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IMPROVING THE OPTICAL TUNING AND SPECTRAL EFFICIENCY IN CHALCOGENIDE PHOTONIC QUANTUM WELL STRUCTURES

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We report the results obtained on the localized modes developed due to defect layer of As-S-Se material sandwiched between symmetrical As_2S_3/air multilayered one dimensional photonic crystals. The modes give rise to quantum well with consequent number of resonant peaks which increase with increasing defect layer thickness. In case of alternatively stacked step-index films, the resonant peaks are shifted, which can be tuned with changing film thickness. It is shown that the normalized frequency shifts to lower values with increasing step-size. The spectral efficiency can thus be increased as a result of increase in refractive index without increasing the volume of the optical device.

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1. Introduction

Photonic crystals (PCs) attracted a lot of scientific interest in the last decade due to their electromagnetic properties and their potential applications as optical limiter, optical switch, optical diode etc. [1-3]. The reason to form a photonic band gap (PBG) is the interference of Bragg scattering in a periodic dielectric structure. One particular behavior of these systems is the ability to create crystal defects that confine light in localized modes. The discovery of the localized mode opens a wide array of future photonic circuit application [4]. Understanding of the behavior of these defects is significant for making effective applications of photonic crystals. Using the localization effect of defect-modes, many photonics components have been proposed and studied in detail, including sharp band waveguide of photonic crystal, quasi-periodic waveguide, channel-drop tunneling, wide-angular splitter, resonator, filter and optical switching [5-7].

The linear photonic crystal components are understood much more than that of nonlinear photonic crystal components. Light propagated in photonic crystals has lower group velocity, while light field localized in defect-modes is very intense. Therefore, the nonlinear effects in the defect-modes are greatly intensified due to increasing intensity of optical field and lengthening time of interaction between the optical field and the nonlinear medium [8]. Thus, the nonlinear photonic crystal component is an important device and indispensable for photonic circuits in the future.

Chalcogenides as optical materials have generated great deal of interest as outlined by various workers [9, 10]. This is due to their attractive properties: 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)[10]. Therefore, the chalcogenide glass PC platform appears to be a promising architecture for confining and guiding light [11, 12]. Although, there are numerous approaches to understand the defect modes in photonic crystals, but only a few are concerned about increasing the spectral efficiency. Previously, we have calculated the transmission spectrum for chalcogenide defect nonlinear photonic crystal [13]. In this paper,

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*Corresponding author: bhuvneshwer@gmail.com we present the results obtained by introducing number of layers of (As-S-Se/air) as defect layer in the symmetrical multilayered As_2S_3/air photonic crystals and analyzing the frequencies of confined states with the variation in Se concentration. In this case, multiple defect modes could be generated in a PBG without increasing the volume of the device.

2. Theoretical Method

The Structural configuration used in this work may be expressed as $(HL)^nD(LH)^n$, where H and L stand for the different layers with high and low refractive indices n_H and n_L, respectively, D defect layer with refractive index n_D and n is the number of layers. We have chosen As_2S_3 (chalcogenide glass in annealed form) and air representing n_A=2.405 and n_B=1 and d_H=d_L=0.5*a*, respectively, where the parameter *a* is the lattice constant. The thickness of defect layer d_D varies in the range from about 300nm to 2000nm. Here D is taken to be annealed glasses $As_{40}S_{60-x}Se_x$ with refractive index varying between 2.405 and 2.832 at wavelength of 1550nm [14]. In other case, D is a dielectric slab as a defect consisting of alternating A/B films (denoted as $(AB)^MA$, in which the B film is sandwiched between two A films with small refractive index contrast. M represents the number of AB layers). The refractive indices and the thickness of these two films are as follows: n_A = 2.832, n_B = 1 (corresponding to air) and $d_A = d_B = d_D/(2M+1)$, d_D is the total thickness of the D slab. For a single film, M = 0. The structure of the proposed configuration is as shown in Fig. 1. We have used the Transfer Matrix method of evaluating the transmission spectra using the standard codes. The formulation is simple and accurate [15]. We have considered a monochromatic light of wavelength λ incident normally on the crystal surface. The normalized frequencies are represented by $\omega a/2\pi c$ with *c* is the speed of light in vacuum and ω is the angular frequency. The transmission coefficient is taken as the ratio of transmitted power to the incident power.

