

Two Channel Thermally Tunable Band-Stop Filter for Wavelength Selective Switching Applications by Using 1D Ternary Superconductor Photonic Crystal

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Abstract By studying temperature-dependent dispersion characteristics and group velocity of 1D ternary photonic crystal (TPC) composed of dielectric-superconductor-dielectric materials, a thermally tunable band-stop filter which is capable of stopping unique wavelength channels without causing any interference amongst equally spaced wavelength channels of full width at half maximum of 1 nm each as per the requirement of wavelength division multiplexing standards adopted by the International Telecommunication Union specifying channel spacing in terms of frequency (wavelength) is suggested. The proposed structure can efficiently work as a two-channel wavelength selective switch for wavelength division multiplexing (WDM)-based all-optical networks. This study also gives theoretical insight to design some new kind of optical memories and tunable buffers which holds data temporary and have potential applications in modern communication systems.

Keywords Photonic crystal · Dispersion relation · Group velocity · Superconductor · Wavelength division multiplexing · Wavelength selective switching

1 Introduction

Over the past two and half decades, much research work has been devoted to the concept of photonic crystals (PCs), because of their novel important scientific and engineering applications [1, 2]. PCs are artificial materials with 1D, 2D, or 3D periodicity in which the index of refraction modulates between high and low index regions. These PCs are characterized by an unusual dispersion relation which might show a photonic band gap (PBG) analogous to electronic bands of semiconductor, i.e., a range of frequencies in which the propagation of light is not permitted. Optical buffers [3, 4], dielectric reflecting mirrors [5], low-loss waveguides [6], optical switches [7], optical multiplexers and demultiplexers [8], optical filters [9], and trapping of light [10] are some reported examples of photonic crystal based optical devices.

Conventional PCs have fixed PBG and can be used only in unique wavelength region. Thus, they have limited applications at normal incidence. For different PBG regions, different PCs have to be designed and fabricated in tune with the experimental requirement. This tunability, called the internal tunability [11–13] causes the necessity of having to have large number of PCs leading to enhanced cost of the system. A lot of attention has of late, been paid to the investigation of PCs with tunable PBG [11–17] that can function in a wide range of wavelengths by varying external parameters [14–17] and also on the manipulation of light propagation in PCs by external parameters, which enhance its application [18]. Although the external tunability can be achieved in all kinds of PCs by varying the

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angle of incidence of light, however, this procedure disturbs the system setting (condition of normal incidence) and limits the system performance because it is difficult to tune PBG swiftly at smaller angles. Moreover, at oblique incidence, polarization-dependent behavior of PBG must also be taken into account. These limitations can be overcome by tuning the PBG externally without disturbing the system settings. It is a well-established fact that if the constituent materials of PCs have electric permittivity and magnetic permeability dependent on external electric field or magnetic field or both, tuning of PBGs can be achieved by altering such fields externally. Though by this approach, the response to alter the PBGs is very fast, yet anisotropy is the major challenge which brings a lot of difficulties in fabrication. Recently, Kong et al. discussed the tunable feature of defect mode inside PBG in the wider frequency range by changing the external magnetic field without altering the structural parameters of the PC. Besides this, dielectric constant of some semiconductors [19, 20] and superconductors [21, 22] is temperature dependent. Therefore, PBGs of PCs composed of such materials can be tailored by changing the temperature externally. A superconductor is a novel advanced material with several unique properties, suggesting a diverse range of promising applications due to the possibility of tuning its equivalent refractive index which is dependent on the London penetration depth (λ_L) and external temperature of the SC material [22, 23].

During the last decade, a lot of interest has also been given to slow down the light [18]. Slow light pulses in atoms travelling with velocities of only 17 m/s at nanokelvin temperature were observed by Marangos et al. [24] and another idea was suggested by Heebner et al. to get ultra-slow group velocities of slowly moving optical solitons in ref. [25]. Kumar et al. [10] also studied theoretically how light (input radiation carrying information) can be trapped inside nonlinear PC by applying high intensity controlling wave perpendicular to the direction of propagation of signal wave, which affects the signal group velocity. Though the controlling wave generates some nonlinear effects, authors have tried to minimize it by applying high intensity controlling wave. However, at normal incidence, nonlinear PC requires a lot of input power to get tunable behavior of dispersion relation as well as group velocity. To overcome this issue, we are suggesting how dielectric material can be replaced by superconductor one to get a tunable behavior of PBG in PC composed of dielectric and superconductor materials by varying the temperature of superconductor, over conventional PCs at normal incidence.

