Chalcogenide Letters Vol. 6, No. 11, November 2009, p. 623 – 627

# TUNING THE LOCALIZED MODE IN POINT DEFECT CHALCOGENIDE PHOTONIC CRYSTAL

B. SUTHAR* , A.K. NAGAR, A. BHARGAVA
*Nanophysics Laboratory, Department of Physics, Govt. Dungar College, Bikaner-334001 India.*

The photonic band structure has been investigated in 2D chalcogenide photonic crystal of $As_2S_3$ rods in air medium for square lattice structure. The localized mode is generated in photonic bandgap region due to point defect in regular crystal. The localized defect mode can be tuned with the size of the defect rod in photonic crystal. It is shown that the normalized frequency shifts to lower values with increasing selenium concentration of the defect layer. The spectral efficiency can be increased without increasing the total volume of the optical devices.

(Received November 23, 2009; accepted November 30, 2009)

*Keywords:* Localized mode, Chalcogenide photonic crystal, photonic bandgap etc.

## 1. Introduction

Photonic crystals (PCs) attracted much scientific interest in the last decade due to their electromagnetic properties and their potential applications as optical limiter and switch, optical diode etc. [1, 2]. The reason to form a photonic band gap (PBG) is the inference of Bragg scattering in a periodic dielectric structure. When the periodicity is broken by introducing a defect into a PC, a localized defect mode will appear inside the PBG due to change of the interference behavior of light. The defect modes lead to the selective propagation in the 2D PCs and they can be utilized as filters and splitters [3]. Therefore, the study of the properties of defect modes in PCs is one of the most attractive subjects since photons can be localized [4, 5]. To achieve suitable defect modes, there are great efforts to obtain tunability of the position and intensity of the defect modes.

Mostly, Photonic Crystals have been made from Si or III–V semiconductors. While their active functions have typically exploited thermal or free-carrier nonlinear effects, both of which are relatively slow [6]. Chalcogenides have generated great deal of interest 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 Si). Therefore, the chalcogenide glass PC platform appears to be a promising architecture for confining and guiding light [7]. In this paper, we have presented the results obtained by introducing a point defect of $As_{40}S_{60-x}Se_x$ in the symmetrical $As_2S_3$/air two dimensional photonic crystals and analyzing the frequencies of localized modes which can be tuned properly.

## 2. Theoretical method

The structural configuration used in this work for chalcogenide photonic crystal as a square lattice of dielectric rods of $As_2S_3$ in air medium with lattice constant *a* and radius *r*, illustrated in Fig. 1. We consider a basic structure with $r = 0.2a$ as radius of $As_2S_3$ rods while $a =$

*Corresponding author: bhuvneshwer@gmail.com

1500 nm as lattice constant. The Chalcogenide PC has a PBG in the frequency range of 0.387–0.466 (in unit: *ωa/2πc*) for TM-like mode as shown in Fig. 1. The point defect is introduced by reducing the rods radius of a center rod of 5x5 supercell containing 25 $As_2S_3$ rods in air. In the study we modify the structure by tuning the radius of defect rod ($r_0$). The dispersion relation of the point defect chalcogenide photonic crystal is calculated by well known the plane wave expansion method with supercell [8], [9]. In the PBG, there is a single localized mode. Fig. 2 shows the typical band diagram of 2D simulation results, the normalized dispersion relations are found for wavevectors *k* [10]. As seen, the point defect chalcogenide photonic crystal supports one localized mode in the PBG.