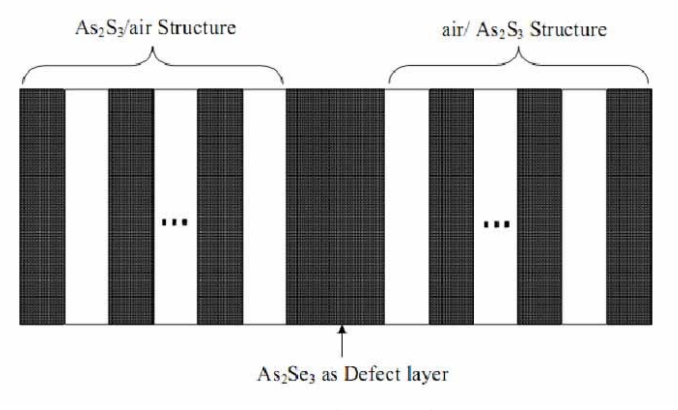

Fig. 1. Schematic diagram of 1-D Defect Photonic crystal.

3. Results and discussion

The transmission spectrum for the perfect truncated $(HL)^nH$ PC with n = 10, shown in Fig.2 (a). The reason why we chose n = 10 is that there is no significant difference in transmission spectra when n is much larger than 10. It is clearly shown that the first PBG is from 0.22 to 0.35, in which light possessing certain values of wave vector is not allowed to propagate. Fig.2 (b), (c), (d) display transmission spectra of $(HL)^5D(LH)^5$ with $d_D = a, 2a, 3a$ for defect layer as As_2Se_3 ($n_D = n_A$).

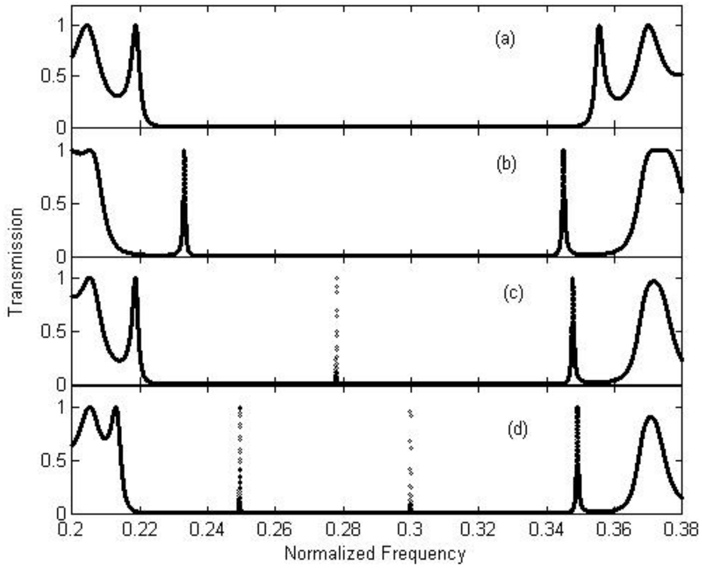

Fig. 2. Transmission spectra for 1-D chalcogenide photonic crystal (a) regular As_2S_3/air periodic crystal and (b), (c), (d) with defect layer of As_2Se_3 of thickness d_D=a, 2a, 3a, respectively.

The break in periodicity generates the defect which may permit localized modes to exist, with frequencies inside the PBG. As the mode has a frequency in the PBG, then it must exponentially decay once it enters the crystal. The number of defect modes and their locations can be controlled by changing either thickness of the defect layer or refractive index of the defect layer [3, 13]. In the present case, the concentration of the defects or the total volume of the defect layer is not changed while increasing the defect layer thickness. In such case, we anticipate that the localized states corresponding to these defect modes are spread out so as to allow fields to be concentrated more and more in the high-ε defect layer. The localized states thus generated cause the shifting of frequency to lower values, as has been displayed. The number of defect mode frequencies in the bandgap also increases with thickness due to the above said reason as shown in Fig. 2. Thus, photonic single quantum well (QW) structures are constructed owing to quantum confinement effects. Here, the defect slab D can be regarded as a well. These peaks can be termed as 'Confined states' which can be used as frequency carriers in optical communication. These states can be completely transmitted through the quantum well as a result of resonant tunneling.

