Progress In Electromagnetics Research Letters, Vol. 33, 27–35, 2012

TUNABLE WAVELENGTH DEMULTIPLEXER FOR DWDM APPLICATION USING 1-D PHOTONIC CRYSTAL

A. Kumar[1], B. Suthar[2, *], V. Kumar[3], Kh. S. Singh[3], and A. Bhargava[4]

[1]AITTM, Amity University, Noida, India

[2]Department of Physics, Government College of Engineering & Technology, Bikaner 334004, India

[3]Department of Physics, Digamber Jain (P.G.) College, Baraut 250611, India

[4]Nanophysics Laboratory, Department of Physics, Government Dungar College, Bikaner 334001, India

Abstract—Transmission characteristics of 1-D photonic crystal (PC) structure with a defect have been studied. We consider a Si/ZnS multilayer system. We also consider the refractive index of both layers to be dependent on temperature and wavelength simultaneously. The refractive indices of Si and ZnS layers are functions of temperature as well as of the wavelength of incident light. This property can be used to tune the defect modes at desired wavelength. 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 each defect mode is 0.07 nm/K. This property can be exploited in the design of a tunable wavelength demultiplexer for DWDM application in optical communication.

1. INTRODUCTION

Dense Wavelength division multiplexer (DWDM) is a key component of modern optical communications systems. This component is used to divide and combine different wavelength channels, each carrying an optical data signal. Channel drop filters may be used in DWDM network to drop a channel. An optical filter is a device, which has the

Received 20 April 2012, Accepted 18 June 2012, Scheduled 21 June 2012
* Corresponding author: Bhuvneshwer Suthar (bhuvneshwer@gmail.com).

property of adding or dropping a particular wavelength channels from the multi wavelength network. There are different technologies for making optical filters, namely, diffraction gratings [1], dielectric thin-film filters [2], fiber Bragg gratings [3], arrayed waveguide gratings (AWGs) [4], etc. To achieve a large number of sufficiently spaced wavelength channels, the size of these devices must be of the order of centimetres, which is very far from the demands of integrated optical components. Recently optical devices based upon PCs have attracted great research interest [5–9]; they have very high potential applications because of their unique characteristics and such structures may lead the realization of miniaturized optical integrated devices and systems with sizes of the order of several wavelengths. This miniaturization is possible because of the light confinement yielded by photonic band gap effects. Many researchers have studied DWDM based on photonic crystal [10, 11]. Cedric et al. gave the design of a tunable demultiplexer using logarithmic filter chains [12]. This multiplexer uses an apodized one dimensional photonic crystal structure on a ridged semiconductor waveguide.

Recently, a wavelength division demultiplexer using multilayer band pass filters was fabricated [13]. This multiplexer contains 184 layers of low and high refractive index materials. Also, Gerken and Miller fabricated a wavelength division demultiplexer using the spatial dispersion of multilayer thin film structures [14]. They use a single 66-layer non-periodic thin film stake to separate four wavelength channels by spatial beam shifting. They demonstrate that this device can demultiplexed channels with spacing of approximately 4 nm in the first transmission window of optical communication, i.e., at 850 nm wavelength. The structure proposed here does not require apodization and number of layer is also less. So, the fabrication of the proposed structure will be comparatively simpler. Also, line width of transmission is also less in our case, which is desirable for DWDM application.

There may be a mismatch between the simulated results and practical performance of the fabricated photonic crystal structure. During the device fabrication process, some errors occur automatically. Then, the compensation of these errors is important so that the response of the device is within the tolerance limit. In this present communication, a high-resolution and tunable demultiplexer is proposed using 1-D PC with a defect. Its operating principle is based on the tuning of defect modes in 1-D PC structure. Refractive indices of Si and ZnS layers depend on temperature and wavelength simultaneously. So, the refractive indices of Si and ZnS layers are functions of temperature of medium as well as the wavelength of incident light and this property can be exploited for the tuning of defect modes. As each defect mode is a function of temperature, one can tune each defect mode to desire wavelength. The proposed structure has an appropriate performance and is very suitable for DWDM multi-channel systems with 0.8 nm spacing.

