

Thermal Tuning of Defect Modes in Si-based One-dimensional Photonic Crystal with a Defect

J.V. Malik, Vipin Kumar, Arun Kumar, T.P. Singh, Kh.S. Singh

Abstract—Thermal tuning of defect modes in one-dimensional photonic crystal structure has been studied. We consider a Si/air multilayer system. Also we consider the refractive index of Si layer to be dependent on temperature and wavelength simultaneously. As the refractive index of Si layer is a function of temperature of medium as well as the wavelength of incident light, this results to the tuning of defect modes. As defect modes are function of temperature, one can tune the defect modes to desired wavelength. It is found that the average change in central wavelength of defect modes is 0.0375 $\mu\text{m}/100\text{K}$. This type of tunable filter may be used as thermal sensing optical device etc.

Index Terms— Defects, Optical Properties, Photonic band-gap materials, Transfer Matrix Method etc.

I. INTRODUCTION

During the last two and a half decades, Photonic crystals (PCs), in particular, photonic band gap (PBG) materials have become area of interest of considerable number of researchers leading to various potential applications of photonic crystal based devices [1-4]. The main attraction of PBGs is the existence of forbidden band gaps in their transmission spectra. Band gaps in a PC are analogous to the electronic band gap in a solid as there is a similarity between the structural periodicity of a PC and the periodic potential energy in a solid. Of the various applications of PCs, some of important applications are tunable optical filters, monochromators, optical switches, resonance cavities, omni-directional reflectors, DWDM applications, superluminal propagations, negative refraction, temperature sensors and waveguides [5-16]. Recently, many studies have been focusing on changing the parameters in a PC to fabricate devices with modulation capability. For example, a slight change of the dielectric constant can be applied to optical switching devices [17].

In addition to the existence of wide band gaps in some properly designed PCs, the feature of a tenability of PBGs in PCs attracts the attention of investigators in recent years. PBGs can be tuned by means of some external agents. For instance, it can be changed by the operating temperature and we call it T-tuning. A superconductor/dielectric PC belongs to this type because of the temperature and we call it the T-tuning. This happens because of the temperature-dependent London perturbation length in the superconducting materials [18-20]. Using a liquid crystal as one of the constituents in a PC, the T-tuning optical response

is also obtainable [21]. Recently, PCs containing semiconductor as one of the constituents have also been investigated by many researchers. PCs with intrinsic semiconductor belong to T-tuning devices because the dielectric constant of an intrinsic semiconductor is strongly dependent on temperature [22].

The idea of doped PCs comes from the analogy between electromagnetism and solid state physics, which lead to the study of band structures of periodic materials and further to the possibility of the occurrence of localized modes in the band gap when a defect is introduced in the lattice. These defect-enhanced structures are called doped photonic crystals and present some resonant transmittance peaks in the band gap corresponding to the occurrence of the localized states [23], due to the change of the interference behavior of the incident waves. The defect can be introduced into perfect PCs by changing the thickness of a layer [24], inserting another dielectric into the structure [25–27], or removing a layer from it [28].

The introduction of the defect states within PCs has been perceived as a new dimension in the study of photonic crystals, especially in 2D and 3D PCs due to numerous possible applications that can be achieved by using them. In 2D or 3D PCs, it has been also known that a point defect can act as a micro cavity, a line defect like a waveguide, and a planar defect like a perfect mirror [29]. Similar to 2D or 3D PCs, the introduction of the defect layers in 1D PCs can also create localized defect modes within the PBGs. Due to the simplicity in 1D PCs fabrications over 2D and 3D, the defect mode can be easily introduced within 1D PCs for various applications such as in the designing of TE/TM filters and splitters [30], in the fabrication of lasers [31], and in light emitting diodes [32].

However, earlier reports on the defect modes were mainly based on the linear variation of refractive index with temperature and non-dispersive media. In the present communication, we consider semiconductor media as one of the constituents of a one dimensional photonic crystal, since the dielectric property of semiconductors depends not only on temperature but also on wavelength. Here we consider the Si/air multilayer system with Si layer defect in the middle. In this communication, thermal tuning of defect modes in one-dimensional crystal structure has been studied. The refractive index of air is independent of temperature and wavelength. But the refractive index of silicon layer is taken as a function of temperature and wavelength both [22]. Therefore, this study may be considered to be more physically

realistic.

