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ORIGINAL PAPER

Temperature-dependent tuning of photonic band gaps for wavelength-selective switching applications

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Abstract: Transmission characteristics of a thermally tunable optical filter system composed of two 1D silicon–air photonic crystals with different periods have been explored by transfer matrix method. The proposed structure is capable of separating and switching unique wavelength channel without interfering with others amongst 11 equally spaced wavelength channels. Each channel has full width at half maximum of 1 nm as per the wavelength-division multiplexing standards developed by the International Telecommunication Union specifying channel spacing between the adjacent channels in terms of wavelength for wavelength-selective switching applications. The refractive index of silicon is known to be dependent on both temperature and wavelength. Thus, any change in the operating temperature of both photonic crystals by same amount causes their photonic band gaps to alter simultaneously and significantly in such a way as to switch the wavelength-division multiplexing channels one by one as per requirement. The working of the proposed filter system is dependent only on tuning the photonic band gaps and is completely different from the conventional photonic crystals with defect.

Keywords: Photonic band gap materials; Photonic switching; Optical filters

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1. Introduction

Optical devices based on photonic crystals (PCs) have inspired great deal of interest due to their photonic band gaps (PBGs) in which propagation of electromagnetic waves whose frequencies lie within the PBG region is completely prohibited, similar to electronic band gap in semiconductors. PCs have fascinating ability to control and manipulate light wave propagation and thus find their novel scientific, technical and technological applications in photonics and optoelectronics [1–5]. Nowadays, a lot of attention has been paid to design tunable optical filters consisting of PCs due to their vast potential for many applications in modern optical communication [6]. The most significant feature of such tunable filters is the control and monitoring of their transmission properties externally [7–13]. For instance, Kong et al. [13] have focused on how the transmission properties of the defect mode for the transverse electric (TE) wave in 1D PC doped with magnetized plasma are influenced by the external magnetic field, etc. Suthar et al. [10] have investigated the transmission properties of the 1D photonic quantum well (PQW) structure with single defect by transfer matrix method (TMM) and pointed out that defect mode inside the PBG of PQW structure can be utilized as a high-quality single channel filter only by changing the temperature of the structure externally.

All the aforementioned studies have focused on the defect mode properties of the 1D PCs. Though the temperature-dependent tuning of band edge resonant modes in 1D PCs has been studied by Yeong et al. [14] for designing optical thermal sensing devices, none of the studies have

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investigated the temperature-dependent tuning of PBG for wavelength-selective switching (WSS) applications without using defect in conventional 1D PCs. In the present communication, we have proposed thermally tunable optical filter system (TTOFS) for WSS application. The proposed filter is composed of two 1D silicon–air PCs (PC_1 and PC_2) and two highly reflecting mirrors M_1 and M_2. The transmission characteristic of the structure is investigated through TMM [15]. The operating temperature of both the PCs is same and has a marked influence on the transmission spectra as well as on the range of the PBGs of both PCs. The proposed filter may also be used to enhance the capacity and flexibility of wavelength-division multiplexing (WDM) networks by overcoming the fundamental limitations of semiconductor optical amplifier (SOA)-based WSS systems, such as power consumption, signal-to-noise ratio, speed, polarization and size. [16].

The paper is organized as follows. The theoretical formulation is introduced in Sect. 2. Numerical results are presented and discussed in Sect. 3. Finally, conclusions are given in Sect. 4.

2. Theoretical formulation

The structural configuration of the proposed TTOFS for WSS is depicted in Fig. 1. Both PCs are put close to each other in such a way that radiation after coming out of PC_1 is allowed to reach normally on PC_2 via two highly reflecting parallel mirrors M_1 and M_2 through air. The two mirrors are inclined at an angle 45° with respect to the direction of periodicity (z axis). Both PCs are denoted by $[(AB)^N]$ where A and B represent layers of high and low index materials of PC_1 and PC_2 with equal number of periods N. The thicknesses of layers A and B of PC_1 are denoted by d_1 and d_2 while those of PC_2 by d_3 and d_4, respectively. The entire TTOF is assumed to be surrounded by air with refractive index 1.

