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Tuning of Photonic Band Gap by Electric Field in a Nonlinear Composite Material

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Abstract

We theoretically investigate the tuning of Photonic band gaps in one dimensional photonic crystals based on Nano composite of silver nanoparticle embedded in SiO_2 by applying electric field. In addition, the tuning can be done by considering the filling fraction and the radius of the nanoparticle. The evolution of these results to provide new possibilities of designing the desired photonic crystals.
Keyword- Nonlinear Composite Material, Photonic Crystals (PCs), PBG

I. Introduction

Photonic Crystals (PCs) have attracted an important attention due to potential applications of Photonic band gap (PBG) [1]. PCs are periodic structures with different refractive indices that may exhibit ranges of forbidden frequencies for the propagation of light. The operating range of currently available PCs covers a range of frequencies from the microwaves [2] through the terahertz range [3] up to the visible [4]. It finds many potential applications in optoelectronics and optical communications. The PBG can be tuned by means of some external agents. Temperature tuning of photonic band gap is predicted using a liquid crystal as one of the constituents in a PC [5]. The PBGs can also be tuned by magnetic fields [6] or mechanical force [7]. To obtain tunability of PBG, the dielectric permittivity or magnetic permeability of one of the constituent materials must depend on some external parameters such as electric or magnetic fields. The position and the width of PBG depend on the dielectric permittivity of the host matrix, the concentration and the size of the nanoparticle. Very large nonlinear optical effects are often observed in composite materials. By embedding metallic nanoparticles in a dielectric host leads to an increase in the nonlinear susceptibility of a composite material resulting in an enhancement of local electric field [8,9].

In the present work, we consider one dimensional PCs consisting of alternate layers of composite layer in which nonlinear nanoparticles are randomly embedded in a dielectric host (SiO_2) and air layer. The dielectric permittivity of composite materials can be altered by applying an external pump electric field because of the third order nonlinearity.

II. Theory

The transmission properties of one dimensional PC consisting of Nano composite metal nanoparticles randomly distributed in a transparent matrix are investigated. Let us consider a one dimensional PC, with N elementary cells with lattice constant a. Each cell consists of one Nano composite layer of width d_1 with permittivity ε_{mix} and one layer of air of width d_2 with permittivity equal to 1. The lattice constant $a=d_1+d_2$. We consider only normal incidence of electromagnetic wave on photonic crystal. The lattice constant is set to equal the plasma wavelength λ_p corresponding to the plasma frequency ω_p $(\lambda_p \equiv \frac{2\pi c}{\omega_p})$ at room temperature (λ_p=138 nm). Here we consider the value of lattice constant $a = 2\lambda_p$. The width of the layers are d_1=0.5a and d_2=a-d_1.

To compute the PBG in the transmission spectra, we employ the transfer matrix method [10]. Each layer of PC has its own transfer matrix and the overall transfer matrix of the system is the product of the individual transfer matrices.
According to TMM, each single layer has a transfer matrix is given by

$$M_l = \begin{pmatrix} \cos\delta_l & \frac{-i}{n_l}\sin\delta_l \\ -in_l\sin\delta_l & \cos\delta_l \end{pmatrix} \quad (1)$$

Where l represent either H or L layer. The suffix H represents the Nano composite layer and L is the air layer.
The phase δ_l is expressed as

$$\delta_l = k_l d_l = \frac{2\pi d_l}{\lambda} n_l \tag{2}$$

For the entire structure of Air/(HL)^N/Air, the total transfer matrix is given by

$$T = (M_H M_L)^N \tag{3}$$

Where the matrix elements can be obtained in terms of the elements of the single-period matrix. The value of N is taken as 20. The transmission coefficient for tunneling through such a structure is given by

$$t = \frac{4}{(T_{11}+T_{22})^2 + (T_{12}+T_{21})^2} \tag{4}$$

Where T_{ij} are the elements of the matrix T.