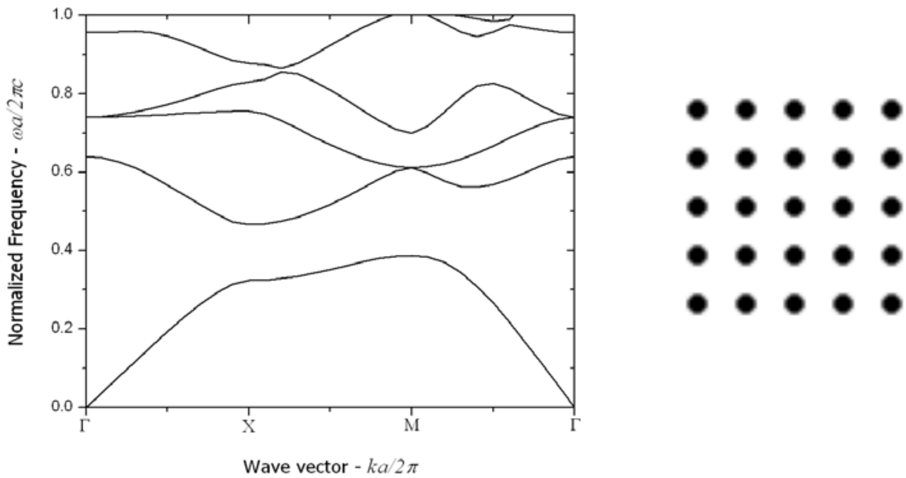



*Fig. 1. Photonic band diagram of 2-D Chalcogenide Photonic crystal of $As_2S_3$ rods in air.*

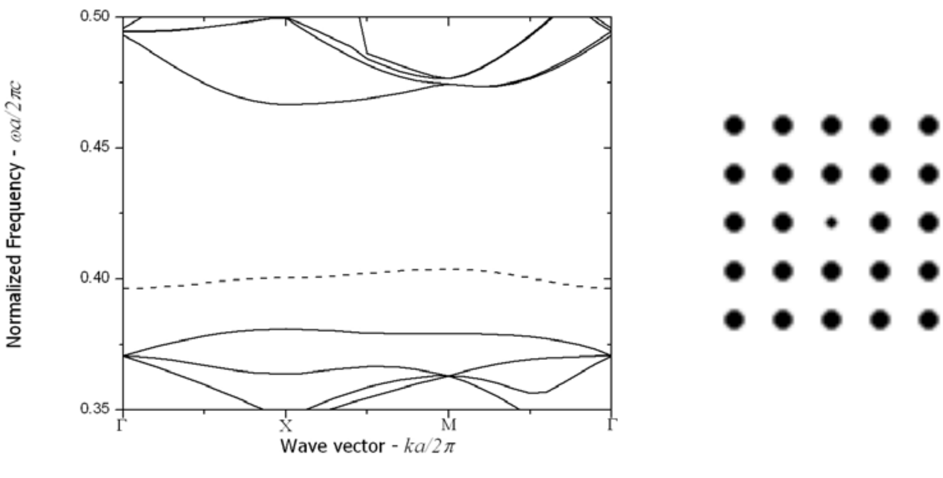



*Fig. 2. Photonic band diagram of 2-D Chalcogenide Photonic crystal of $As_2S_3$ rods in air with point defect ($r_0$=0.1a), in which the dotted line shows the localized defect mode in PBG.*

## 3. Results and discussion

The Band structure diagram for point defect Chalcogenide photonic crystal is described in previous section. The point defect introduces a localized mode in PBG region, which is almost flat. So, this doesn't cause direct transmission of light through crystal. But the regular presence of point defect in crystal allows propagation through these channels of point defect. The localize mode can be tuned with the size of the defect rods ($r_0$), which is shown in Fig. 3.