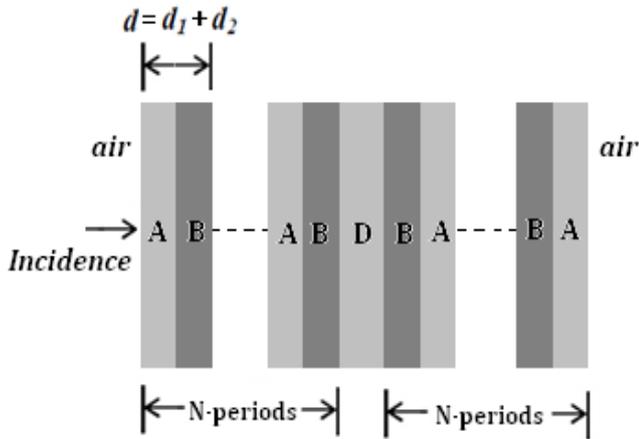


Fig. 1. Schematic Diagram of 1-D Photonic Crystal with Defect

II. THEORETICAL MODEL

The schematic representation of one-dimensional photonic crystal with defect is represented in Figure 1. We consider $\text{air}/(\text{AB})^N \text{D} (\text{BA})^N / \text{air}$, in which A and B represents the high and low refractive index materials, and D is the defect layer. To compute the defect mode in the transmission spectrum, we employ the transfer matrix method (TMM) [33, 34]. In this method, the transfer matrix for each layer can be written as

$$M_j = D_j P_j D_j^{-1}; \quad (1)$$

for TE mode of polarization

$$D_j = \begin{pmatrix} 1 & 1 \\ n_j \cos \theta_j & -n_j \cos \theta_j \end{pmatrix} \quad (2)$$

and for TM mode of polarization

$$D_j = \begin{pmatrix} \cos \theta_j & \cos \theta_j \\ n_j & -n_j \end{pmatrix} \quad (3)$$

Also, the propagation matrix P_j can be defined as

$$P_j = \begin{pmatrix} e^{i\delta_j} & 0 \\ 0 & e^{-i\delta_j} \end{pmatrix} \quad (4)$$

where the phase is written as

$$\delta_j = \frac{2\pi d_j}{\lambda} n_j \cos \theta_j \quad (5)$$

The transfer matrix, for the structure embedded in air, $\text{air}/(\text{AB})^N \text{D} (\text{BA})^N / \text{air}$ can be written as

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} (M_A M_B)^N M_D (M_A M_B)^N D_0 \quad (6)$$

Where, D_0 is called the dynamical matrix for air.

The transmittance (T) and reflectance (R) can be calculated by using the matrix elements M_{11} and M_{21} given in equation (6) as follows

$$T = \left| \frac{1}{M_{11}} \right|^2 \quad \text{and} \quad R = \left| \frac{M_{21}}{M_{11}} \right|^2 \quad (7)$$

In the next section, we will compute the transmission spectra by using equation (7) of photonic crystal with defect as shown in Figure 1.

III. RESULTS AND DISCUSSION

In this section, we have presented the transmission spectra for defect modes in one dimensional photonic crystal with defect. We choose Si for the materials A and D, air for material B and $N=5$ in Figure 1. So, the proposed structure will be $[(\text{Si}/\text{air})^5 \text{Si} (\text{air}/\text{Si})^5]$. We take silicon and air as the high and the low refractive index materials respectively and an additional silicon layer (D) as the defect layer. The geometrical parameters are so chosen that the thicknesses of high and low refractive index materials are same at 300K temperature i.e. $d_1 = d_2 = 1700\text{nm}$ and the thickness of defect layer is taken 1300nm. The layer of Si will be expanding with the increase in temperature in the following manner;

$$d_1(T) = d_1 + \alpha d_1 \Delta T \quad (8)$$

Where α is the thermal expansion coefficient for silicon layer and taken to be $2.6 \times 10^{-6}/\text{K}$ [35]. We consider there will not be any expansion in air with temperature. Because the structure embedded in the air, therefore the corresponding expansion in Si layer will lead to the contraction in the layers of air. The contraction in air corresponding to the expansion in Si layer will be in the following manner;