To determine the refractive index of the composite, the local electric field enhancement induced by the third-order nonlinearity is to be considered as the metallic nanoparticles are embedded in a dielectric host. The nonlinear dielectric permittivity can be written as [11]

$$\overline{\varepsilon_m} = \varepsilon_m + \chi_p^{(3)} = \varepsilon_m + \chi_p^{(3)} \langle |E_p{}^2| \rangle \tag{5}$$

Where $\chi_p{}^{(3)}$ is the third order susceptibility of the nanoparticle, E_p the local electric field inside the nanoparticle.

To determine the permittivity of the Nano composite $\varepsilon_{mix}(\omega)$, we use the Maxwell- Garnett formula [11]

$$\frac{\varepsilon_{mix} - \varepsilon_d}{\varepsilon_{mix} + 2\varepsilon_d} = f \frac{\overline{\varepsilon_m} - \varepsilon_d}{\overline{\varepsilon_m} + 2\varepsilon_d} \tag{6}$$

Where ε_d is the dielectric permittivity of the transparent matrix, f is the volume fraction of the nanoparticle.

The dielectric constant of the metal nanoparticles is determined in accordance with the drude model

$$\varepsilon_m(\omega) = \varepsilon_0 - \frac{\omega_P^2}{\omega(\omega + i\gamma)} \tag{7}$$

where ε_0 is a constant (ε_0 =5 for silver [12]), ω_p is a plasma frequency (ω_p= 9 eV [12]), γ is a relaxation constant Substituting equation (7) in equation (1), we can deduce the real and imaginary parts of the composite material.

$$\varepsilon_{mix}(\omega) = \varepsilon'_{mix}(\omega) + i\varepsilon''_{mix}(\omega) \tag{8}$$

The relaxation constant can be written as [13]

$$\gamma = \frac{v_F}{l} + \frac{v_F}{r} \tag{9}$$

where v_F is the Fermi velocity (v_F =1.39 x 10^6 m/s [12]), l is the electron mean free path at room temperature (l= 52 nm [12]) and r is the radius of the nanoparticle.

The volume-averaged local electric field $\langle |E_p{}^2| \rangle$ is given by [11]

$$\langle |E_p{}^2| \rangle = \frac{9\,|\varepsilon_d|}{|(1-f)\varepsilon_m + (2+f)\varepsilon_d|^2} E_0{}^2 \tag{10}$$

The refractive index of Nano composite layer is taken as $n = \sqrt{\varepsilon_{mix}}$ from equation (8) for our simulation work and air layer as 1. This was made for the sake of simplicity. In this paper, the tunability of PBG in one dimensional PCs by changing pumps electric fields, filling fraction and the radius of the nanoparticle. We use the term $\chi_p{}^{(3)} E_0{}^2$ represents the strength of an external controlling pump electric field E_0.

III. Results and Discussion

A. Effect of PBG Due to Increase of Filling Fraction

Due to filling factor , we get one larger band gap in UV-Vis-IR and many smaller band gaps in the UV region. The band gaps are specified in terms of (ω/ω_p) normalized frequency and the frequency are calculated as (0.1293) ω_p. For example, the band gaps are (0.1293 – 0.4640) ω_p, (0.0836 – 0.6147) ω_p and (0.0265 – 0.7658) ω_p for the filling fraction f=0.2, f=0.5 and f=0.9 respectively when the radius of the nanoparticle is 2 nm and $\chi_p{}^{(3)} E_0{}^2$ = 0.1. Fig (1) shows the transmission spectra of PBG for different filling fraction. The width of the PBG are represented in terms of wavelength as 768.5 nm, 1423.7 nm and 5018.4 nm for the filling fraction f=0.2, f=0.5 and f=0.9 respectively. We conclude that by increasing the filling fraction, the width of the PBG is increased and is shifts towards the UV-Vis to UV-Vis-IR region. If the filling fraction is high, we get the largest band gap.