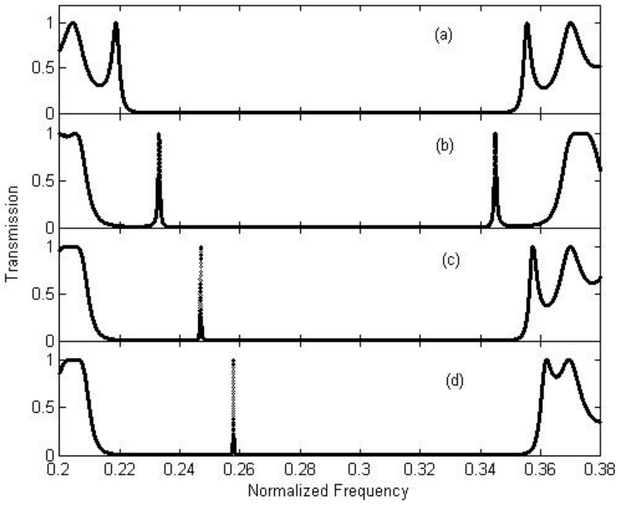

Fig. 3. Transmission spectra for 1-D chalcogenide photonic crystal (a) regular As_2S_3/air periodic crystal and with defect layer as $As_{40}S_{60-x}Se_x$ of thickness d_D= a in (b) for x=60, (c) for x=30 and (d) for x=0.

The transmission spectra for perfect 1D photonic crystal is plotted in fig. 3(a), while for defect layer $As_{40}S_{60-x}Se_x$ with thickness of layer as $d_D=a$ in fig. 3(b), (c) and (d) for x=60, x=30 and x=0, respectively. The variation of normalized frequency as a function of selenium atomic concentration of defect material is shown in Fig.4. The confined state shifts to lower values with increasing selenium atomic concentration. It provides opportunity to control the optical confined modes. This can be thought of as 'coarse' tuning of spectra. The spectral efficiency can be increased substantially. Therefore, the defect layer in PBG crystal works as a single wavelength waveguide for a particular number of wavelengths. The defect mode works as a guided mode for waveguide application in narrow band region. This is extremely useful as a filter device [11].

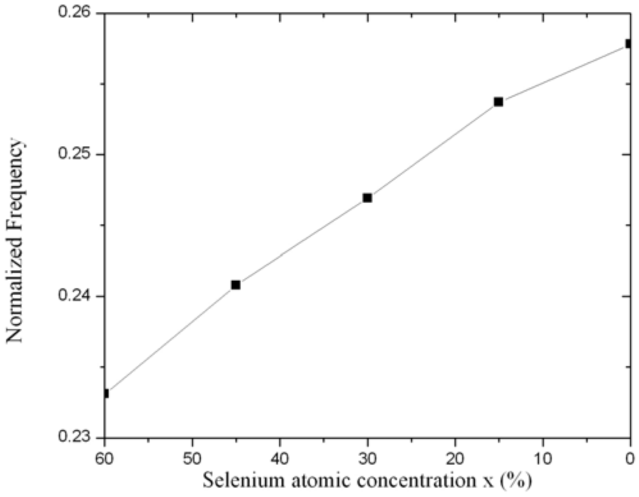

Fig. 4. The variation in Normalized frequency of guided mode with Selenium atomic concentration in defect layer $As_{40}S_{60-x}Se_x$.

The change in the constituent atom results in the reflection from the multilayers. The amorphous chalcogenides are known to have localized states present during their fabrication [16]. This allows frequencies to be available inside the PBG. The effect of Se concentration can be understood as follows. The value of the band gap in chalcogenide glasses is determined by the energy difference between the non-bonding valence band and the anti-bonding conduction band and not by the bond between the chalcogen and the arsenic atoms. The replacing sulfur atoms by selenium atoms decrease the value of the band gap from 2.1 eV for As_2S_3 down to 1.5 eV for As_2Se_3. The decrease in band gap causes increase in the values of nonlinearity which gives rise to the refractive indices from As_2S_3 for 2.405 to As_2Se_3 for 2.832 [17]. Arsenic based chalcogenides are highly nonlinear compared to Silica, in which long range order is possible and is normally used for the study of PC multilayer as a high dielectric layer.

