omni-directional reflection bands in one-dimensional plasma dielectric photonic crystals

G.N. Pandey [a,*], Khem B. Thapa [b], S.P. Ojha [c]

[a] Department of Applied Physics, Amity Institute of Applied Sciences, Amity University, Noida, UP, India
[b] Department of Physics, U.I.E.T., C.S.J.M. University, Kanpur 208024, UP, India
[c] I.I.M.T., Greater Noida, UP, India

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ABSTRACT

In this paper the omni-directional reflection bands in one-dimensional plasma photonic crystal (PPC) have been studied theoretically. We present the study of plasma photonic crystal, having alternate regions of plasma–dielectric ($Al_2O_3$ or ZnS). Reflectances from this periodic multilayered structure in TE- and TM-modes are calculated for different angles of incidence in microwave region for omni-directional reflection bands. The reflectance is obtained by solving a Maxwell's equation using a translational matrix method. In addition to this, we have also studied the effect of variation of plasma width as well as plasma density on the reflection properties of plasma dielectric photonic crystal in TE- and TM-modes. The study of reflectance bands of such plasma photonic crystals shows that it can be used as omni-directional reflector.



## 1. Introduction

Photonic crystals (PCs) known to possess several unique and interesting features have been gaining attention very fast in the area of optical and solid state physics [1,2]. The photonic crystals having dusty plasma and discharged micro-plasma are known with the nomenclature as plasma photonic crystals [3,4]. These classes of materials have wide applications such as the inhibition of spontaneous emission [5], low loss wave guide with sharp bands [6], narrow-band filters, frequency converters and strong field enhancement related to the group velocity, mode propagating at frequencies near band edge [7,8]. The plasma photonic crystal in one-, two- and three-dimensional periodic arrangement of dynamically controlled micro plasma plays a very significant role in changing the refraction of electromagnetic waves. Kiskinen and Fernsler [3] have theoretically studied photonic band gaps in dusty plasma crystals for the first time. The importance of dusty plasma is attributed to the dynamic structure and general phenomenology. Several aspects of dusty plasma crystals e.g. wave and structure have been studied [9–12]. The band gap features are dependent on the plasma sheath characteristics of the dusty plasma crystal i.e. the relative size of the particle plus plasma sheath width with respect to the lattice constant of the dusty plasma crystal. The effects of the plasma sheath are to increase the band gap. In addition, the band gap is a function of the ratio of dielectric constant of dust and the background plasma. The application of such dusty particle is used to control the electromagnetic energy in plasma processing system and also to development of plasma mirror [13].

Marklund et al. [14,15] studied the quantum electrodynamical effect in dusty plasma. They have predicted a new non-linear electromagnetic wave mode in magnetized dusty plasma; its existence depends on the interaction of an intense circularly polarized electromagnetic wave with dusty plasma where quantum electrodynamical photon–photon scattering is taken into account. Hojo et al. have theoretically studied the dispersion relation and reflectionless transmission of electromagnetic wave in one-dimensional photonic crystal. The dispersion relation is obtained by solving a Maxwell's equation using a method analogous to Kroning–Penney's model [16,17]. Recently Shiveshwari and Mahto [18] studied the propagation of electromagnetic waves in one-dimensional plasma-air photonic crystal with finite and infinite periodic structure.

In this paper, we have studied the reflection properties of plasma dielectric photonic crystals. Further, we have also studied the effect of variation of plasma width as well as plasma density on the reflection properties of plasma dielectric photonic crystal in TE- and TM-modes.

* Corresponding author.
*E-mail address:* girijeshpandey_itbhu@rediffmail.com (G.N. Pandey).

