OPTICAL SWITCHING IN KERR NONLINEAR CHALCOGENIDE PHOTONIC CRYSTAL

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Nonlinear Photonic Crystals are interesting materials from the point of view of the optical communication and transmission. In the present work, the parameters governing the optical switching in the one dimensional photonic crystal using As_2S_3/air multilayers have been studied. It has been found that the input light pulse beam amplitude can modify the bandstructure so that the group velocity dispersion characterstics and the dielectric bands are changed. The results have been discussed using simple explanations of the optical processes in Kerr nonlinear chalcogenide material multilayers.

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1. Introduction

In recent years, the researchers have been attracted a lot towards photonic crystals due to their control over light propagation [1, 2]. The reason to form a photonic band gap (PBG) is the inference of Bragg scattering in a periodic dielectric structure. The physical phenomenon of optical nonlinearity describes that high intensity of light can modify the dielectric constant of the material in which it propagates [3]. The emerging field of nonlinear photonic crystals (NLPC) has been of great interest to researchers for their applications in nonlinear optical devices as waveguide, all-optical switches, short pulse compressor, nonlinear optical diodes etc. [4-6]. The calculation of bandstructure in these materials is important to investigate the properties for a particular system. There have been numerous approaches of estimating the band structure of nonlinear photonic crystals [7, 8]. The Plane Wave Expansion method (PWEM) is well known and has been used in this work.

Mostly, Photonic Crystals have been made from III–V semiconductors. While their active functions have typically exploited thermal or free-carrier nonlinear effects, both of which are relatively slow [9]. Chalcogenides have generated great deal of interest due to their attractive properties [10]. Some of these are : can be formed over a large range of compositions; refractive index is high, linear absorption losses are low over a wide wavelength range and a large $\chi^{(3)}$ nonlinearity (much larger than Silica) [11]. Therefore, the chalcogenide glass photonic crystal platform appears to be a promising architecture for confining, guiding light and all-optical switching applications [12, 13].

In this paper, we have presented the results obtained on the symmetrical multilayered As_2S_3/air structures and by analyzing the parameters governing the frequencies of allowed band states, which can be tuned properly with the external control of beam intensity.

2. Numerical method

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A straightforward way of solving for eigenvalues and eigenfunctions is to expand the dielectric constant as well as the periodic part of the Bloch function into a Fourier series on the reciprocal lattice, transforming equation into an eigenvalue problem for an infinite matrix which must be suitably truncated to become accessible to an approximate numerical solution. Owing to its simplicity and flexibility in handling practically any geometry of the unit cell, this so-called plane wave method (PWM) has become the work house for most investigations of photonic bandstructures [14].

The Maxwell's equation of electric field for the nonlinear medium is given as

$$-\nabla^2 E-\frac{\omega^2}{c^2}\varepsilon_L E=\frac{\omega^2}{\varepsilon_0 c^2}P^{NL} \tag{1}$$

where ε_L is the dielectric constant and $P^{NL}=\varepsilon_0\chi^{(3)}IE$ defines the polarization for Kerr nonlinear medium, while I is the intensity of field. Putting the value of P^{NL} in equation (1), we get

$$-\nabla^2 E=\frac{\omega^2}{c^2}\left(\varepsilon_L+\chi^{(3)}I\right)E \tag{2}$$

Let $\varepsilon_L+\chi^{(3)}I=\varepsilon_{NL}$ defined as dielectric constant of nonlinear medium. This is wave equation for nonlinear medium, which becomes for linear as Kerr coefficient ($\chi^{(3)}=0$).
Parameters that define a one-dimensional photonic crystal are dielectric constants of the alternating layers ε_1 and ε_2, width of the layers *(d-a)* and *d*, respectively and thickness of unit cell *a* for photonic crystal. The periodicity is in the z-direction. The structure is assumed to be infinite in the *x* and *y* direction, but limited in the *z* direction. One of the dielectric materials, say, the material with ε_2, is taken to be nonlinear and of thickness *d*. Kerr nonlinearity of the dielectric material changes its properties depending on the intensity of light *I*(*z*). The dielectric constant of the nonlinear photonic crystal is

$$\varepsilon_r=\begin{cases} \varepsilon_1 & -a/2<z<-d/2 \\ & d/2<z<a/2 \\ \varepsilon_2+\chi^{(3)}I & -d/2\le z\le d/2 \end{cases} \tag{3}$$

where $\chi^{(3)}$ is the Kerr coefficient.