$$d_2(T) = d_2 - \alpha d_1 \Delta T \quad (9)$$

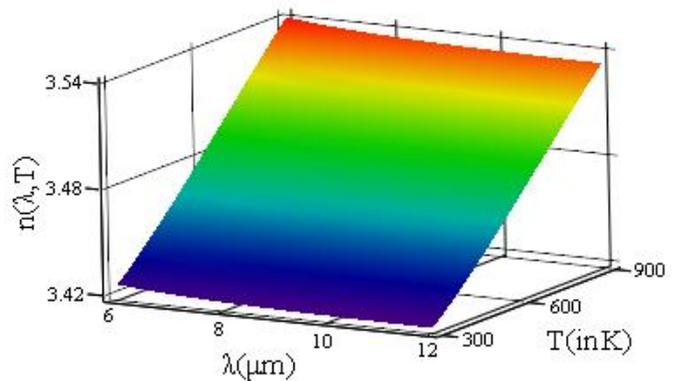


Fig. 2. Variation of Refractive Index as a Function of Wavelength and Temperature

The refractive index of air is independent of temperature and wavelength. But the refractive index of silicon layer is taken as a function of both wavelength and temperature. The refractive index of Silicon (Si) in the ranges 1.2 to 14 μm and 20-1600K is represented as [22]

$$n^2(\lambda, T) = \varepsilon(T) + \frac{e^{-3\Delta L(T)/L_{293}}}{\lambda^2}$$

$$(0.8948 + 4.3977 \times 10^{-4} T + 7.3835 \times 10^{-8} T^2)$$

(10)

Where

$$\varepsilon(T) = 11.4445 + 2.7739 \times 10^{-4} T +$$

$$1.7050 \times 10^{-6} T^2 - 8.1347 \times 10^{-10} T^3$$

and

$$\frac{\Delta L(T)}{L_{293}} = -0.071 + 1.887 \times 10^{-6} T + \text{for } 293\text{K} \leq T \leq 1600\text{K}$$

$$1.934 \times 10^{-9} T^2 - 4.554 \times 10^{-13} T^3$$

$$\frac{\Delta L(T)}{L_{293}} = -0.021 - 4.149 \times 10^{-7} T - \text{for } 20\text{K} \leq T \leq 293\text{K}$$

$$4.620 \times 10^{-10} T^2 + 1.482 \times 10^{-11} T^3$$

The plot of the refractive index as the function of wavelength and temperature is shown in Figure 2. From Figure 2, it is clear that the refractive index of silicon layer increases with the increase in wavelength and temperature both. Therefore the refractive index contrast increases with wavelength and temperature.

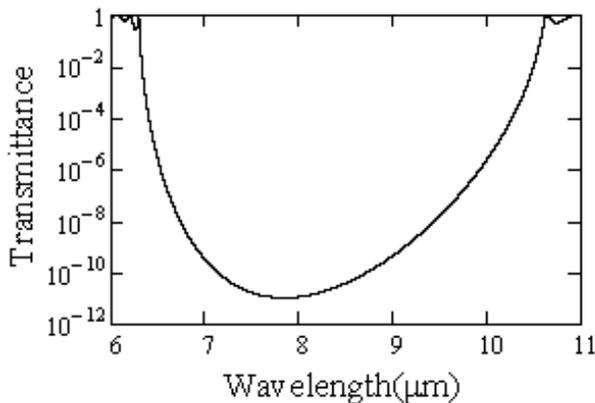


Fig. 3. Transmittance for an ideal PC of (Si/air)¹⁰ at 300K temperature.