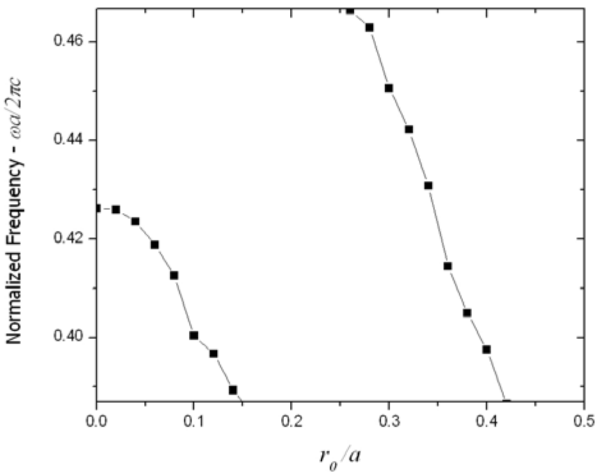



*Fig. 3 The normalized frequency of localized mode of 2-D chalcogenide photonic crystal with point defect as size of the defect rod.*

The break in periodicity causes the defect which may permit localized modes to exist, with frequency inside the PBG. As the mode has a frequency in the PBG, then it must exponentially decay once it enters the crystal. The frequency of defect mode can be controlled by changing either size of the defect rod or refractive index of the defect rod [11, 12]. In such case, we anticipate that the localized state corresponding to the defect mode are spread out so as to allow fields to be concentrated more and more in the high-ε defect layer. The localized state thus generated cause the shifting of frequency to lower values, as has been displayed. Thus, photonic single quantum well (QW) structures are constructed owing to quantum confinement effects. Here, the point defect rod $r_0$ can be regarded as a well.

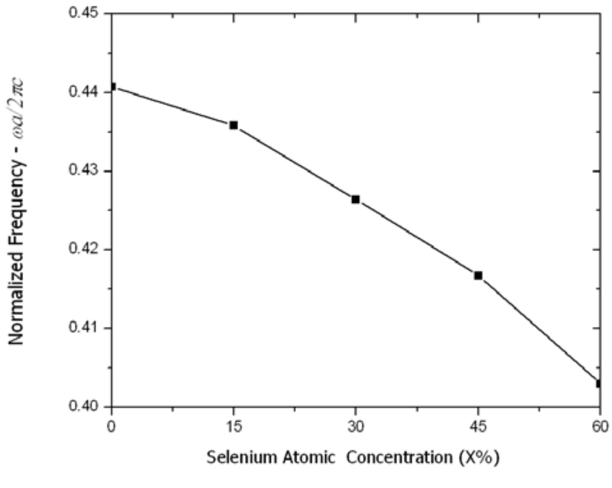
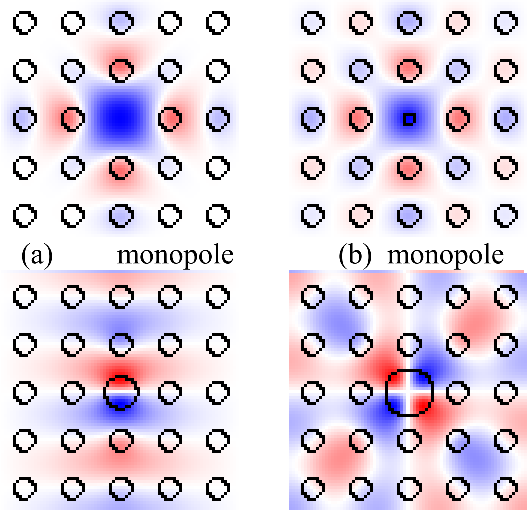



*Fig. 4. The variation in Normalized frequency of localized mode with Selenium atomic concentration in defect rod $As_{40}S_{60-x}Se_x$.*

The variation of normalized frequency as a function of selenium atomic concentration of defect material is shown in Fig.4. The localized mode shifts to lower values with increasing selenium atomic concentration similar as investigated for one dimensional photonic crystal previously [12]. 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 [7].

The change in the constituent atom results in the reflection from the multilayers of periodic rods. The amorphous chalcogenides are known to have localized states present during their fabrication [13]. This allowed 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 [14]. Arsenic based chalcogenides are highly nonlinear compared to Si, in which long range order is possible and is normally used for the study of PC multilayer as a high dielectric layer.