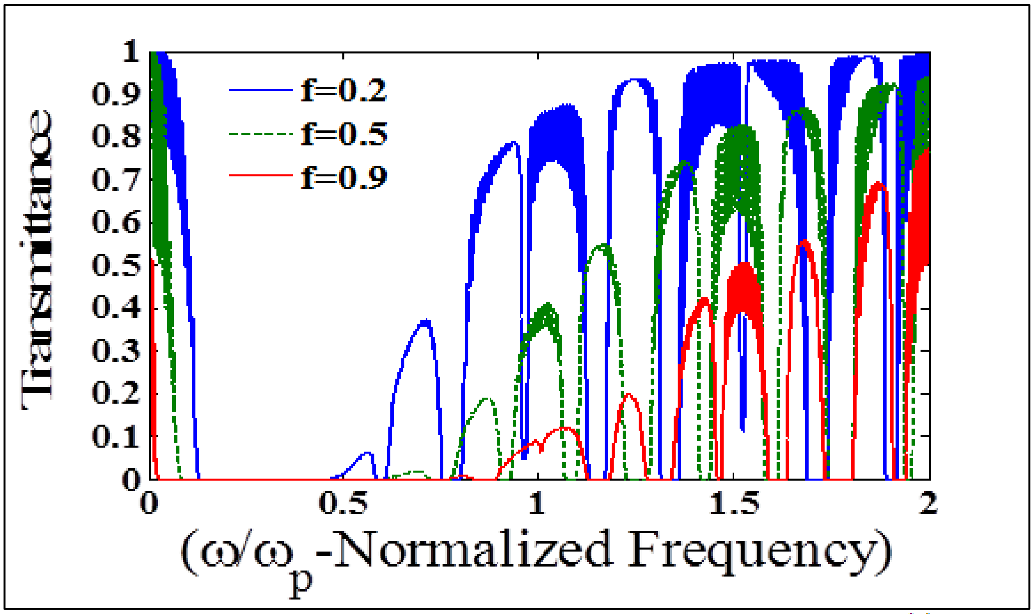

Fig. 1: Transmission spectra of PBG for filling factor f=0.2, f=0.5 and f=0.9 when r=2 nm , $\chi_p^{(3)} E_0^{2}$ = 0.1

B. Effect of PBG Due to Increase in Size of the Nanoparticle

The width of the PBG gets reduced when we increase the size of the nanoparticle. The band gaps are specified in terms of wavelength are 1421.3 nm, 1306.9 nm and 1268.9 nm for the radii 2 nm, 5 nm and 10 nm respectively when the filling fraction f=0.5 and $\chi_p^{(3)} E_0^{2}$ =0.3. Fig 2 shows the transmission spectra for different radii of the nanoparticle.

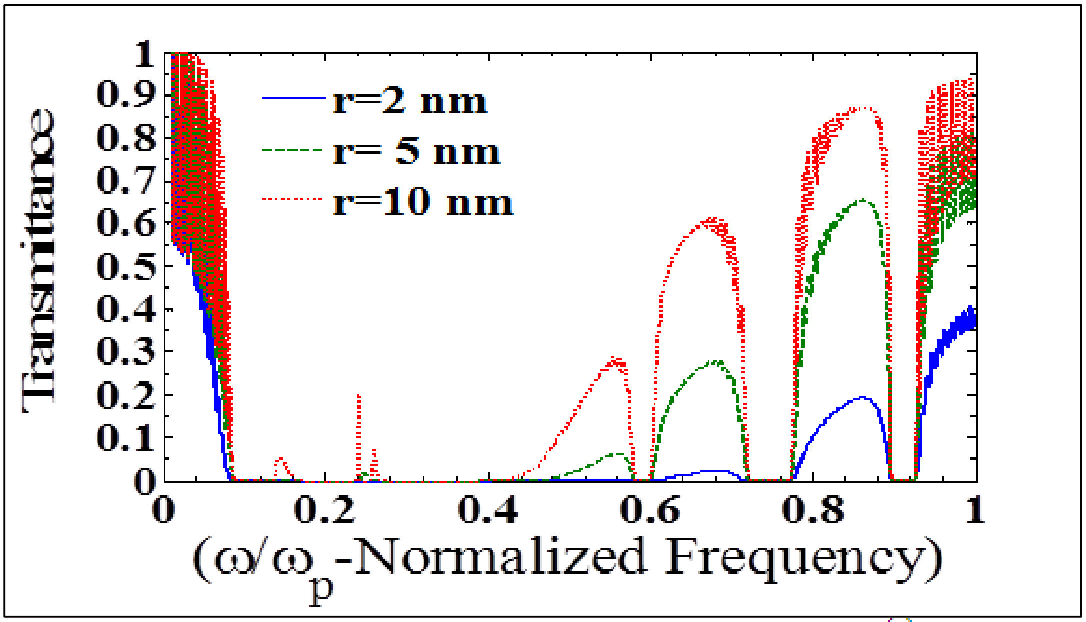

Fig. 2: Transmission spectra of PBG for radii 2 nm, 5 nm and 10 nm when f=0.5 , $\chi_p^{(3)} E_0^{2}$ = 0.3