In the present communication, we have proposed two channel thermally tunable band stop filter for wavelength selective switching (WSS) application in wavelength division multiplexing (WDM)-based all-optical networks by 1D ternary dielectric-superconductor-dielectric photonic

crystal (DSDPC). The temperature-dependent behavior of dispersion characteristics and group velocity of 1D DSDPC are investigated through transfer matrix method (TMM) [26, 27].

The structure of manuscript is organized as follows: The theoretical model is introduced in Section 2. Numerical results are presented and discussed in Section 3. Finally, conclusions are given in Section 4.

2 Theoretical Formulation

In order to study the electromagnetic (EM) wave propagation in 1D DSDPC composed of N alternate layers of dielectric, superconductor, and dielectric materials of thicknesses a, b , and c , respectively, as shown in Fig. 1, we consider 1D Maxwell wave equation for EM waves propagating along the x -axis at normal incidence as

$$\frac{d^2 E(x)}{dx^2} + k_0^2 \{n(x)\}^2 E(x) = 0 \tag{1}$$

where $k_0 = \omega/c$ is the wave vector, ω is the wave frequency, and c is the velocity of light in air. The refractive index profile $n(x)$ of 1D DSDPC is given by

$$n(x) = \begin{cases} n_1, & -c \leq x \leq 0 \\ n_2, & 0 \leq x \leq a, \\ n_3, & a \leq x \leq b \end{cases} \text{ with } n(x + md) = n(x) \tag{2}$$

where n_1, n_2 , and n_3 are the refractive indices of dielectric (SiO_2), superconductor ($\text{YBa}_2\text{Cu}_3\text{O}_7$) and dielectric (Te) materials respectively and $d = a + b + c$ is the period of 1D DSDPC with $m = \pm 1, \pm 2, \dots$. The London penetration depth and refractive index of superconductor material (n_2)

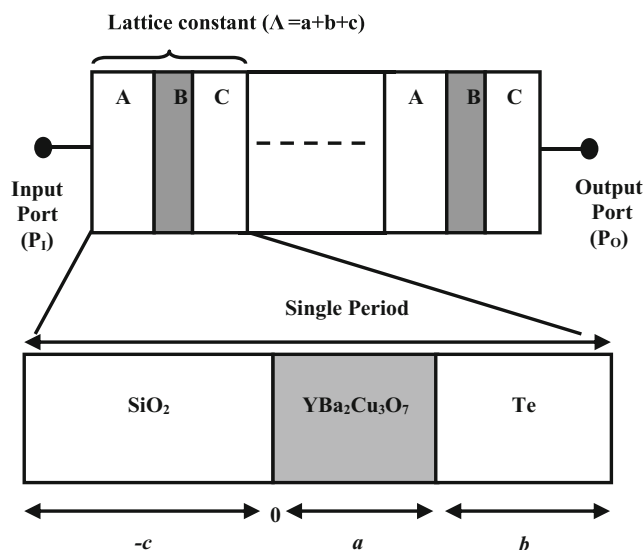


Fig. 1 Schematic of 1D ternary dielectric superconductor dielectric photonic crystal (top view). Magnified view showing period of the proposed structure

can be expressed as

$$\lambda_L(T) = \lambda_L(0) \left(1 - \left(\frac{T}{T_c}\right)^p\right)^{-\frac{1}{2}} \tag{3}$$

$$n_2 = \left(1 - \frac{c^2}{\omega^2(\lambda_L(T))^2}\right)^{1/2}, \tag{4}$$

respectively. Here, T and T_c are the external and transition temperatures of SC, respectively, $\lambda_L(T)$ and $\lambda_L(0)$ are the London penetration depths at temperatures T and zero, respectively. The exponent $p = 2$ for high-temperature superconductor and $p = 4$ for low-temperature superconductor.