(a) monopole (b) monopole

(b) dipole (d) quadrupole

(c)

*Fig. 5. The field distribution of localized mode in point defect chalcogenide photonic crystal of r=0.2a, (a) $r_0$=0.0a, (b) $r_0$=0.1a, (c) $r_0$=0.33a and (d) $r_0$=0.5a.*

As the defect involves removal of dielectric (as in the case of vacancy or $r_0$=0.0$a$) then the localized mode evolves from the dielectric band and can be made to sweep across the gap by adjusting the amount of dielectric removed. In such case, only one localized mode is corresponding to monopole structure of field distribution. While the defect involves the addition dielectric (as increase the $r_0$ by $r$) then the localized mode drops from the air band into PBG. In this case, the dielectric defect increases the number of defect localized mode also increases. This causes the dipole and quadrupole structure of electric field distribution due to two and four localized modes in PBG. The very specific symmetry associated with each photon mode translates into an orbital angular momentum for each photon mode which can exist in addition to its intrinsic spin angular momentum. The flexibility in tuning the symmetry, frequency and localization propagation of defects makes photonic crystals a very attractive medium for the design of novel types of filters, couplers, lasers, light-emitting diodes (LEDs).

## 4. Conclusions

In the present work, it is found that propagation of 2D chalcogenide photonic crystal of square lattice structures can be modified by changing the point defect rod as well as concentration of defect rod's material. The structures of 2D PCs gives better results using chalcogenides compared to the other conventional materials. Localized States generated within the PBG can be tuned by changing the defect rod features in chalcogenide/air square lattice photonic crystal. The spectral efficiency can be increased without increasing the total volume of the devices. The work can be useful for improving the optical communication systems and establishing chalcogenides as suitable materials with regards to other materials.

**Acknowledgement**

One of us (B. Suthar) is thankful to CSIR, New Delhi for financial support in form of a fellowship.

## References

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[2] S. John, Phys. Rev. Lett. **58**, 2486 (1987).
[3] Z.M. Jiang, B. Shi, D.T. Zhao, J. Liu, X. Wang, Appl. Phys. Lett. **79**, 3395 (2001).
[4] R. Ozaki, T. Matsui, M. Ozaki, K. Yoshino, Appl. Phys. Lett. **82**, 3593 (2003).
[5] G. Q. Liang, J.W. Dong, H.Z. Wang, Phys. Rev. E **71**, 066610 (2005).
[6] T. Tanabe, M. Notomi, S.Mitsugi, A. Shinya, E. Kuramochi, Appl. Phys. Lett. **87**(15), 151112 (2005).
[7] D. Freeman, C. Grillet, M.W. Lee, C.L.C. Smith, Y. Ruan, A. Rode, M. Krolikowska, S.T. Hanic, C.M. S.terke, M.J. Steel, B.L. Davies, S. Madden, D.J. Moss, Y.H. Lee and B.J. Eggleton, Photonics and Nanostructures: Fundamentals and Applications **6**, 3 (2008).
[8] S.G. Johnson, J.D. Joannopoulos, Opt. Express, **8**, 173 (2001).
[9] S. Guo, S. Albin, Opt. Express, **11**, 1080 (2003).
[10] S.G. Johnson, Shanhui Fan, P.R. Villeneuve, J.D. Joannopoulos, Phys. Rev. B **60**, 5751 (1999).
[11] J.D. Joannopoulos, R.D. Meade and J.N. Winn, Photonic Crystals: Molding of Flow of Light, Princeton University Press, Princeton (1995).
[12] A. Bhargava and B. Suthar, Chalcogenide Lett. **6(10)**, 529 (2009).
[13] R. Zallen, The Physics of Amorphous Solids, John Wiley & Sons, Toronto (1983).
[14] J.S. Sanghera, C.M. Flora, L.M. Shaw, P. Pureza, V.Q. Nguyen, M. Bashkansky, Z. Dutton, J.D. Aggarwal, J. Non-Cryst. Solids, **354**, 462 (2008).