Let a plane wave be incident normally from left onto the 1D PC_1 along z axis as shown in Fig. 1. The characteristic matrix which connects electric and magnetic fields in the two interfaces of ith layer can be obtained via TMM as

$$M_i = \begin{pmatrix} \cos\ \gamma_i & -\frac{i}{p_i}\sin\ \gamma_i \\ -ip_i\sin\ \gamma_i & \cos\ \gamma_i \end{pmatrix}, \tag{1}$$

where $\gamma_i = \frac{2\pi}{\lambda_0} n_i d_i$, $n_i d_i$ represents the optical thickness of the ith layer. $p_i = n_i$, n_i is the refractive index of ith layer of thickness d_i, and λ_0 is the free space wavelength.

The characteristic matrix of the entire structure that connects the electric and magnetic fields of first and last layer can be shown to be

$$\begin{pmatrix} E_1 \\ H_1 \end{pmatrix} = M_1 M_2 \cdots M_l \cdots M_N \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix}, \tag{2}$$

$$= M_A M_B M_A \cdots M_A M_B \begin{pmatrix} E_{n+1} \\ H_{n+1} \end{pmatrix}$$
$$= M \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix} \tag{3}$$
$$= \begin{pmatrix} \chi_{11} & \chi_{12} \\ \chi_{21} & \chi_{22} \end{pmatrix} \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix}.$$

where χ_{11}, χ_{12}, χ_{21} and χ_{22} are the matrix elements of transfer matrix representing the whole structure. The transmission coefficient of the electromagnetic wave passing through the structure with N identical periods is

$$t = \frac{2\eta_0}{\chi_{11}\eta_0 + \chi_{12}\eta_0\eta_{N+1} + \chi_{21} + \chi_{22}\eta_0} \tag{4}$$

where η_0 and η_{N+1} represent the coefficients of medium on either side of the structure. Since entire structure is kept in

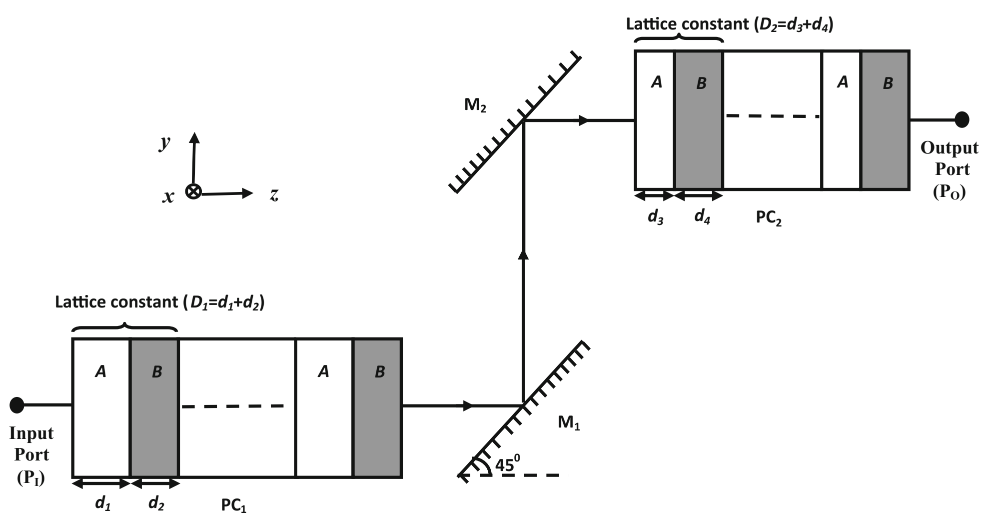

Fig. 1 A schematic drawing of TTOF system consisting of two 1D PCs (PC_1 and PC_2) along with two highly reflecting mirrors M_1 and M_2

air, $\eta_0 = n_0$ and $\eta_{N+1} = n_0$. Here n_0 is the refractive index of air.