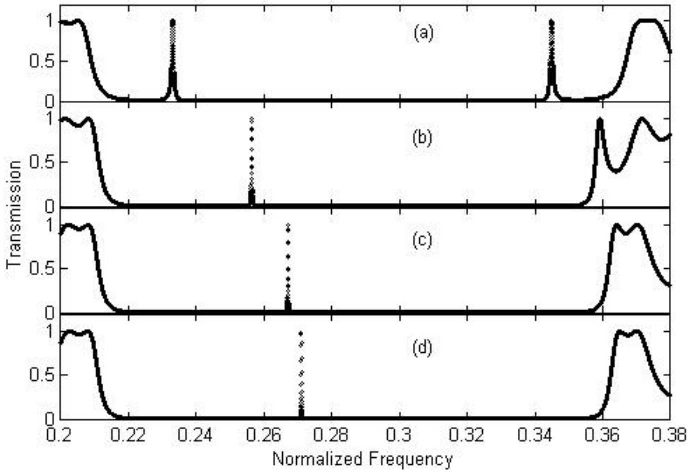

Fig. 5. Transmission spectra of 1-D chalcogenide photonic crystal for d_D=a (a) for M=0, (b) for M=2, (c) for M=4 and (d) for M=6.

Next, taking the slab thickness d_D = a as a case, we first consider the transmission spectra while d_D is divided equally into 2M+1 parts by alternatively stacked A/B films. Apparently, in the case of the fixed slab thickness d_D, the bigger the M, the narrower the thickness of A and B films. Results of transmission spectra with M = 2, 4, 6 (corresponding to $d_A = d_B = a/5$, $a/9$, $a/13$ for $d_D = a$) are shown in Figs. 5(b)–(d). It is clearly observed that the different confined states can be obtained by changing the film thicknesses. With the number M changing, the confined states shift to higher frequencies with the increase in number M. The variation of normalized frequency as a function of M of defect layer material is shown in Fig.6. The confined state shifts to higher frequency values with increasing M upto certain value and remains unchanged after that. Therefore, the values of M give noticeable effect only for small value.

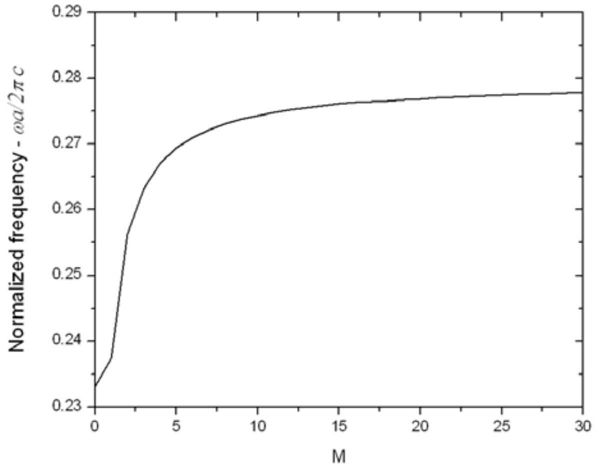

Fig. 6. The variation of Normalized frequecy of the localized defect mode in PBG with M.

The variation of transmission with M values can be understood in the following way. Considering the refractive index of A film as standard, the effective refractive index of defect slab is reduced by introducing the B film. Up to a certain limit, the increase in the number of B films induces a decrease in the effective refractive index, leading the frequencies to shift towards higher-frequency regions. It provides an opportunity for increasing the optical confined states. Therefore, the lower values of M are sufficient to understand the shifting of localized defect mode in PBG region. It provides opportunity to control the optical confined modes finely. This can be thought of as 'fine' tuning of transmission spectra. Therefore, the defect layer in PBG crystal works as a single wavelength waveguide for a particular number of wavelengths and correspond to fine tuning of the spectra [18]. The defect mode works as a guided mode for waveguide application in narrow band region. This is extremely useful as a filter device [11]. The frequency interval between adjacent confined states can be filled finely and regularly by other confined states. Thus, confined states in a certain frequency region can be increased in a multiple quantity.

The process of adding slab thickness which gives rise to coarse tuning of the material to input signal can be coupled with the concentration modification introduced by changing M values can be used to fine tune the spectra. This results in the reduction of frequency interval, so that spectral density is reduced and spectral efficiency is increased substantially.

4. Conclusions

In the present work, 1D Photonic Quantum well structure with alternatively stacked dielectric–dielectric material films for constituting a slab have been suggested. It is found that the frequency of confined states can be tuned finely by properly adjusting film thickness with the fixed slab thickness in the case of a small refractive index contrast. The structures of 1D PCs gives better results using chalcogenides compared to the other conventional materials. In this case, the spectra efficiency can be optimized without increasing the volume of the device. The work can be useful for improving the optical communication systems and establishing chalcogenides as suitable materials in competition with other materials.

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