For three different regions, (1) can be rewritten as

$$\frac{d^2 E(x)}{dx^2} + k_0^2 n_1^2 E(x) = 0, -c \leq x \leq 0 \tag{5}$$

$$\frac{d^2 E(x)}{dx^2} + k_0^2 n_2^2 E(x) = 0, 0 \leq x \leq a \tag{6}$$

$$\frac{d^2 E(x)}{dx^2} + k_0^2 n_3^2 E(x) = 0, a \leq x \leq b \tag{7}$$

The general solution of (5), (6) and (7) are given by

$$E(x) = \begin{cases} Ae^{ik_1x} + Be^{-ik_1x}, & -c \leq x \leq 0 \\ Ce^{ik_2x} + De^{-ik_2x}, & 0 \leq x \leq a \\ Fe^{ik_3x} + Ge^{-ik_3x}, & a \leq x \leq b \end{cases} \tag{8}$$

where $k_1(= \omega n_1/c)$, $k_2(= \omega n_2/c)$ and $k_3(= \omega n_3/c)$ are the wave vectors in three different regions and $A, B, C, D, F,$ and G are constants to be determined by imposing electrostatic boundary condition of electric field $E(x)$ and its derivative at interfaces and using transfer matrix method [26–29] the following matrix relation is obtained

$$\begin{pmatrix} a_{m-1} \\ b_{m-1} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} a_m \\ b_m \end{pmatrix} \tag{9}$$

where $m_{11}, m_{12}, m_{21},$ and m_{22} are the matrix elements of unit cell translation matrix that relates the complex amplitude of the incident wave a_{m-1} and the reflected wave b_{m-1} in one layer of a unit cell to those of the equivalent layer in the next unit cell. From Bloch-Floquet theorem [30], the dispersion relation for 1D DSDPC depicted in Fig. 1 is given by [27, 29]

$$\cos \{k(\omega)d\} = \frac{1}{2}(m_{11} + m_{22})$$

Here, $k(\omega)$ is known as frequency-dependent Bloch wave number and can be rewritten as

$$k(\omega) = \frac{1}{d} \cos^{-1} \left[\cos(k_1a) \cos(k_2b) \cos(k_3c) - \frac{1}{2} \left(\frac{k_3}{k_2} + \frac{k_2}{k_3}\right) \sin(k_1a) \cos(k_2b) \sin(k_3c) - \frac{1}{2} \left(\frac{k_1}{k_3} + \frac{k_3}{k_1}\right) \cos(k_1a) \sin(k_2b) \sin(k_3c) - \frac{1}{2} \left(\frac{k_1}{k_3} + \frac{k_3}{k_1}\right) \sin(k_1a) \sin(k_2b) \cos(k_3c) \right] \tag{10}$$

As suggested by Sakoda [28], the group velocity ($V_g(\omega)$) can be defined appropriately in the PCs as

$$V_g = \left(\frac{dk}{d\omega}\right)^{-1}, \tag{11}$$

3 Results and Discussion

We have studied the dispersion characteristics and group velocity of light at normal incidence in 1D DSDPC structure containing alternate layers of dielectric high-temperature superconductor and dielectric materials by varying the temperature of high-temperature superconductor. The dielectric materials are taken to be silica (SiO_2) and tellurium (Te) with refractive indices 1.5 and 4.6, respectively, in the region of investigation. The high-temperature superconductor is taken as $\text{YBa}_2\text{Cu}_3\text{O}_7$ with $\lambda_L(0) = 145$ nm and $T_c = 93$ K as reported in ref. [22]. We have chosen the thicknesses of layers $\text{SiO}_2(\text{Te})$ to be 850 (300) nm. The thickness of $\text{YBa}_2\text{Cu}_3\text{O}_7$ is selected as 50 nm in order to get a PBG in the near-infrared spectral region, ranging from 1347 to 1366 nm at temperature 0 K.

Now, we present the working principle of proposed two channel thermally tunable band stop filter for WSS applications in WDM-based all-optical networks. An input radiation which contains two independently modulated light sources, each emitting signals at unique wavelengths λ_1 and λ_2 as listed in Table 1, incident normally on proposed PC via input port (P_1) as shown in Fig. 1. The intensity profile of these two signals, centered at wavelengths 1350 and 1370 nm respectively versus their free space wavelength (λ_0), is depicted in Fig. 2.