Then, transmittance T of 1D PC

$$T = (t)^2 \tag{5}$$

The wavelength- and temperature-dependent refractive index of silicon (Si) in the ranges 1.2–14 μm and 293–1600 K, respectively, is defined as [17]

$$n(\lambda, T) = \left\{ \varepsilon(T) + \frac{L(T)}{\lambda^2}(A_0 + A_1 T + A_2(T)) \right\}^{1/2} \tag{6}$$

where $\varepsilon(T) = 11.4445 + 2.7739 \times 10^{-4}T + 1.7050 \times 10^{-6}T^2 - 8.1347 \times 10^{-10}T^3$, $L(T) = e^{-3\Delta L(T)/L_{293}}$, λ = wavelength in units of μm, T = temperature in units of K, $A_0 = 0.8948$, $A_1 = 4.3977 \times 10^{-4}$, $A_2 = 7.3835 \times 10^{-8}$, and $\frac{\Delta L(T)}{L_{293}} = -0.071 + 1.887 \times 10^{-6}T + 1.934 \times 10^{-9}T^2 - 4.544 \times 10^{-13}T^3$. The temperature-dependent thickness of Si layer is given by

$$d(T) = d_{293}(1 + \alpha\Delta T) = d_{293}\left(1 + \frac{\Delta L(T)}{L_{293}}\right) \tag{7}$$

where d_{293} and $d(T)$ represent the thicknesses of Si layer at temperatures 293 K and T K, respectively, α is the coefficient of thermal expansion of Si with numerical value 2.5×10^{-6}/K, and ΔT is the change in temperature of Si layer. Due to the thermal expansion in Si layer, the thicknesses d_1, d_2 and d_3, d_4 of layers A and B of PC_1 and PC_2 at temperature 293 K will be modified in accordance with Eq. (7) as [7, 10, 11]

$$d_1(T) = d_1 + \Delta d_1, d_2(T) = d_2 - \Delta d_1 \text{ and } d_3(T) = d_3 + \Delta d_3, d_4(T) = d_4 - \Delta d_3 \tag{8}$$

Here $\Delta d_i = d(T) - d_i(293)$ is the change in the thickness of Si layer due to corresponding change in ΔT. The subscripts i = 1 and 3 are used to represent Si layer of PC_1 and PC_2, respectively.

3. Results and discussion

In our calculations, we have taken $(AB)^N$ as 1D Si–air PC (PC_1) with refractive index of layer A (Si), dependent on temperature and wavelength both in accordance with Eq. (6). The refractive index of layer B (air) is taken to be 1 [10]. For the proposed 12 period structure of PC_1, we have chosen the thicknesses of layers A and B as d_1 = 419 nm and d_2 = 105 nm in order to get wider PBG in the near-infrared spectral region, ranging from 1372 to 1650 nm at a temperature of 293 K because this is a low-loss region in silica fibres [18]. Now, any change in temperature of PC_1 and PC_2 changes the thicknesses of layers A and B of both PCs according to Eq. (8) which in turn influences the range of PBGs of PC_1 and PC_2. Using TMM as discussed above, the transmission spectrum of PC_1 at normal incidence is plotted as a function of wavelength in Fig. 2. It shows PBG of PC_1 at temperature 293 K extending from λ_l = 1372 nm to λ_r = 1650 nm which lies within the spectral band (1260–1675 nm) used for optical fibre communications. The range of PBG of PC_1 is dependent on the temperature of Si besides other parameters such as lattice constant and refractive indices of materials.