2. THEORETICAL MODEL

We consider air/$(AB)^N D(BA)^N$/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) [15, 16]. Here, we would like to propose a high-resolution and tunable demultiplexer using 1-D PC with a defect as shown in Figure 1. Si and ZnS have been taken as the high and the low refractive index materials. Also Si has been chosen as the defect layer. Hence, the proposed structure will be $[(\mathrm{Si/ZnS})^5\mathrm{Si}(\mathrm{ZnS/Si})^5]$. The geometrical parameters, i.e., thicknesses of high and low refractive index materials is taken at 300 K. The layer of Si and ZnS will be expanding with the increase in temperature in the following manner;

$$a\,(T) = a(1 + \alpha\Delta T) \ \text{ and } \ b\,(T) = b(1 + \beta\Delta T) \tag{1}$$

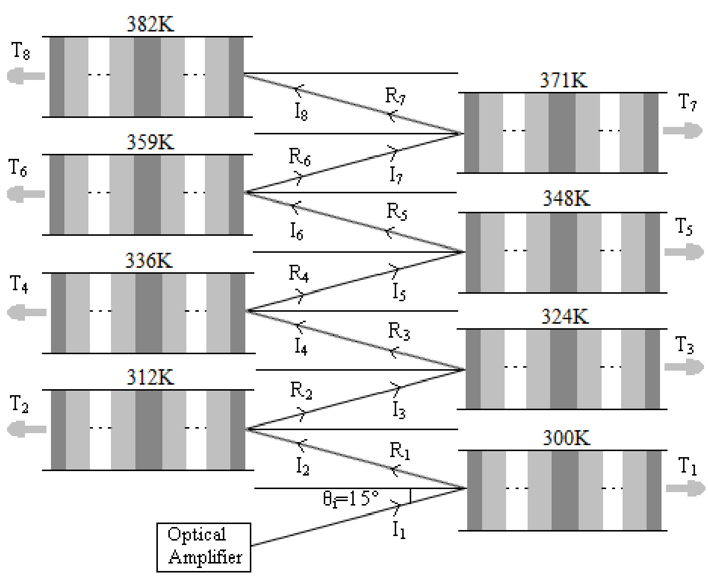

Figure 1. Proposed wavelength division demultiplexer based on one-dimensional photonic crystal with a defect.

where α is the thermal expansion coefficient for Si layer and taken to be 2.5×10^{-6}/K and β is the thermal expansion coefficient for ZnS layer and taken to be 6.1×10^{-6}/K [17]. The melting points for Si and ZnS layers are 1210 K and 1830 K respectively [17]. The refractive index of Silicon (Si) in the ranges 1200 to 14000 nm and 20–1600 K is represented as [18]

$$n^2(\lambda, T) = \varepsilon(T) + \frac{e^{-3\Delta L(T)/L_{293}}}{\lambda^2}\left(0.8948 + 4.3977\times10^{-4}T + 7.3835\times10^{-8}T^2\right) \quad (2)$$

where

$$\varepsilon(T) = 11.4445 + 2.7739\times10^{-4}T + 1.7050\times10^{-6}T^2 - 8.1347\times10^{-10}T^3$$

and

$$\frac{\Delta L(T)}{L_{293}} = -0.071 + 1.887\times10^{-6}T + 1.934\times10^{-9}T^2 - 4.554\times10^{-13}T^3 \quad \text{for } 293\,\mathrm{K} \le T \le 1600\,\mathrm{K}$$

$$\frac{\Delta L(T)}{L_{293}} = -0.021 - 4.149\times10^{-7}T - 4.620\times10^{-10}T^2 + 1.482\times10^{-11}T^3 \quad \text{for } 20\,\mathrm{K} \le T \le 293\,\mathrm{K}$$

similarly, the refractive index of ZnS layer is taken as a function of both wavelength and temperature. The refractive index of ZnS in the ranges 1200 to 14000 nm and 293–700 K can be expressed as a function of both the wavelength and temperature as [19]

$$n_2^2(\lambda, T) = \varepsilon_1(T) + \frac{A(T)}{\lambda^2 - \lambda_1^2} + \frac{B(T)}{(\lambda/\lambda_2)^2 - 1} \quad (3)$$

where $\lambda_1 = 0.23979 + 4.841\times10^{-5}T_1$, $\lambda_2 = 36.525 + 4.75\times10^{-3}T_1$ and $T_1 = T - 293$ and