C. Effect of PBG under External Pump Fields

If the pump fields are applied to a composite material, there is a variation in the dielectric permittivity. Fig (3) shows the transmission spectra due to increase in the term of external pump fields. The band gaps are 1084.5 nm and 1072.1 nm for $\chi_p^{(3)} E_0^{2}$ =0.1 and $\chi_p^{(3)} E_0^{2} =$ 0.5 respectively when the filling fraction is f=0.4 and the radius of the nanoparticle is 5 nm. We conclude that the widths of the band gaps are reduced due to the increase in the term of external pump fields $\chi_p^{(3)} E_0^{2}$.

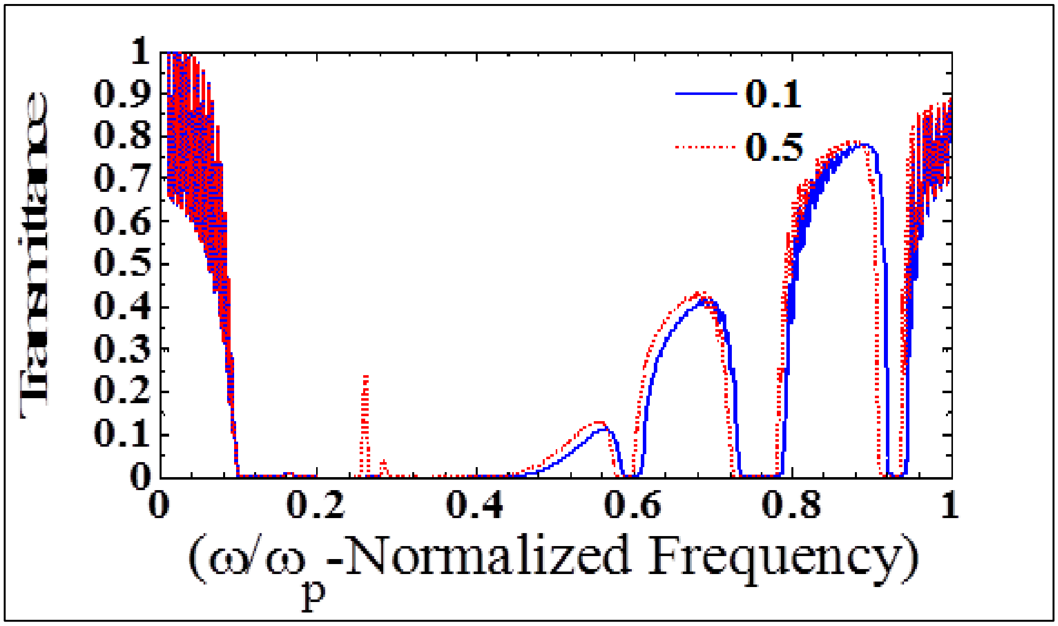

Fig. 3: Transmission spectra of PBG for $\chi_p^{(3)} E_0^2 = 0.1$ and $\chi_p^{(3)} E_0^2 = 0.5$ when f=0.4 and r= 5 nm

IV. CONCLUSION

In this work, the PBG can be tuned in a non-linear composite material which possesses third-order nonlinear susceptibility by applying an electric field. Due to variation in electric field, the width of the PBG is decreased. Due to the increase in the filling fraction by applying an electric field, the width of the PBG is increased. Similarly, the width of the PBG is decreased by increasing the radius of the nanoparticle. We conclude that, the band gaps can be tuned by changing the external pump electric fields. These new optical properties can be used in the manufacturing of optical devices.

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