Now consider an input signal consisting of 11 independently modulated light sources, each having a unique wavelength ranging from 1391 to 1591 nm as listed in Table 1, incident normally on PC_1 through input port P_I (Fig. 1). Since all these wavelengths lie within the PBG of PC_1 (Fig. 3), they are reflected back by PC_1 and do not reach at output port P_o through the combination of mirrors M_1 and M_2 as shown in Fig. 1. The reason behind the selection of this combination of mirrors M_1 and M_2 is to keep the phase difference between the signals reflected by

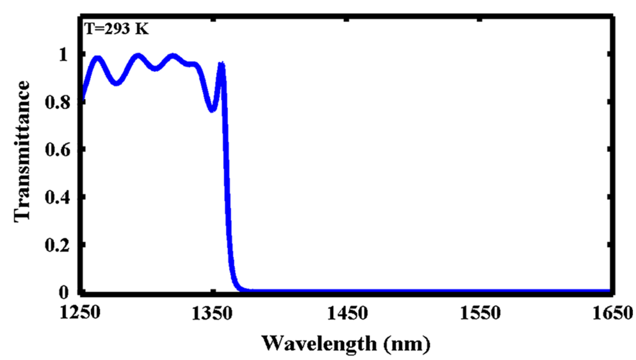

Fig. 2 Transmittance spectra at normal incidence of PC_1 by blue colour (d_1 = 419 nm, d_2 = 105 nm, N = 12 and T = 293 K)

Table 1 List of 11 wavelength channels with specific wavelength, separation and line width of input signal

Wavelength channels	Specific wavelength (nm)	Separation (nm)	Line width (nm)
λ_1	1391	20	1
λ_2	1411	20	1
λ_3	1431	20	1
λ_4	1451	20	1
λ_5	1471	20	1
λ_6	1491	20	1
λ_7	1511	20	1
λ_8	1531	20	1
λ_9	1551	20	1
λ_{10}	1571	20	1
λ_{11}	1591	20	1

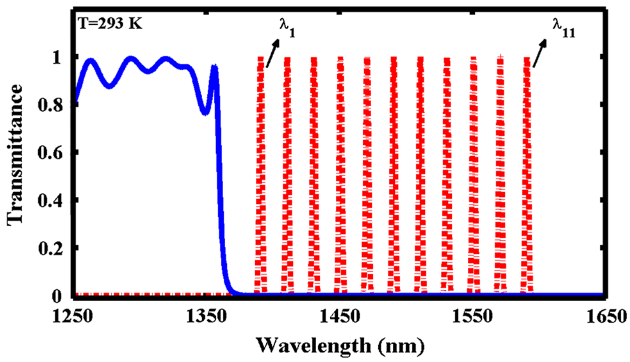

Fig. 3 Transmittance spectra (*blue colour*) of PC_1 ($d_1 = 419$ nm, $d_2 = 105$ nm, $N = 12$ and $T = 293$ K) at normal incidence. Also shown are 11 wavelength channels (*red colour*) injected from input port P_I. These channels with separation 20 nm and width 1 nm fall within the PBG of PC_1. (Color figure online)

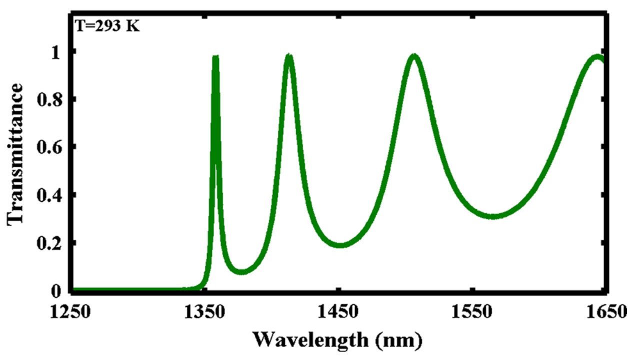

Fig. 4 Transmittance spectra at normal incidence of PC_2 by *green colour* ($d_3 = 86.5$ nm, $d_4 = 148$ nm, $N = 12$ and $T = 293$ K). (Color figure online)