Table 1 List of two wavelength channels with specific wavelength, separation, and line width of input signal

Wavelength channels	Specific wavelength (nm)	Separation (nm)	Line width (nm)
λ_1	1350	20	1
λ_2	1370	20	1

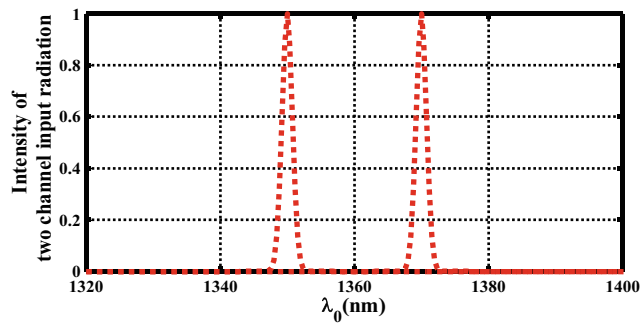


Fig. 2 A schematic drawing of input radiation showing two wavelength channels (by red dots) centered at 1350 and 1370 nm

Figure 3a, b shows the plot of dispersion relation (kd) versus λ_0 , for $\text{YBa}_2\text{Cu}_3\text{O}_7$ at temperatures 0 and 92.5 K, respectively. Since the refractive index of $\text{YBa}_2\text{Cu}_3\text{O}_7$ is dependent both on London penetration depth and external temperature, therefore, by changing the temperature of the superconductor layer, its refractive index can be changed and hence the extent of the PBG. It is evident from Fig. 3a that the proposed structure has PBG from 1347 to 1366 nm at temperature 0 K and will not allow the input radiation centered at 1350 nm to pass through the structure because it falls inside the PBG. On the one hand, input radiation

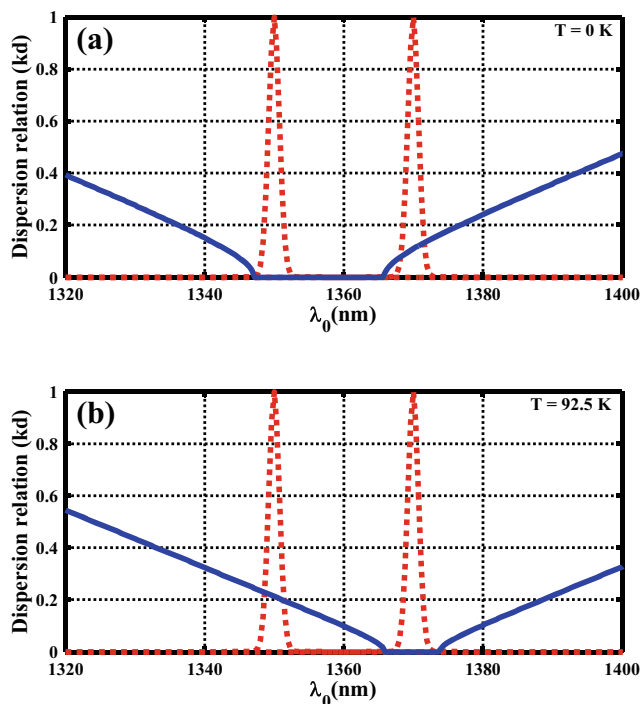


Fig. 3 Working principle of proposed band-stop filter. Dispersion curve (blue color) of 1D DSDPC ($d_1 = 850$ nm, $d_2 = 50$ nm, and $d_3 = 300$ nm at $T = 0$ K (a) and 92.5 K (b)) at normal incidence. Also shown are two discrete wavelength channels centered at 1350 and 1370 nm with separation 20 nm and width 1 nm (red color) injected from input port (P_1) into the structure

centered at 1370 nm is outside from this PBG, and it will reach at the output port (P_0). As we increase the temperature of $\text{YBa}_2\text{Cu}_3\text{O}_7$ from 0 to 92.5 K below T_c , PBG starts to shrink in the region of investigation and shifts towards higher wavelength side, which confirms the findings of Lee and Wu [31]. Thus, allowing the first wavelength channel centered at wavelength 1350 nm of input radiation to pass through the structure as shown in Fig. 3b. This is due to the fact that the relative refractive index contrast of dielectric and high-temperature superconductor material decreases as the temperature of superconductor increases. Thus, by flipping the temperature of superconductor from 0 to 92.5 K or 92.5 to 0 K, any one of the two input wavelength channels can be allowed to reach the output port P_0 . In this way, the temperature of $\text{YBa}_2\text{Cu}_3\text{O}_7$ layer controls the width and position both of the band gap. Table 2 shows how this controlling feature is utilized to separate and switch specific wavelength channels without their interfering with each other as per the WDM standard for wavelength selective switching applications [32].