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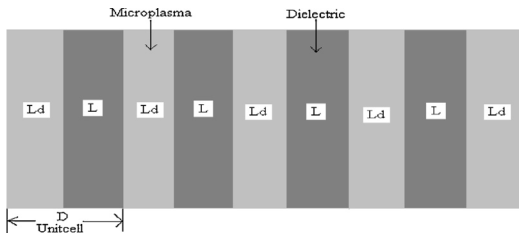


**Fig. 1.** Periodic variations of plasma and dielectric showing 1-D plasma photonic crystals.

## 2. Theory

One-dimensional Maxwell's wave equation is given by [19–21]

$$\frac{d^2 \vec{E}(x)}{dx^2} + \left(\frac{\omega^2 \varepsilon(x)}{c^2} - \beta^2\right) \vec{E}(x) = 0, \tag{1}$$

where $\beta = (\omega/c)\varepsilon(x) \sin\theta$, $\omega$ is wave frequency, $\theta$ is angle of incidence, $c$ is the velocity of light in vacuum and $\beta$ is $z$-component of wave vector. To study the wave propagation in one-dimensional plasma dielectric photonic crystals composed of $N$ unit cells i.e. $N$ alternate layers of plasma and dielectric material (like ZnS and $Al_2O_3$) of thickness $Ld$ and $L$ respectively. The geometry of the structure is shown in Fig. 1.

The profiles of plasma and dielectric permittivity are given by;

$$\varepsilon(x) = \begin{cases} \varepsilon_p = \left(1 - \dfrac{\omega_p^2}{\omega^2}\right) & -Ld \le x \le 0 \\ \varepsilon_m & 0 < x < L \end{cases} \tag{2}$$

with $\varepsilon[x + L(1 + d)] = \varepsilon(x)$, Here $\omega_p$ is the plasma frequency given by $\omega_p = ((n_p e^2)/(\varepsilon_0 m))^{1/2}$, where $e$ and $m$ are charge and mass of electron with a density $n_p$ and $\varepsilon_m$ is the dielectric constant of the material. Where $L$ and $Ld$ are the thickness of dielectric and plasma layers and $L(1 + d)$ is the period of unit cell. For solving the propagation of electromagnetic wave in these media, we use $2 \times 2$ matrix formulation. The electric field distribution $E(x)$ with each homogeneous layer can be expressed as the sum of incident wave and a reflected plane wave. The complex amplitude of these two waves constitutes the component of a column vector. The electric field in the $n$th unit cell, can be written as follows.

For $\omega > \omega_p$

$$E(x) = \begin{cases} a_n \exp(ik_m x) + b_n \exp(-ik_m x) & 0 < x < L \\ c_n \exp(ik_p x) + d_n \exp(-ik_p x) & -Ld \le x \le L \end{cases} \tag{3}$$

where $k_p = \varepsilon_p(\omega/c)\cos\theta_p$ and $k_m = \varepsilon_m(\omega/c)\cos\theta_m$, here $\theta_p$ and $\theta_m$ are angles in the layers and are related by the equation $\varepsilon_p \sin\theta_p = \varepsilon_m \sin\theta_m$, employing the matrix method for $\omega > \omega$, the constant $a_n$, $b_n$, $c_n$ and $d_n$ have been deduced and are found to be;

$$\left(\frac{a_{n-1}}{b_{n-1}}\right) = M_1 \left(\frac{c_n}{d_n}\right) \tag{4}$$

and

$$\left(\frac{c_n}{d_n}\right) = M_2 \left(\frac{c_n}{d_n}\right) \tag{5}$$

For nonmagnetic materials $\mu_i = 1$ and for the TE mode, by eliminating $(c_n/d_n)$ in Eqs. (4) and (5), the matrix equation is obtained as

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = \begin{pmatrix} m_{1,1} & m_{1,2} \\ m_{2,1} & m_{2,2} \end{pmatrix} \begin{pmatrix} a_n \\ b_n \end{pmatrix} \tag{6}$$