mirrors M_1 and M_2 unaltered. Now we have chosen another 1D PC (PC_2) composed of same materials as that of PC_1. The thickness of the layers A and B of PC_2 is selected as $d_3 = 86.5$ nm and $d_4 = 148$ nm, respectively, in order to get a narrow PBG extending from 1250 to 1344 nm in the near-infrared region at the same temperature 293 K (Fig. 4). Total number of periods of PC_2 is also 12. Both PCs are put close to each other in such a way that radiation after coming out of PC_1 falls normally on PC_2 via the two highly reflecting parallel mirrors M_1 and M_2 through air, to avoid Fabry–Perot resonance between PC_1 and PC_2 in the event of PC_1 and PC_2 being put in cascade. Mirrors M_1 and M_2 are inclined at an angle 45° with respect to direction of periodicity of PC_1 and PC_2, respectively. This arrangement also ensures the condition of normal incidence for the signals coming out of PC_1 and reaching to PC_2. Since the refractive index of Si is dependent on the temperature as well as on the wavelength, any change in the temperature of Si layer changes its refractive index, thus altering the PBG of both PC_1 and PC_2. As we increase the operating temperature of Si from 625 to 1585 K, PBG of PC_1 starts to shrink in the region of investigation and shifts towards the higher side of the wavelengths, thus allowing different unique wavelength channels of input signal to pass through PC_1 and reach normally at PC_2 (Table 2). But due to this temperature variation, the PBG of PC_2 starts to expand and moves towards the higher side of the wavelengths in such a way as to select and switch only the desired wavelength channel from PC_2 to reach P_o. This temperature-dependent tunability of PBG of PC_2 reflects all the wavelength channels of input radiation coming out from PC_1 and transmits only one single wavelength channel at a time depending upon the temperature as shown in Fig. 5(a) and 5(b). Table 2 shows how temperature-dependent tunability of PBGs of both PCs (PC_1 and PC_2) of the proposed system can be used to separate and switch specific wavelength channels. The crosstalk between adjacent channels has been avoided by selecting the channel spacing to be 20

Table 2 Control table of TTOFS for selecting different wavelength channels

S. no.	T (K)	PC_1		PC_2	
		PBG (nm)	Wavelength selection through M_1 and M_2	PBG (nm)	Selected wavelength at P_o
1.	625	1407–1650	λ_1	1250–1377	λ_1
2.	760	1427–1650	$\lambda_1 + \lambda_2$	1250–1396	λ_2
3.	885	1448–1650	λ_1 to λ_3	1250–1417	λ_3
4.	990	1468–1650	λ_1 to λ_4	1250–1436	λ_4
5.	1090	1488–1650	λ_1 to λ_5	1250–1455	λ_5
6.	1181	1508–1650	λ_1 to λ_6	1250–1474	λ_6
7.	1270	1529–1650	λ_1 to λ_7	1250–1494	λ_7
8.	1353	1549–1650	λ_1 to λ_8	1250–1515	λ_8
9.	1432	1569–1650	λ_1 to λ_9	1250–1535	λ_9
10.	1510	1589–1650	λ_1 to λ_{10}	1250–1556	λ_{10}
11.	1585	1610–1650	λ_1 to λ_{11}	1250–1576	λ_{11}