Next, we consider variation of group velocity (V_g) with respect to λ_0 at temperatures 0 and 92.5 K, shown in Fig. 4a, b, respectively. A look at Fig. 4 shows that with increasing wavelength, V_g decreases from a maximum positive value to zero near the photonic band edges and then further decreases to negative minimum value. Our simulations show that as wavelength increases V_g modulates between the positive maximum value (0.3571c) and the negative minimum value ($-0.3582c$) at 0 K, while at temperature 92.5 K, the maximum value of V_g is swiftly increased to 0.3725c, and its minimum value is further reduced to $-0.3732c$ as shown in Fig. 4a, b. Furthermore, as temperature changes from 0 to 92.5 K, the region of zero group velocity gets narrower and also shifts its position towards the higher wavelength side (Fig. 4). This temperature-dependent behavior of group velocity of light inside PC holds the key to the ultimate control of light and has very specialized applications in the field of optical communications technology. One such key application is in the design of all optical tunable buffers for storing optical data temporally without converting these into electronic format.

Moreover, at 0 K, V_g of input radiation corresponding to wavelength channel centered at 1350 nm is found to be zero

Table 2 Control table showing temperature-dependent WSS of two different wavelength channels of input radiation

S. No.	Temperature of $\text{YBa}_2\text{Cu}_3\text{O}_7$ (K)	PBG (nm)	Selected wavelength channels at P_0 (nm)
1.	0	1347–1366	λ_1
2.	92.5	1366–1374	λ_2

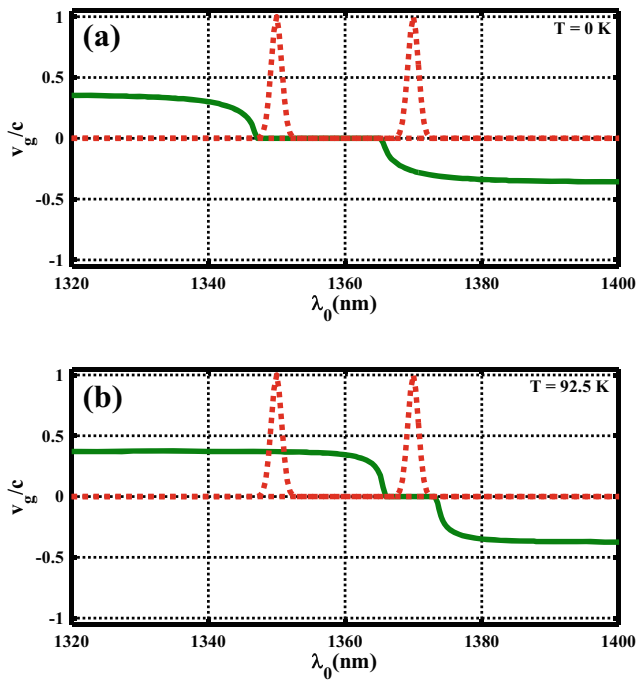


Fig. 4 Normalized group velocity (green color) inside 1D DSDPC ($d_1 = 850$ nm, $d_2 = 50$ nm, and $d_3 = 300$ nm at $T = 0$ (a) and 92.5 K (b)) at normal incidence. Also shown are two discrete wavelength channels centered at 1350 and 1370 nm with separation 20 nm and width 1 nm (red color) injected from input port (P_1) into the structure

which stops the propagation of the signal in the structure. While the V_g of the second wavelength channel centered at 1370 nm is found to be negative due to extremely strong material dispersion which generates slow light in the vicinity of the PBG edges as shown in Fig. 4a, b. It refers to reduction of the group velocity and has strong application possibilities in optical buffers and other optical storage devices. Besides this, at temperature 92.5 K, the V_g of the first wavelength channel centered at 1350 nm is found to be 0.3684c which allows this channel to pass through the structure, while the second wavelength channel with zero group velocity will not be allowed to come out from the structure, i.e., trapped inside the structure (Fig. 4b). Such temperature-dependent behavior of signal group velocity of input radiation having two wavelength channels centered at 1350 and 1370 nm are listed in Table 3.