The matrix elements are given by, for $\omega < \omega_p$

$$m_{1,1} = e^{ik_m L}\left[\cos(k_p Ld) + \frac{1}{2} i \left(\gamma + \frac{1}{\gamma}\right) \sin(k_p Ld)\right], \tag{7}$$

$$m_{1,2} = e^{-ik_m L}\left[\frac{1}{2} i \left(\gamma - \frac{1}{\gamma}\right) \sin(k_p Ld)\right], \tag{8}$$

$$m_{2,1} = e^{ik_m L}\left[-i\frac{1}{2} \left(\gamma + \frac{1}{\gamma}\right) \sin(k_p Ld)\right], \tag{9}$$

$$m_{2,2} = e^{-ik_m L}\left[\cos(k_p Ld) - i\frac{1}{2} \left(\gamma + \frac{1}{\gamma}\right) \sin(k_p Ld)\right], \tag{10}$$

where $\gamma = (k_p/k_m)$ for TE-mode and $\gamma = ((k_p \times n_m^2)/(k_m \times n_p^2))$ for TM-mode.

A layered media is equivalent to a one-dimensional lattice that is invariant under the lattice translation i.e. $\varepsilon[x + L(1 + d)] = \varepsilon(x)$. According to the Floquat–Bloch theorem, solutions of wave equation for a periodic media are of the form, $E_K(x, z) = E_K(x)e^{-i\beta z}\, e^{-iKx}$, where $E_K(x)$ is periodic with a period $L(1 + d)$ that is $E_K(x + L(1 + d)) = E_K(x)$. The subscript $K$ indicates that the function $E_K(x)$ depends on $K$, the constant $K$ is known as the Bloch wave number.

In terms of four-column vector representation and from Eq. (6) the periodic condition for the Bloch wave is simply;

$$\begin{pmatrix} a_n \\ b_n \end{pmatrix} = e^{-iK[L(1+d)]} \begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} \tag{11}$$

The two eigen values in Eq. (6) are inverse of each other. Since translational matrix is uni-modular, which gives the dispersion relation between $\omega$, $\beta$ and $K$ for the Bloch wave function as

$$K(\beta, \omega) = \frac{1}{L(1+d)} \cos^{-1}\left[\frac{1}{2}(m_{1,1} + m_{2,2})\right], \tag{12}$$

where $\left|1/2(m_{1,1} + m_{2,2})\right| < 1$ correspond to real $K(\omega, \beta)$ and propagating block waves, where $\left|1/2(m_{1,1} + m_{2,2})\right| > 1$ correspond to imaginary $K(\omega, \beta)$, so that the Bloch waves is evanescent. These are so called for forbidden bands of the periodic medium. The band edges are the regimes where $\left|1/2(m_{1,1} + m_{2,2})\right| = 1$.

Therefore the dispersion relation for $\omega > \omega_p$ will be

$$K(\beta, \omega) = \frac{1}{L(1+d)} \cos^{-1}\left[\cos(k_m L)\cos(k_p Ld) - \frac{1}{2}\left(\frac{k_p^2 + k_m^2}{k_m k_p}\right) \times \sin(k_m L)\sin(k_p Ld)\right] \tag{13}$$

For a periodic layer medium that consist of the $N$ unit cell and bounded by homogenous media of index $n_0 = 1.0$ (air), the matrix equation becomes;

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}^N \begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{14}$$

or

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} a_N \\ b_N \end{pmatrix} \tag{15}$$

where $M_{11} = m_{11}U_{N-1} - U_{N-2}$, $M_{12} = m_{12}U_{N-1}$, $M_{21} = m_{21}U_{N-1}$, $M_{22} = m_{22}U_{N-1} - U_{N-2}$ and $U_N = ((\sin[(N+1)KL(1 + d)])/(\sin[KL(1 + d)]))$. So, that the reflection and transmission coefficient are given by;

$$r = \left(\frac{b_0}{a_0}\right)_{b_N=0} = \frac{M_{21}}{M_{11}} \tag{16}$$