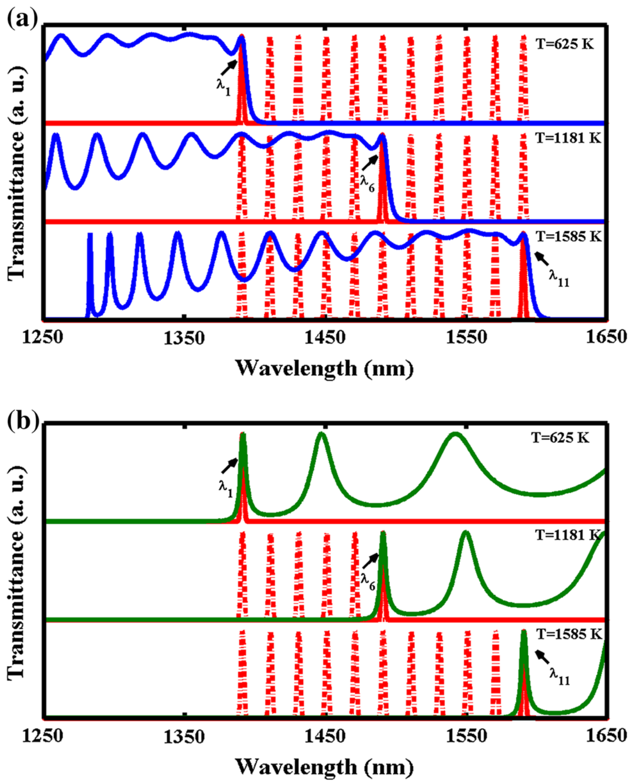

Fig. 5 Working principle of TTOFS. (**a**) Transmittance spectra (*blue colour*) of PC_1 ($d_1 = 419$ nm, $d_2 = 105$ nm, $N = 12$ and $T = 625$, 1181 and 1585 K) at normal incidence. The 11 wavelength channels (*red colour*) injected from input port P_I. (**b**) Transmittance spectra (*green colour*) of PC_2 ($d_3 = 86.5$ nm, $d_4 = 148$ nm and $N = 12$ and $T = 625$, 1181 and 1585 K) at normal incidence. The selected wavelengths λ_1, λ_6 and λ_{11} by PC_2 corresponding to temperatures 625, 1181 and 1585 K. (Color figure online)

times the signal spectral width though the standard value is only 10 times [19]. If we reduce the number of periods of both PCs from the proposed 12, their PBGs contract and also their PBG edges are modified significantly. Thus, the period selection of both PCs is dependent on the number of equally spaced wavelength channels to be switched from the proposed design.

The working of the proposed TTOFS does not suffer from drawbacks of temperature-dependent tunability of defect mode inside PBG of defect PCs (DPCs) as reported in [8–12]. In order to filter number of closed and equispaced wavelength channels (Table 1) one by one at a time from PCs, temperature-dependent feature of defect mode inside PBG plays crucial role. The effect of temperature variation causes significant impact on the intensity as well as full width at half maximum (FWHM) of the defect mode, which limits the application of such structures as wavelength-selective switches for switching number of wavelength channels. Contrary to this, our structure works on the principle of temperature-dependent tunability of PBG which affects neither the intensity nor FWHM of individual and closely spaced wavelength channels to be filtered. In the proposed structure, the left and right band edges of PBGs of PC_1 and PC_2 can be simultaneously changed to allow only the desired wavelength channel to reach at P_o by controlling the temperature of both PCs in accordance with Table 2. Besides this, for achieving WSS from DPCs to switch large number of closely spaced wavelength channels, crosstalk between adjacent channels must also be taken into account. Its value should be as minimum as possible to improve performance of the filter. In the proposed design, crosstalk does not contribute to the performance of the system, because PBGs of both PCs are tuned in such a way as to allow only one wavelength channel at P_o without causing any interference between adjacent channels.

Thus, it is seen that for proper switching action of the proposed TTOFS, the only requirement is precise control of temperature. Presently available high-temperature technologies [20–22] can be used for this purpose. Hence, the proposed design is a better alternative to serve the objective over the conventional technologies being used for this purpose. It would be seen that, though, in order to switch the number of wavelength channels one by one from the proposed structure, some amount of signal power is lost due to two main reasons. Firstly, because of two high-quality reflective mirrors incorporated in the design and secondly due to temperature-dependent left and right band edge resonant modes of PC_1 and PC_2, respectively, as per the findings of Yeong et al. [14]. However, this power loss is much above the threshold value of detector to detect the power significantly.

4. Conclusions

A new and simple design of TTOFS composed of two 1D PCs (PC_1 and PC_2), and two highly reflecting mirrors (M_1 and M_2) have been proposed. This design is capable of separating and switching unique wavelength channels without interfering with each other, amongst 11 equally spaced wavelength channels each having FWHM of 1 nm as per the WDM standards developed by International Telecommunication Union (ITU) specifying channel spacing in terms of wavelength for WSS applications. The proposed TTOFS may play an important role in the design of some new kind of optical components in WDM environment which can ensure that optical signal power from one channel does not drift into the spectral territory occupied by adjacent channels.

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