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Nonlinear transmission and reflection characteristics of plasma/polystyrene one dimensional photonic crystal

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ABSTRACT

Reflection and transmission properties of one-dimensional plasma/polystyrene nonlinear photonic crystal have been investigated theoretically. Reflectance and transmitted amplitude of electromagnetic waves through these periodic multilayered structures are calculated for different intensities of controlling wave. It is found that the reflectance of the proposed structures depends on the intensity of the controlling wave and this property can be exploited in the design of WDM coupler, filter, optical logic gates, etc.

1. Introduction

Photonic crystals, which are known to exhibit many unique features, drew attention of many researchers working in the field of solid state physics and optical physics [1,2]. Various studies on photonic crystal structures lead to a variety of possible applications such as the inhibition of spontaneous emission [3], strong localization of photons [4], omnidirectional mirror [5], coaxial waveguides [6] etc. Different types of materials are considered for the design of photonic crystal structures. However, Kiskinen and Fernsler [7] and Hojo and Mase [8] have studied photonic band gaps in photonic crystals for the first time, using dusty plasma and discharged microplasma respectively. Such structures are now known as plasma photonic crystal (PPC). One dimensional plasma photonic crystal is a periodic array composed of alternate layers of plasma and dielectric materials. Hojo and Mase studied plasma photonic crystal and showed that photonic band gap(s) increase as we increase the width of plasma layer as well as the plasma density. It is also confirmed by Ojha et al. [9]. The structure of dusty plasma photonic crystals can be one-, two- and three-dimensional and contain face centred cubic (fcc), body central cubic (bcc) and other symmetries. Several aspects of dusty plasma photonic crystals have been studied [10–12]. Using plane wave expansion techniques, the propagation of the electromagnetic wave in a dusty plasma photonic crystal is forbidden for certain range(s) of wavelength, called photonic band gaps, which occur for a range of Debye length scale sizes with respect to the dust particle size. 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 with respect to the lattice constant of the dusty plasma crystal. The main effect of the plasma sheath in photonic crystals is to increase the band gap width. In addition, the band gap width is a function of the ratio of the dust dielectric constant with respect to the background plasma. Quantum electrodynamical effect in plasma has been studied by Marklund et al. [13]. They predicted a new nonlinear electromagnetic wave mode in magnetized dusty plasma. Its existence depends on the interaction of an intense circularly polarized electromagnetic wave with a dusty plasma where quantum electrodynamical photon–photon scattering is taken into account. Kumar et al. have studied the linear property of one dimensional plasma photonic crystal [14]. Replacing the dielectric material by nonlinear material in the conventional one dimensional plasma photonic crystal can change the transmission characteristic of these photonic crystals. When a non-linear refractive index material is introduced as alternate layers of conventional one dimensional dielectric photonic crystal, the reflection and transmission properties of the structure got changed and such structures can be made transparent at high intensity in that region of frequency for which the composite material is opaque at low intensity thereby suggesting that it can work as a switch [15–18].

In this present communication, nonlinear reflectance and transmission through one dimensional nonlinear-plasma photonic crystals has been presented. Special emphasis has been given on the effect of thickness of plasma layers on the reflectance and

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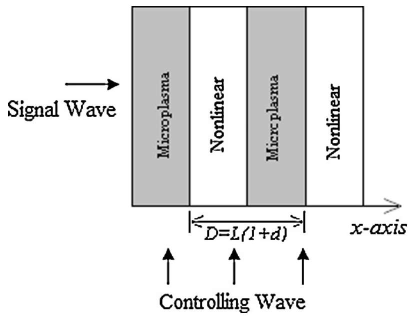

Fig. 1. Periodic variation of plasma and nonlinear material showing 1-D nonlinear-plasma photonic crystals.

transmission spectra of the proposed structure. Here we considered that electromagnetic wave incident perpendicular to the layers. The controlling wave, which produces the nonlinear effect, is propagating perpendicular to the direction of propagation of the incident wave. Also, we considered that the amplitude of the controlling wave much higher than the amplitude of the incident wave thereby we can safely neglect the nonlinear effect of the incident wave on nonlinear layers. We shall rather confine our study around one particular photonic band gap within which the centre of the wave to be propagated in the structure falls.

2. Theoretical model

We consider one-dimensional nonlinear-plasma photonic crystals having alternate layers of nonlinear material and micro-plasma as shown in Fig. 1. The reflectivity of such one-dimensional nonlinear-plasma photonic crystals is computed using the transfer matrix method, for different intensities of controlling wave; and we also computed the output amplitude of the wave for an incident signal wave with a Gaussian spectral distribution, centred at 0.935 normalized frequency with 0.126 FWHM.