$$\begin{aligned}
\varepsilon_1(T) &= 8.34096 + 1.29107\times10^{-3}T_1 + 4.68388\times10^{-7}T_1^2 \\
&\quad -1.31683\times10^{-9}T_1^3 - 6.64356\times10^{-12}T_1^4 \\
A(T) &= 0.14540 + 1.13319\times10^{-5}T_1 + 1.05932\times10^{-8}T_1^2 \\
&\quad +1.06004\times10^{-10}T_1^3 + 2.27671\times10^{-13}T_1^4 \\
B(T) &= 3.23924 + 1.096\times10^{-3}T_1 + 4.20092\times10^{-7}T_1^2 \\
&\quad +1.1135\times10^{-9}T_1^3 + 7.2992\times10^{-12}T_1^4
\end{aligned}$$

The thickness of the layers are taken as $a(\mathrm{Si}) = 110.7$ nm and $b(\mathrm{ZnS}) = 170.2$ nm according to the quarter wave stack condition $a = \lambda_c/4n_1$ and $b = \lambda_c/4n_2$, corresponding to the critical wavelength, λ_c =1546 nm. We choose $n_1(\mathrm{Si}) = n_1(1546\,\mathrm{nm}, 300\,\mathrm{K}) = 3.492$ and $n_2(\mathrm{ZnS}) = n_2(1546\,\mathrm{nm}, 300\,\mathrm{K}) = 2.271$. Thickness of the defect layer (Si) is $2a$.

3. RESULTS AND DISCUSSION

In this section, we have presented the working principle of the proposed demultiplexer. A schematic diagram of the proposed DWDM is shown in Figure 1. Input radiation which contains eight different wavelengths is incident on first PC at an angle 15°. The first wavelength transmits through first PC while remaining wavelengths reflected at an angle 15°. After this each reflected part is incident at an angle 15° on the next PC. This process is going on up to eight PC structures. The temperature of all structures is different, the reason for that will be discussed in the following part. The consequence of maintaining the PCs at different temperatures is that each structure will pass a very narrow band of wavelength. There will be some loss of power at each photonic crystal, but this loss of power may be compensated by applying the optical amplifier before the first crystal. Amplification of the optical signal is a common practice in almost all wavelengths demultiplexing scheme. After this output power will, in general, be much above the threshold power of optical detector.

The transmission spectra of $[(Si/ZnS)^5Si(ZnS/Si)^5]$ at 300 K are shown in Figure 2 for TE mode. As shown in this figure, a defect mode has been observed around 1539.97 nm wavelength with line width of 0.4 nm. Our aim is to study this defect mode by varying the temperature of the PCs. This dropping line width is narrow enough for the DWDM system. Thus, from this figure it is clear that if input radiation containing different wavelengths ranging from 1530 nm to 1555 nm is incident at an angle 15° on the proposed structure at 300 K, then it will pass only an extremely narrow band of wavelength centred at 1539.97 nm and all other wavelengths will be reflected. Thus, it can work as a single channel wavelength demultiplexer. More interestingly, this defect mode can be tuned by variation of temperature. The transmission spectra of the proposed structure

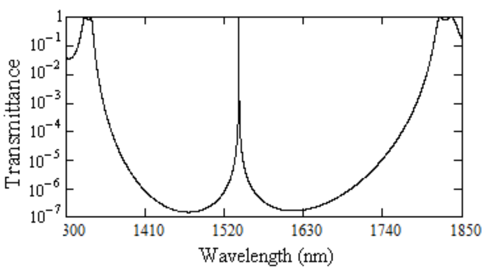

Figure 2. The defect mode for a PC with defect of $[(Si/ZnS)^5Si(ZnS/Si)^5]$ at 300 K temperature.

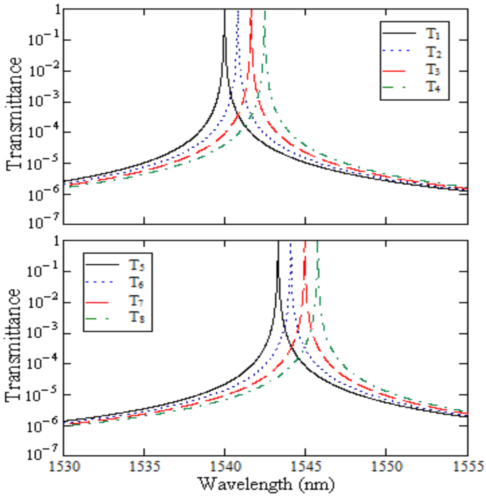

Figure 3. Transmission spectra of proposed structure at different temperature.