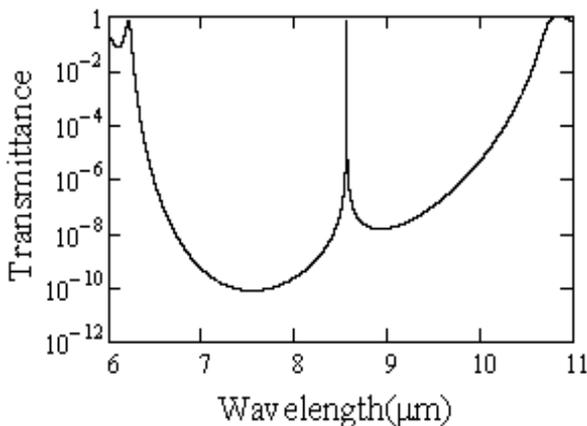


Fig. 4. The defect mode for a PC with defect of [(Si/air)⁵Si(air/Si)⁵] at 300K temperature.

The transmittance spectra of the ideal PC (Si/air)¹⁰ at 300K temperature are shown in figure 3. Our study is restricted to the case of normal incidence only. Our purpose is to produce the defect mode in these spectra, which can be tuned by the variation of temperature. The transmittance spectra of the defect PC [(Si/air)⁵Si(air/Si)⁵] at 300K temperature are shown in figure 4. Due to the Si defect layer, a defect mode is created at 8.557 μm wavelength. This defect mode can be tuned by variation in temperature.

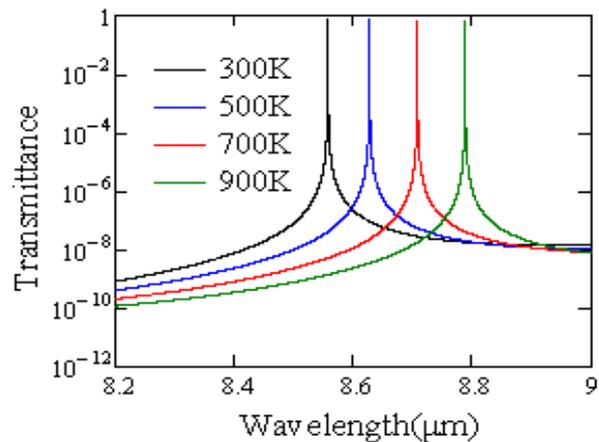
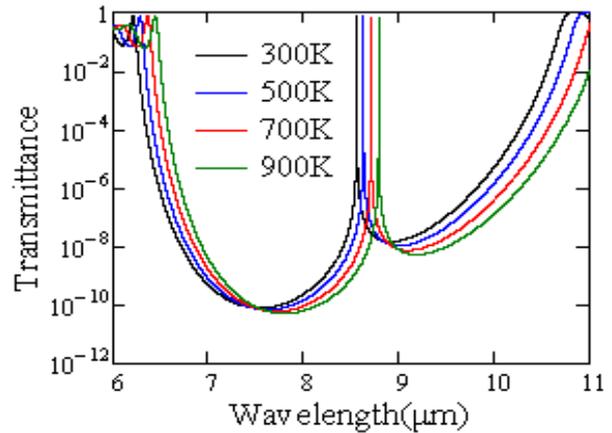


Fig. 5. The defect mode for a PC with defect of [(Si/air)⁵Si(air/Si)⁵] at 300K temperature.

TABLE I. CENTRAL WAVELENGTH OF DEFECT MODES AT VARIOUS TEMPERATURES

Temperature(in K)	Central wavelength of defect modes (μm)
300	8.557
500	8.632
700	8.707
900	8.783

The transmittance spectra of the defect structure at various temperatures, is shown in Figure 5 and the corresponding data tabulated in table 1. From figure 5 and Table 1, it is clear that the transmission peaks are centered at 8.557 μm,

8.632 μm , 8.707 μm and 8.783 μm corresponding to temperatures at 300K, 500K, 700K and 900K respectively. Therefore, as we increase the temperature, the defect mode of transmission shifts towards the higher wavelength region. The dependence of defect modes on temperature is due to the two factors. First one is the thermal expansion of Si layer and second one due to the dependency of refractive index on temperature as given in equation (8). The shifting behavior can be explained by using the phase equation (5). According to this phase equation as $n(\lambda, T)$ increase with temperature, the wavelength must increase accordingly to keep the phase δ unchanged. Correspondingly the value of wavelength must be increased. The variation of central wavelength of defect modes with temperature is shown in Figure 6. It is found that the central wavelength of defect modes changes approximately linearly with temperature. So, we can use the proposed structure as temperature sensing device, narrow band optical filter, etc. From the figure 6 and Table 1, it is clearly seen that the defect mode peak shifts towards the higher wavelength region. Also, it is clear that the average change in wavelength of defect modes is 0.0375 $\mu\text{m}/100\text{K}$.