It is worthwhile to mention that this study provides additional degree of freedom to control dispersion properties of proposed 1D DSDPC by varying the temperature of superconductor material and can be used to manage switching speed of optical switches composed of 1D DSDPC as well as delay time of input signal inside PC for optical time division multiplexing significantly. This property may also be further utilized to design some new kind of optical devices like thermally tunable multichannel narrow

Table 3 Control table showing temperature-dependent behavior of signal group velocity of two channels of input radiation

S. No.	Temperature of YBa ₂ Cu ₃ O ₇ (K)	Peak wavelength (nm)	Group velocity (V_g)
1.	0	1350	0
		1370	-0.269c
2.	92.5	1350	0.3684c
		1370	0

band-stop and band-pass filters, which find important applications in optical communication. Moreover, the study of Fig. 4 also predicts that V_g attains positive, zero, and negative values in certain wavelength regions as usual as in the case of conventional PBG materials. This abnormal behavior of V_g inside 1D DSDPC leads superluminality ($V_g < 0$ or $V_g > 0$) [12, 33].

In addition to this, a very remarkable fact is noticed that in 1D DSDPC, all these regions of V_g can be retuned further in the region of investigation by changing the temperature of superconductor layers as per our desire. Since V_g becomes zero in certain wavelength region, therefore, the information carried by the light (photon) can be stored or trapped inside the proposed structure. This idea may be explored to design new kind of thermally tunable optical memories.

4 Conclusion

A thermally tunable two channel band-stop filter based on 1D DSDPC is proposed and its wavelength selective switching properties are theoretically investigated by studying temperature-dependent behavior of dispersion characteristics and group velocity of light of the proposed structure using transfer matrix method. The temperature-induced tunability of PBG brings the proposed structure to work efficiently as a wavelength selective switch for WDM-based all-optical networks in such a way that optical signal power from one channel does not drift into the spectral territory occupied by the second channel. This study also focuses how the information carried by these channels can be stored or delayed depending upon the different values of temperature dependent V_g , which may also be explored to design some new kind of thermally tunable optical devices like optical memories and buffers.