The Maxwell wave equations for electromagnetic wave propagation along the x-axis in one-dimensional nonlinear-plasma photonic crystal may be written as

$$\frac{d^2E(x)}{dx^2} + k_0^2\varepsilon(x)E(x) = 0 \quad (1)$$

with

$$n(x) = \begin{cases} \left(1 - \dfrac{\omega_p^2}{\omega^2}\right)^{1/2}, & -Ld < x < 0, \\ n_0 + \Delta nI, & 0 < x < L, \end{cases} \quad (2)$$

and

$$n(x) = n(x + D), \quad (3)$$

where, $k_0 = \omega/c$ is the wave frequency, c is the speed of light, $\omega_p = (e^2 n_p/\varepsilon_0 m)^{1/2}$ is the electron plasma frequency with density n_p, $n_0 + \Delta nI$ is the refractive index of the nonlinear material.

The schematic diagram of the spatial variation of micro-plasma and nonlinear material is given in Fig. 1, where $D = L(1 + d)$ is the lattice period with the widths of nonlinear and micro-plasma being L and Ld respectively.

The general transfer matrix method [14] could not deal with the non-linear propagation problem in the presence of other high intensity controlling wave. Hence, we adopted an approximate approach to considering the nonlinearity. Under excitation of controlling wave, the refractive index of polystyrene could be calculated according to the optical Kerr effect. Therefore, with the calculated refractive index of polystyrene, the transmittance T_N of the proposed photonic crystal with different controlling wave intensity could be calculated. Johnson et al. [19] and Xiaoyong et al. [20] have confirmed the convergence and the correctness of this approximate approach. They pointed out that this approximate approach could lead to the right results. Now, if the following Gaussian wave incident on the structure

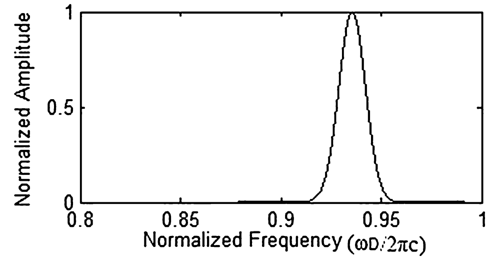

Fig. 2. Incident Gaussian wave centred at 0.9356 normalized frequency with 0.126 FWHM.

$$u = u_0 \exp\left[-\left(\frac{\lambda - \lambda_0}{\lambda_0}\right)^2\right] \quad (4)$$

where λ_0 is the centre wavelength, and u_0 is the peak amplitude of the wave.

Then, the amplitude of the output wave is given by

$$v = u \times T_N \quad (5)$$

3. Result and discussion

In this section, we compute the reflection spectra and output amplitude of the wave on the scale of normalized frequency ($\omega D/2\pi c$) for a one-dimensional nonlinear-plasma photonic crystal and for different intensities of the controlling wave. The thickness of plasma layer is taken as Ld with plasma frequency 5.6×10^{11} Hz. Polystyrene has been chosen as a nonlinear material. The thickness of polystyrene is taken as L with refractive index $n = 1.59 + \Delta nI$ where Δn is the Kerr coefficient of polystyrene, $\Delta n = 1.12 \times 10^{-12}$ cm^2/W [21]. Here I is the intensity of controlling wave. Two cases of different thickness ratios ($Ld/L = d$) are considered for which the ratios are 0.01 and 0.05. In the proposed structure, we have taken the number of layers for each material, N to be equal to 50 and thickness of polystyrene 7×10^{-5} m and of plasma $7 \times 10^{-5} \times d$ m. The incident Gaussian wave is shown in Fig. 2. We analyzed the structure at four different intensities of controlling wave 1 GW/cm^2 (low), 10 GW/cm^2 (moderate), 40 GW/cm^2 (high) and 100 GW/cm^2 (very high).

When the intensity of the controlling wave is 1 GW/cm^2, the reflection spectra of the proposed multilayer structure has been shown in Fig. 3a and an incident Gaussian wave centred at 0.9356 of the normalized frequency with 0.126 FWHM are shown in Fig. 2. It is clear from Fig. 3a that for this intensity of the controlling wave, the structure has photonic band gap from 0.9307 to 0.9417 of the normalized frequency for $d = 0.1$ and from 0.8746 to 0.9539 of the normalized frequency for $d = .05$. Thus, it is clear from Figs. 2 and 3a that the incident wave centred at 0.9356 of the normalized frequency falls inside the band gap for both the case i.e. for $d = 0.01$ as well as $d = 0.05$. From Fig. 3b and c, we see that the wave suffer nearly hundred percent reflection and there will be no transmission of wave through the proposed multilayer structure in both the cases. For the case in which intensity of the controlling wave is moderate (10 GW/cm^2), the reflection spectra and incident wave have been shown in Figs. 4a and 2 respectively. At this intensity of the controlling wave, the structure has a photonic band gap from 0.9247 to 0.936 of the normalized frequency for $d = 0.01$ and from 0.8693 to 0.9479 of the normalized frequency for $d = 0.05$. From