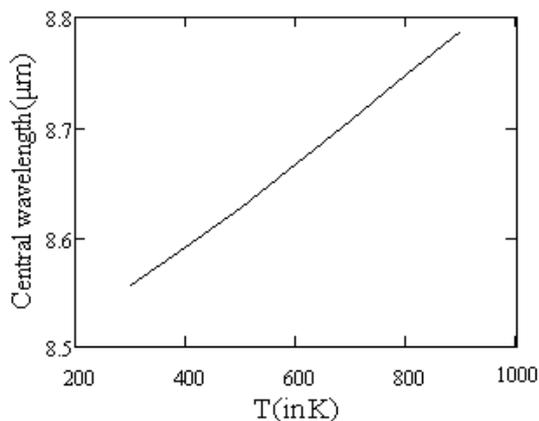


Fig. 6. The Variation Of Central Wavelength Of Defect Modes Temperature

IV. CONCLUSION

Effect of the temperature on the defect mode in transmission spectra has been investigated. The refractive index of silicon layers is taken as a function of temperature and wavelength both. Therefore, this study may be considered to be more physically realistic than other previous works. Also, it may be useful for computing the optical properties for wider range of wavelength as well as temperature. We can use the proposed structure as temperature sensing device, narrow band optical filter and in many optical systems.

ACKNOWLEDGMENT

Our sincere thanks to Prof. S.P. Ojha and Dr. B. Suthar for their support in many aspects while making this research paper.

REFERENCES

- [1] E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics," *Phys. Rev. Lett.* Vol. 58, pp. 2059-2062, May 1987.
- [2] S. John, "Strong localization of photons in certain disordered dielectric super lattices," *Phys. Rev. Lett.* Vol. 58, 2486-2489, Jun. 1987.
- [3] J. D. Joannopoulos, R. D. Meade and J. N. Winn, *Photonic Crystals*, Princeton University Press, Princeton, 1995.
- [4] C. M. Soukoulis, *Photonic Band Gap Materials*, NATO ASI, Kluwer Academic Publishers, Dordrecht, 1986.
- [5] X. Gu, X.F. Chen, Y.P. Chen, X.L. Zheng, Y.X. Xia, Y.L. Chen, "Narrowband multiple wavelengths filter in a periodic optical super lattice", *Opt. Commun.* Vol. 237, pp. 53-58, Jul. 2004.
- [6] A. Kumar, B. Suthar, V. Kumar, A. Bhargava, Kh.S. Singh and S.P. Ojha, "Design of a thermally tunable filter using Si-based one-dimensional photonic crystals", *Optic (In Press) DIO*: <http://dx.doi.org/10.1016/j.ijleo.2012.08.030>
- [7] V. Kumar, Kh. S. Singh and S. P. Ojha, "A simple design of a monochromator by cascading photonic band-gap filters", *International Journal of Microwave and Optical Technology* Vol. 5(3), pp. 162-165, 2010.
- [8] S.W. Leonard, H. Van Driel, J. Schilling and R.B. Wehrspohn, "Ultra fast band-edge tuning of a two-dimensional silicon photonic crystal via free-carrier injection", *Phys. Rev. B* Vol. 66, 161102(R) pp. 1-4, Oct. 2002.
- [9] B. Li, J. Zhou, L. Li, X.J. Wang, X.H. Liu and J. Zi, "Ferroelectric inverse opals with electrically tunable photonic band gap", *Appl. Phys. Lett.* Vol. 83, pp. 4704-4706, Dec. 2003.
- [10] S.-Y. Lin, E. Chow, V. Hietala, P.R. Villeneuve and J.D. Joannopoulos, "Experimental Demonstration of Guiding and Bending of Electromagnetic Waves in a Photonic Crystal", *Science* Vol. 282, pp. 274-276, Oct.1998.
- [11] V. Kumar, Kh. S. Singh, S. K. Singh and S. P. Ojha, "Broadening of omni directional photonic band gap in Si-based one-dimensional photonic crystals", *Progress in Electromagnetic Research M* Vol. 14, pp. 101-111, 2010.
- [12] B. Suthar, V. Kumar, Kh. S. Singh and A. Bhargava, "Tuning of photonic band gaps in one-dimensional chalcogenide based photonic crystal", *Optics Communications (Elsevier)* Vol. 285, pp. 1505-1509, 2012.
- [13] A. Kumar, B. Suthar, V. Kumar, Kh. S. Singh and A. Bhargava, "Tunable wavelength demultiplexer for DWDM application using 1-D photonic crystal", *Progress in Electromagnetic Research Letters* Vol. 33, pp. 27-35, 2012.
- [14] V. Kumar, Kh. S. Singh and S. P. Ojha, "Band structure, reflection properties and abnormal behavior of one-dimensional plasma photonic crystals", *Progress in Electromagnetic Research M* Vol. 9, pp. 227-241, 2009.
- [15] V. Kumar, Kh. S. Singh and S. P. Ojha, "A simple design of a monochromator by cascading photonic band-gap filters",