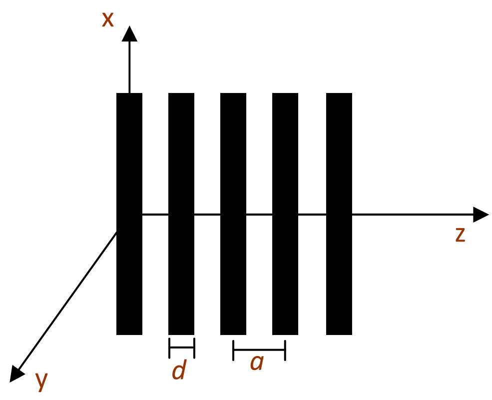

Fig. 1. Schematic diagram of lattice parameters of 1-D photonic crystal.

3. Results and discussion

Band structure diagram for linear and nonlinear chalcogenide photonic crystals is shown in Fig. 2. The parameter values defining the geometry of the As_2S_3/air multilayered photonic crystal are dielectric constants $\varepsilon_1=1$ for air, $\varepsilon_2=6$ for As_2S_3, while the width of layers are *d=0.8a* and *0.2a*, respectively. These parameter values are chosen in order to maximize the lowest band gap of the linear photonic crystal within reasonable limits. The band gap size widens with increasing difference between ε_1 and ε_2. The number of Fourier components is chosen to be N=51. The Kerr coefficient is taken to be $\chi^{(3)}= 2.12x10^{-17}cm^2/W$ [15]. This is not a limiting factor since if the numerical value of $\chi^{(3)}$ is changed, the same results are achieved by multiplying the control field amplitude correspondingly.

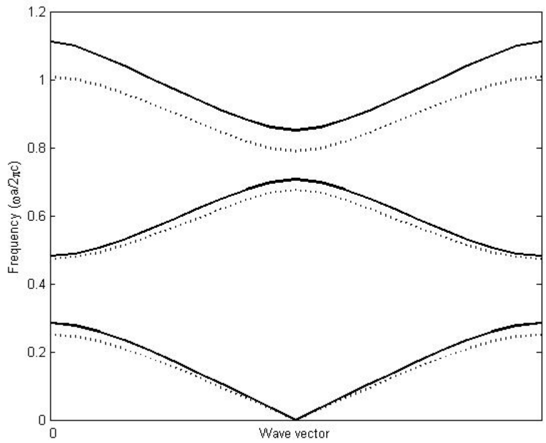

Fig. 2. The Photonic Band for linear Photonic crystal (Solid line) and for Nonlinear Photonic Crystal (Dotted line) with control beam intensity of 100 GW/cm^2.

The variation in allowed frequency of 1-D nonlinear chalcogenide photonic crystals of As_2S_3/air multilayer structure compared to linear photonic crystal at the band edge ($ka/2\pi$=0.5) with control beam intensity are shown in Fig. 3 (Left). The lowest band (known as dielectric band) and the second band (known as air band) are less affected as compared to the third band by the nonlinearity. The third band is highly affected with control beam intensity while the second air band is least affected [7]. Therefore, the third band can be used for all-optical switching properties for wide range of frequencies. Next, the forbidden bandgap for 1-D NLPC at the band edge ($ka/2\pi$=0.5) is plotted with control beam intensity of nonlinearity in Fig. 3 (Right). It is clearly seen that the odd forbidden bandgaps (first and third) are increasing with increase in control beam intensity, while the second forbidden bandgap is decreasing. The dielectric band is ideal for the control beam mode for two reasons. First, the dielectric band does not change much as a function of the magnitude of the nonlinearity allowing the control beam to travel through the crystal. Second, the intensity distribution is concentrated on the nonlinear material, thereby changing the dielectric constant in the greatest possible amount as observed above.

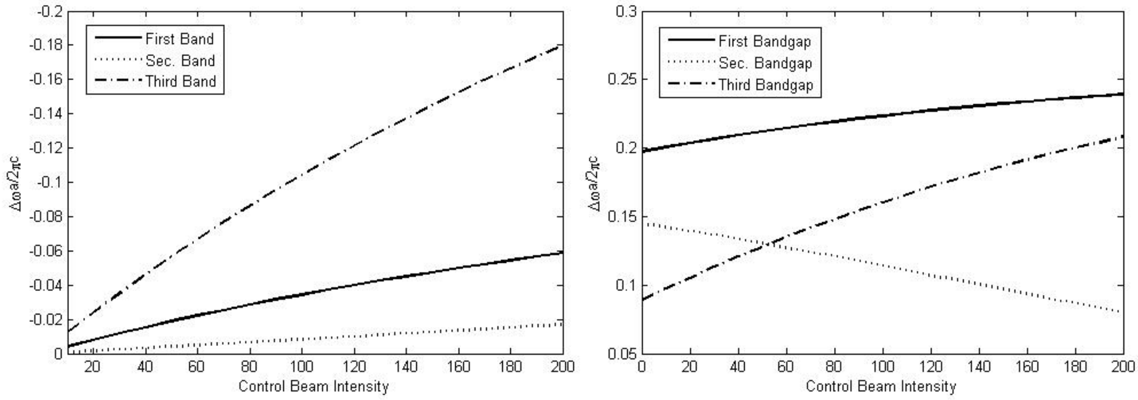

Fig. 3. The variation in normalized frequency values for 1-D NLPC compared to LPC at ka/2π=0.5 verses control beam intensity (Left) and the value of forbidden Bandgap for 1-D NLPC verses control beam intensity (Right).