Table 1. Central wavelength, separation and linewidth of defect modes.

Temperature (K)	Central wavelength of defect mode (nm)	Separation (nm)	Line width (nm)
300	1539.77	–	0.40 nm
312	1540.58	0.81 nm	0.40 nm
324	1541.39	0.81 nm	0.40 nm
336	1542.22	0.83 nm	0.40 nm
348	1543.06	0.84 nm	0.40 nm
359	1543.90	0.84 nm	0.40 nm
371	1544.70	0.80 nm	0.40 nm
382	1545.52	0.82 nm	0.40 nm

at various temperature, is shown in Figure 3. From Figure 3, it is clear that the transmission peak centered at 1539.97 nm at 300 K has been shifted to 1540.79 nm, 1541.61 nm, 1542.44 nm, 1543.28 nm, 1544.09 nm, 1544.93 nm and 1545.73 nm corresponding to temperature at 312 K, 324 K, 336 K, 348 K, 359 K, 371 K, and 382 K respectively. Here in this simulation work, the temperature of the device has been taken arbitrarily, so we can tune centre of the defect mode at any desired wavelength by varying the temperature as shown in Table 1.

Further, it is also clear that as we increase the temperature, the defect mode of transmission shifts towards the higher wavelength region. It is found that the central wavelength of defect modes changes approximately linearly with temperature. The average change in central wavelength of defect mode is 0.07 nm/K. It is also observed that the linewidth of the defect mode is not affected by the variation of the incident angle; these detailed results are not presented in this paper. Hence the proposed structure may be used as a single channel tunable DWDM. Thus, we can extract any desired wavelength by changing the temperature of the structure. So, all eight wavelengths can be demultiplexed by using the structure 1 to structure 8, as shown in Figure 1.

Crosstalk between the two adjacent channels is defined as $10\log_{10}$ times the ratio of the power of the adjacent channel to the power of the channel both at central wavelength of the channel under consideration. As output power of the photonic channel is directly proportional to the transmittance of the crystal at that wavelength, we can define crosstalk as $10\log_{10}$ times the ratio of the transmittance of the adjacent channel to the transmittance of the channel both at central wavelength of the channel under consideration. It is clear from Figure 3, that the transmittance of any adjacent channel of any transmission channel is approximately 0.055%. Central wavelengths and crosstalk of different channels is tabulated in Table 2. Thus, crosstalk between the adjacent channel has comes out -32.5 dB, which is, of course, well below the standard limit of crosstalk of -25 dB between adjacent channel in optical communication systems.

Also, the line-width of the transmitted wavelength is 0.4 nm, and separation of wavelength is 0.8 nm, so the proposed structure has all appropriate characteristics to be used to demultiplex the signal with

Table 2. Central wavelengths and crosstalk of different channels.

Sl. No.	Central Wavelength of transmission	Transmittance of adjacent channels (%) and corresponding Crosstalk			
		On the shorter wavelength side of the central wavelength	Crosstalk	On the longer wavelength side of the central wavelength	Crosstalk
1	1539.77	–	–	0.055	– 32.5 dB
2	1540.58	0.055	−32.5 dB	0.055	– 32.5 dB
3	1541.39	0.055	−32.5 dB	0.055	−32. 5 dB
4	1542.22	0.055	−32.5 dB	0.055	– 32.5 dB
5	1543.06	0.055	−32.5 dB	0.055	– 32.5 dB
6	1543.9	0.055	−32.5 dB	0.055	– 32.5 dB
7	1544.7	0.055	−32.5 dB	0.055	– 32.5 dB
8	1545.52	0.055	−32.5 dB	–	–

0.8 nm separation, which corresponds to the ITU grid for DWDM. The PCs are used as a tunable structure at different but fixed temperatures. So, it must be noted that the tunable property of PCs is not in the time domain and such PCs cannot be used as switches in time domain.

4. CONCLUSIONS

A tunable device has advantage that it may overcome the discrepancies between the real function of fabricated devices and their simulation results. In this work, the design of a tunable DWDM has been proposed. The proposed structure used in demultiplexing scheme is based on the 1-D photonic structure with defect. In this work, tuning has been achieved by the variation of temperature of the Si layers, because refractive index of the Si depends on the temperature. So, we can use the proposed device as a tunable demultiplexer in optical communication. Detailed analysis shows that the proposed structure is suitable for dense wavelength-division multiplexing (DWDM) multi-channel systems with 0.8 nm channel spacing. The proposed device may also be used as a single channel drop filter, monochromator, temperature sensor, and it may have many applications in different optical systems.