International Journal of Microwave and Optical Technology
Vol. 5(3), pp. 162-165, 2010.

- [16] A. Kumar, V. Kumar, B. Suthar, A. Bhargava, Kh. S. Singh and S. P. Ojha, "Wide range temperature sensor based on one dimensional photonic crystal with a single defect", International Journal of Microwave Science and Technology, Vol. 2012, Article ID 182793, 5 pages, doi:10.1155/2012/182793.
- [17] X. Wang, K. Kempa, Z.F. Ren, B. Kimball, "Rapid photon flux switching in two-dimensional photonic crystals", Appl. Phys. Lett. Vol. 84, pp. 1817-1819, Mar. 2004.
- [18] O. L. Bermann, Y. E. Lozovik, S. L. Eiderman, R. D. Coalson, "Superconducting photonic crystals: Numerical calculations of the band structure", Phys. Rev. B Vol. 74, pp. 092505 1-3, Sep. 2006.
- [19] H. Takeda and K. Yoshino, "Tunable photonic band schemes in two-dimensional photonic crystals composed of copper oxide high-temperature superconductors", Phys. Rev. B Vol. 67, pp. 245109 1-6, Jun. 2005.
- [20] W.-H. Lin, C.-J. Wu, T.-J. Yang, S.-J. Chang, Optics Express 18, (2010) 27155.
- [21] P. Halevi, J. A. Reyes-Avendano, J. A. Reyes-Cervantes, "Electrically tuned phase transition and band structure in a liquid-crystal-infilled photonic crystal", Phys. Rev. E Vol. 73, pp. 040701(R) 1-4, Apr. 2006.
- [22] H. H. Li, "Refractive Index of Silicon and Germanium and Its Wavelength and Temperature Derivatives", J. Phys. Chem., Ref. Data Vol. 9 No. 3, pp. 561-658, 1980.
- [23] G. Guida, A. de Lustrac, A. Priou, Prog. Electromagnet. Res. PIER 41 (2003) 1.
- [24] G. Baedeker, C. Henkel, Opt. Express 11 (2003) 1590.
- [25] G.J. Schneider, G.H. Watson, "Nonlinear optical spectroscopy in one-dimensional photonic crystals", Appl. Phys. Lett. Vol. 83, pp. 5350-5352, Dec. 2003.
- [26] H. Inouye, M. Arakawa, J.Y. Ye, T. Hattori, H. Nakatsuka, IEEE J. Quantum Electron. 38 (2002) 867.
- [27] J.A. Monsoriu, C.J. Zapata-Rodriguez, E. Silvestre, W.D. Furlan, Opt. Commun. 252 (2005) 46.
- [28] D.R. Smith, R. Dalichaouch, N. Kroll, S. Schultz, S.L. McCall, P.M. Platzman, J. Opt. Soc. Am. B 10 (1993) 314.
- [29] H.Y. Lee, T. Yao, J. Appl. Phys. 93 (2003) 819.
- [30] Z.M. Jiang, B. Shi, D.T. Zhao, J. Liu, and, X. Wang, "Silicon-based photonic crystal heterostructure", Appl. Phys. Lett. Vol. 79 pp. 3395-3397 Nov. 2001.
- [31] W.D. Zhou, J. Sabarinathan, P. Bhattacharya, B. Kochman, E.W. Berg, P.C. Yu, S.W. Pang, IEEE J. Quantum Electron. 37 (2001) 1153.
- [32] M. W. Feise, I. V. Shadrivov and Y. S. Kivshar, "Bistable diode action in left-handed periodic structures", Phys. Rev. E Vol. 71, pp. 037602 1-4, Mar. 2005.
- [33] P. Yeh, Optical Waves in Layered Media, John Wiley and Sons, New York, 1988.
- [34] M. Born and E. Wolf, Principle of Optics, 4th edition, Pergamon, Oxford, 1970.
- [35] G. Gosh, Handbook of Thermo-Optic Coefficients of Optical Materials with Applications, Academic Press, San Diego, USA 1997.