For switching, we are interested in using the language of PBG theory to study the nonlinear dynamics of a pulse that impinges on such a structure, with its frequency near the gap edge. Here it has been taken to be about 300fs for λ=1.5µm.The changes of the band structure shown here would require intensities of the order of 100 GW/cm^2. The Photonic Band structure diagrams clearly show that as the control beam intensity is increased, the frequency bands shifted towards the lower values. The lowest band is narrowing in case of high control beam intensity for 1-D Kerr nonlinear Photonic crystal. This shift of the band structure can be explained using Scalora's approach [16]. As the dielectric constant depend on the intensity of the incident field, the band structure changes with the incident field intensity. In the frequency domain, the band structure is determined by the difference between the dielectric constants of the materials that form the photonic crystal. This can be expressed as

$$\Delta\varepsilon = [\varepsilon_2 + \chi^{(3)} I] - \varepsilon_1 \tag{4}$$

The value of $\Delta\varepsilon$ increases as the intensity increases if $\chi^{(3)}>0$ and decreases if $\chi^{(3)}<0$. As the magnetic dipole excites the structure, the value of $\Delta\varepsilon$ changes and the bands shift dynamically. This process is the basis of the intensity driven optical limiter and all-optical switching. The results show that for positive value of the Kerr coefficients, the value of $\Delta\varepsilon$ increases with increasing intensity and the width of the gap increases accordingly. If we now select the frequency of operation (ω) of the probe beam (I) somewhere near the edge of the gap, but inside of allowed band, it can be transmitted initially. Applying the control beam will tend to increase the width of the gap, and if a certain power level is surpassed, the probe beam at (ω) may suddenly be found inside of the forbidden gap and its transmission is not allowed. This process constitutes the basis of an optical switch.

The switching time associated with beam shutdown or the turn-on depending on the Kerr coefficient value $\chi^{(3)}$, depends on at least two factors : first, speed at which nonlinearity can be excited and structural geometry. For the first, we chose chalcogenides having high $\chi^{(3)}$ value so that intensity can modify the band gap significantly and secondly changing *r/a* which changes the geometry and hence changing band frequencies. This can be seen in the discussion of density of states and group velocity as follows.

The photonic density of states (DOS) has been calculated using photonic dispersion relation $\omega_n(k)$, which plays a fundamental role in the understanding of the properties of a PC. The photonic DOS N(ω) is defined by "counting" all allowed states with a given frequency ω, i.e., by the sum of all bands and the integral over the first BZ of a Dirac-δ function [14] :

$$N(\omega) = \sum_{n} \int_{\mathrm{BZ}} \mathrm{dk}\, \delta\left(\omega - \omega_n(k)\right) \tag{5}$$

The DOS for 1D Photonic crystal is as shown in Fig. 4, which displays the photonic band gaps as regions of vanishing DOS. A high DOS also corresponds to allow transmission of light while DOS of zero means that there can be no transmission in the band regions.

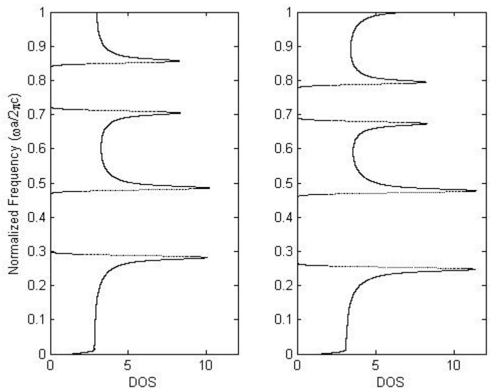

Fig. 4. The photonic DOS for linear photonic crystal (Left), Nonlinear Photonic crystal with control beam intensity 100 GW/cm[2] (Right).