REFERENCES

1. Minowa, J. and Y. Fujii, "Dielectric multilayer thin-film filters for WDM transmission systems," *J. of Lightwave Technol.*, Vol. 1, 116, 1983.
2. Romero, R., O. Frazao, F. Floreani, L. Zhang, P. V. S. Marques, and H. M. Salgado, "Chirped fibre Bragg grating based multiplexer and demultiplexer for DWDM applications," *Opt. Lasers Eng.*, Vol. 43, 987, 2005.
3. Fukazawa, T., F. Ohno, and T. Baba, "Very compact arrayed-waveguide-grating demultiplexer using Si photonic wire waveguides," *Jap. J. Appl. Phys.*, Vol. 43, L673, 2004.
4. Liu, Y., F. Zhou, D. Z. Zhang, and Z. Y. Li, "Energy squeeze of ultrashort light pulse by Kerr nonlinear photonic crystals," *Chin. Phys. Lett.*, Vol. 26, 014208, 2009.
5. Suthar, B. and A. Bhargava, "Tunable multi-channel filtering using 1-D photonic quantum well structures," *Progress In Electromagnetics Research Letters*, Vol. 27, 43, 2011.
6. Bhargava, A. and B. Suthar, "Optical switching in Kerr nonlinear

chalcogenide photonic crystal," *J. Ovonic Research*, Vol. 5, 187, 2009.

7. Suthar, B., V. Kumar, K. S. Singh, and A. Bhargava, "Tuning of photonic band gaps in one dimensional chalcogenide based photonic crystal," *Opt. Commun.*, Vol. 285, 1505, 2012.
8. Kumar, V., K. S. Singh, S. K. Singh, and S. P. Ojha, "Broadening of omnidirectional photonic band gap in Si-based one-dimensional photonic crystals," *Progress In Electromagnetics Research M*, Vol. 14, 101, 2010.
9. Srivastava, S. K. and S. P. Ojha, "Omnidirectional reflection bands in one-dimensional photonic crystal structure using fluorescence films," *Progress In Electromagnetics Research*, Vol. 74, 181, 2007.
10. Zhao, Y.-N., K.-Z. Li, X.-H. Wang, and C.-J. Jin, "A compact in-plane photonic crystal channel drop filter," *Chin. Phys. B*, Vol. 20, 074210, 2011.
11. Habibiyan, H., H. Ghafoori-Fard, and A. Rostami, "Tunable all-optical photonic crystal channel drop filter for DWDM systems," *J. of Opt. A: Pure and Appl. Opt.*, Vol. 11, 065102, 2009.
12. Lam, C. F., R. B. Vrjen, P. P. L. Chang-Chien, D. F. Sievenpiper, and E. Yablonovitch, "A tunable wavelength demultiplexer using logarithmic filter chains," *J. of Lightwave Technol.*, Vol. 16, 1657, 1998.
13. http://www.laserfocusworld.com/articles/print/volume-37/issue-7/features/optical-coatings/wavelength-multiplexers-use-multilayer-bandpass-filters.html.
14. Gerken, M. and D. A. B. Miller, "Wavelength demultiplexer using the spatial dispersion of multilayer thin-film structures," *IEEE Photonics Technology Letters*, Vol. 15, 1097, 2003.
15. Yeh, P., *Optical Waves in Layered Media*, John Wiley and Sons, New York, 1988.
16. Born, M. and E. Wolf, *Principle of Optics*, 4th edition, Pergamon, Oxford, 1970.
17. Ghosh, G., *Handbook of Thermo-optic Coefficients of Optical Materials with Applications*, Academic Press, San Diego, CA, USA, 1997.
18. Li, H. H., "Refractive index of silicon and germanium and its wavelength and temperature derivatives," *J. Phys. Chem. Ref. Data*, Vol. 9, 561, 1980.
19. Li, H. H., "Refractive index of ZnS, ZnSe and ZnTe and its wavelength and temperature derivatives," *J. Phys. Chem. Ref. Data*, Vol. 13, 103, 1984.