AUTHOR BIOGRAPHY



Jaivardhan Malik was born on April 01, 1980, in Mohamadpur Raisingh, Uttar Pradesh, India. He received the B.Sc. degree in Science in 2000 and the M.Sc. degree in Physics in 2002 from the C.C.S. University, Meerut, India. He is registered as a research scholar in the C.C.S. University, Meerut, India. His research interests include Optoelectronics, Photonics, and Nonlinear Optics.



Vipin Kumar was born on July 10, 1980, in Sirsali, Uttar Pradesh, India. He received the B.Sc. degree in Science in 1999, the M.Sc. degree in Physics in 2001 and Ph.D. degree in the field of Photonics in 2012 from the C.C.S. University, Meerut, India. He qualified national-level examinations, namely, Graduate Aptitude Test in Engineering, National Eligibility Test and Joint Entrance Screening Test. He has fifteen published papers in national and international level journals. His research interests include Optoelectronics, Photonics, and Nonlinear Optics.



Arun Kumar was born in Kirthal, Baghpat, UP, India, in 1977. He received the degree of B.Sc. in 1996, M.Sc. (Physics) in 1999 from the C. C. S. University, Meerut, U. P., India and M. Tech. in Laser Science and its Applications in 2002 from Devi Ahilya Vishwavidyalaya, Indore, M.P., India. He received the Ph.D. degree in the field of Photonics in 2012 from the C.C.S. University, Meerut, India. He was the recipient of the research fellowship of CSIR-UGC. He was Lecturer in Department of Physics at the Banasthali University, Rajasthan, India from 2003 to 2006. He is currently Assistant Professor in Amity Institute of Telecom Technology and Management, Amity University, Noida, U. P., India. He has more than ten published papers in national and international level journals and conference proceedings. His research interests include linear and nonlinear photonic crystals. Mr. Kumar is a life member of Indian Laser Association.



T.P. Singh was born in Dhanora Silvernagar, India, in 1951. He received the degree of B.Sc. in 1969, M.Sc. (Physics) in 1971, M.Phil. (Physics) in 1978 and the Ph.D. degree in 1995 from the C.C.S. University, Meerut, India. He is currently Professor of Physics, J.V. College, Baraut, India. He has more than thirty published papers in national and international level journals and conference proceedings. His research interests include Photonic crystals, Solar cells and Quantum mechanical research.



Kh. Saratchandra Singh was born in Imphal, India, in 1966. He received the degree of B.Sc. in physics in 1988 from Manipur University, Imphl, M.Sc. (physics) in 1991 from B.H.U., Varanasi and the Ph.D. degree in the area of Fiber Optics in 1996 from the Institute of Technology, B.H.U., and Varanasi, India. He was the recipient of the research fellowship of CSIR-UGC, India during 1991-96. He was Assistant Professor of Physics at the Radha Govind Engineering College, Meerut from 1998 to 2001. He is currently Associate Professor of Physics, Digamber Jain (P.G.) College, Baraut, India. He has more than thirty published papers in national and international level journals and conference proceedings. His research interests include Fiber Optics, Chiro-waveguide, Photonics and Non-Linear Optics.