The Photonic DOS (PDOS) is inversely proportional to the group velocity (dω/d*k*) from the photonic band structure (i.e. dispersion relation ω v/s k) [17]. There is a singularity in DOS whenever the group velocity is zero. Near the band edge of PBG, group velocity approaches zero. Thus a photon sees an increased path length due to many multiple reflections it undergoes, i.e. photon localization. A pulse at the band edge tends to form a standing wave. As shown in Fig.5(a), v_g decreases with the increase in the beam intensity. The variation of v_g with normalized frequency is shown in Fig. 5(b). Clearly, when the intensity of the beam is increased in the Kerr nonlinear PC, the v_g curves shift towards lower frequencies and the value is decreased at the same time. The same results can be obtained if the fill factor *r/a* is varied in the Kerr nonlinear PC, as displayed in Fig.6. The band gap increases with the beam intensity for a particular value of *r/a*. The said behaviour is observed in v_g with *r/a* [18].

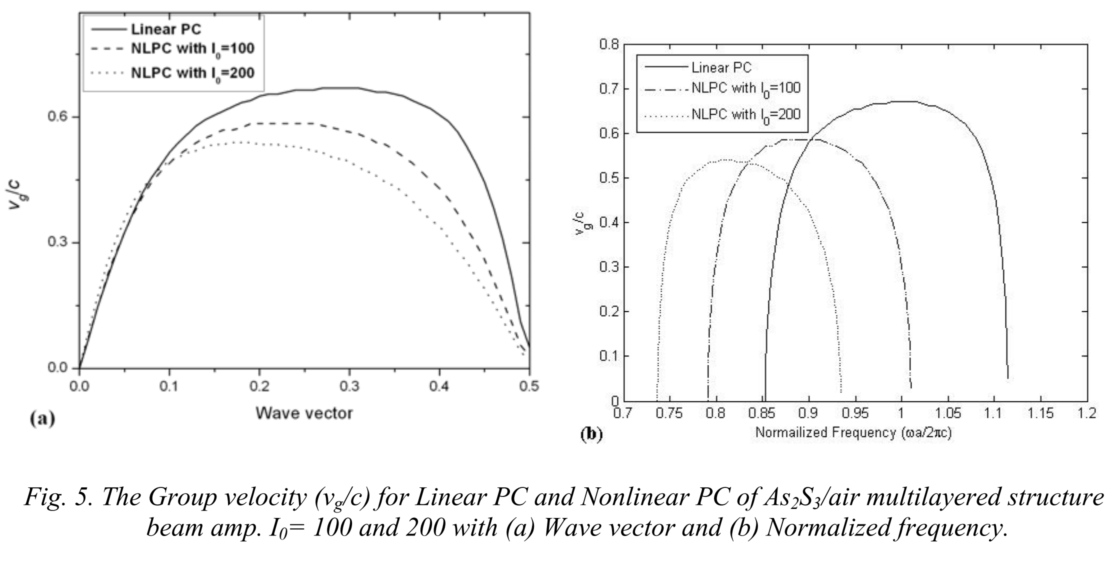

Fig. 5. The Group velocity (v_g/c) for Linear PC and Nonlinear PC of As_2S_3/air multilayered structure at beam amp. I_0= 100 and 200 with (a) Wave vector and (b) Normalized frequency.

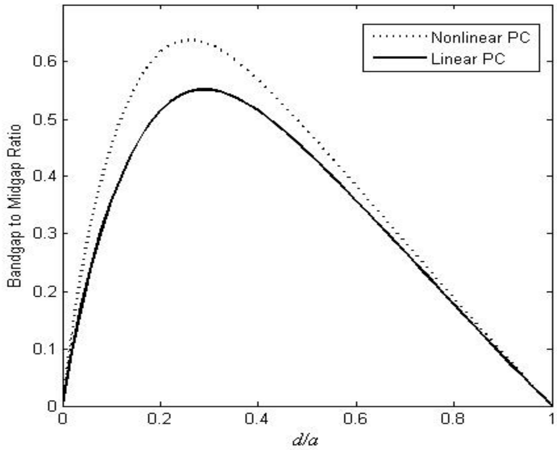

Fig. 6. The photonic bandgap to midgap ratio verses the fill factor (d/a) for linear PC (Solid line), for NLPC with control beam intensity 100 GW/cm^2 (dashed line).

4. Conclusions

The parameters and processes governing the optical switching in chalcogenide photonic crystal photonic crystals having ker nonlinearity has been discussed. It is concluded that the the plane wave expansion method efficiently estimated the band structure and Photonic DOS of Kerr nonlinear photonic crystal. It is found that as the external control beam intensity is increased, the bands shift towards the lower values. The third band is most affected with control beam intensity and can be used for all-optical switching. The second band is least affected with control beam intensity and can be used as a limiter. The group velocity shifts to lower frequencies with increase in beam intensity and is inversely related to the transmission of the beam across the material. The peak in the band gap-to-mid gap ratio with fill factor with beam intensity can be used to estimate the value for optimum switching.

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