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References

1. Yablouitch, E.: Inhibited spontaneous emission in solid-state physics and electronics. *Phys. Rev. Lett.* **58**, 2059–2062 (1987)
2. John, S.: Strong localization of photons in certain disordered dielectric superlattices. *Phys. Rev. Lett.* **58**, 2486–2489 (1987)
3. Tucker R. S., Ku P. C., Chang Hasnain C. J.: Slow light optical buffers: capabilities and fundamental limitations. *J. Lightwave Technol.* **23**, 4046–4066 (2005)
4. Banerjee, A.: Novel applications of one dimensional photonic crystal in optical buffering and optical time division multiplexing. *Optik* **122**, 355–357 (2011)
5. Awasthi S. K., Malaviya U., Ojha S. P.: Enhancement of omnidirectional total-reflection wavelength range by using one-dimensional ternary photonic bandgap material. *J. Opt. Soc. Am. B* **23**, 2566–2571 (2006)
6. Kappeler, R., Kaspar, P., Friedli, P., Jackel, H.: Design proposal for a low loss in-plane active photonic crystal waveguide with vertical electrical carrier injection. *Opt. Exp.* **20**, 9264–9275 (2012)
7. Soto, F.C., Martínez, A., García, J., Ramos, F., Sanchis, P., Blasco, J., Martí, J.: All-optical switching structure based on a photonic crystal directional coupler. *Opt. Exp.* **12**, 161 (2004)
8. Koshiba M.: Wavelength division multiplexing and demultiplexing with photonic crystal waveguide couplers. *J. Lightwave Technol.* **19**, 1970 (2001)
9. Qiu, M., Jaskorzynska B.: Design of a channel drop filter in a two-dimensional triangular photonic crystal. *Appl. Phys. Lett.* **83**, 1074 (2003)
10. Kumar, A., Kumar, V., Suthar, B., Ojha, M., Singh, K.h.S., Ojha, S.P.: Trapping of light in nonlinear 1D photonic crystal. *IEEE Photon. Technol. Lett.* **25**, 279–282 (2013)
11. Srivastava, S.: Photonic band gaps extension in one dimensional metallo-organic multilayer photonic structure: Reflectance Spectra of Ag/N, N'-bis-(1-naphthyl)-N, N'-diphenyl-1; 1biphenyl-4; 4diamine. *SOP Trans. Theo. Phys.* **26** (2014)
12. Ojha, S.P., Srivastava, S.K.: Group velocity, negative and ultra high index of refraction in photonic bandgap materials. *Microw. Opt. Technol. Lett.* **42**, 82–87 (2004)
13. Kocaman, S., Aras, M.S., Hsieh, P., McMillan, J., Biris, C.G., Panoiu, N.C., Yu, M.B., Kwong, D.L., Stein, A., Wong, C.W.: Zero phase delay in negative-refractive-index photonic crystal superlattices. *Nat. Photonics* **5**, 499–505 (2011)
14. Kong, X.K., Liu, S.B., Zhang, H.F., Li, C.Z.: A novel tunable filter featuring defect mode of the TE wave from one-dimensional photonic crystals doped by magnetized plasma. *Phys. Plasmas* **17**, 103506 (2010)
15. Scalora, M., Flynn, R.J., Reinhardt, S.B., Fork, R.L., Bloemer, M.J., Tocci, M.D., Bowden, C.M., Ledbetter, H.S., Bendickson, J.M., Dowling, J.P., Leavitt, R.P.: Ultrashort pulse propagation at the photonic band edges: Large tunable group velocity delay with minimal distortion and loss. *Phys. Rev. E* **54**, R1078–R1081 (1996)
16. Jia, W., Li, Y., Xi, Y., Xiang, P., Xu, X., Liu, X., Fu, R., Zi, J.: Tunability of photonic crystals based on the Faraday effect. *J. Phys. Condens. Matter* **15**, 6731–6737 (2003)
17. Kong, X.K., Yang, H.W., Liu, S.B.: Anomalous dispersion in one dimensional plasma photonic crystals. *Optik* **121**, 1873–1876 (2010)
18. Baba, T.: Slow light in photonic crystals. *Nat. Photon.* **2**, 465–473 (2008)
19. Halevi, P., Mendieta, F.R.: Tunable photonic crystals with semi-conducting constituents. *Phys. Rev. Lett.* **85**, 1875 (2000)
20. Zhou, J., Sun, C.Q., Pita, K., Lam, Y.L., Zhou, Y., Ng, S.L., Kam, C.H., Li, L.T., Gui, Z.L.: Thermally tuning of the photonic band gap of colloid-crystal infilled with ferroelectric. *Appl. Phys. Lett.* **78**, 661 (2001)
21. Li, C.Z., Liu, S.B., Kong, X.K., Bian, B.R., Zhang, X.Y.: Tunable photonic bandgap in a one dimensional superconducting dielectric superlattice. *Appl. Opt.* **50**, 2370 (2011)
22. Marouchkine, A.: Room temperature superconductivity. 1st ed. (Cambridge International Science Publishing), U. K. (2004)
23. Ooi, C.H.R., Gong, Q.: Temperature dependent resonances in superconductor photonic crystal. *J. Appl. Phys.* **110**, 063513 (2011)
24. Marangos, J.: Slow light in cool atoms. *Nature* **397**, 559–560 (1999)
25. Heebner, J.E., Boyd, R.W., Park, Q.H.: Slow light, induced dispersion, enhanced nonlinearity, and optical solitons in a resonator-array waveguide. *Phys. Rev. E* **65**, 0366191–0366194 (2002)
26. Born, M., Wolf, E.: Basic properties of the electromagnetic field. In *Principles of optics*, 1–70 (1980)
27. Orfanidis, S.J.: Multilayer film applications. In: *Electromagnetic Waves and Antennas*, pp. 227–250 (www.ece.rutgers.edu/~orfanidi/ewa)
28. Sakoda, K.: Eigenmodes of photonic crystals. In *Optical properties of photonic crystals*, pp. 13–40, Springer Verlag (2001)
29. Yeh, P.: Optics of periodic layered media. In *Optical waves in layered media*, 118–127 (1988)
30. Sanada, A., Caloz, C., Itoh, T.: Characteristics of composite right/left handed transmission lines. *IEEE Microw. Wirel. Components Lett.* **68**, 2004
31. Lee, H.M., Wu, J.C.: Transmittance spectra in one-dimensional superconductor-dielectric photonic crystal. *J. Appl. Phys.* **107**, 09E149 (2010)
32. Keiser, G.: Overview of Optical Fiber Communications. in *Opt. Fiber Commu. Edition 4*, pp. 4–7 (2012)
33. Ojha, S.P., Thapa, K.B., Singh, S.K.: Superluminal propagation in plasma photonic band gap materials. *Optik* **119**, 81–85 (2008)