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Add/drop filters for coarse wavelength division multiplexing-demultiplexing based on photonic crystal with defects

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A novel concept for introducing defects in 1D photonic crystal, to be used as filter for coarse wavelength division multiplexing-demultiplexing, and a methodology to design such filters are reported. The defects are introduced in the periodic structure through extension of dielectric layer in selective unit cells. Simulation results show that additional phase shifts, due to such extensions, open up precisely controlled narrowband transmission windows within the photonic band gap of the crystal. The transmission windows facilitate filtering of wavelength channels with spacing of about 20 *nm* as required for coarse wavelength division multiplexing (CWDM) systems. Our proposed photonic band gap (PBG) structures with engineered defects can serve as optical filters in multiplexer-demultiplexer (MUX-DEMUX) that exactly fulfill the specifications described by ITU-T Recommendation G.694.2, regarding channel allocation and inter-channel separation for CWDM systems. A detailed methodology to develop a filter for channels with proposed spacing is also described and validated for two ITU-T recommended channels. Due to inherent simplicity in the scheme of incorporating defects in the photonic crystal, the resulting structure is expected to offer better reproducibility and less fabrication hazards in comparison to the other photonic crystal based MUX-DEMUXs. Transmission characteristics of the proposed models are analyzed using transfer matrix approach.

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1. Introduction

Photonic crystals (PhCs) are stacks of periodic dielectric hetero-structures with high refractive index contrast [1]. Their inherent capability of controlling light propagation makes them suitable for realizing various optical components needed in integrated optical communication systems [2]-[13].

PhCs are emerging as legitimate candidate for designing multiplexer-demultiplexer (MUX-DEMUX) compatible to coarse wavelength division multiplexing (CWDM) system over the traditionally used WDM component viz., Fiber Bragg Grating (FBG). FBG fails to provide adequate spacing (near about 20 *nm*) and bandwidth for CWDM channels. Above all, the main advantage of PhC over FBG is that it can be integrated to yield photonic integrated circuit, which is not possible with FBG for its inherent structural limitations.

Koshiba [11] proposed MUX-DEMUX based on PhC waveguide coupler, in which coupling coefficient was governed by rows of dielectric rods in the interaction region. Use of such PhC waveguide coupler in place of conventional directional couplers reduces size of the MUX-DEMUX due to very strong coupling. Further, Niemi et. al. [12] reported experimental demonstration of wavelength demultiplexing based on 2D-PhC waveguides. To filter out the desired wavelengths, they shifted the cutoff frequency of the fundamental photonic band gap (PBG) mode by varying size of the border holes adjacent to the waveguide core.

Specific needs of optical filters appropriate for a MUX-DEMUX can also be accomplished through incorporation of artificial periodic disturbances, or 'defects' in a different way into the PhCs. In the present article, we propose a PhC based filter, where defects are introduced through extension of dielectric layers in selective unit cells of the periodic structure. Selection of the denser dielectric layer for this purpose offers additional optical path with minimum increase in structure dimension. Transmittivities of such modified PBG structures are estimated using transfer matrix method. The resulting transmission spectra reveal that phase shifts, thus introduced through defects, open up transmission windows in the photonic band gap of the crystal in accordance with the principle of Bragg reflection. The location, spacing, isolation and width of these transmission windows can be precisely controlled. We outline a general methodology to design a photonic crystal with defects that can be used as narrowband transmission filter in a MUX-DEMUX suitable for CWDM system. Such a filter can then be easily engineered to meet the specifications defined by ITU-T Recommendation G.694.2 regarding channel allocation and inter-channel separation.

2. Theory and modeling

In order to estimate the transmittivity for a PBG structure, a general form of its transfer matrix is formulated. We consider a 1D PBG structure schematically shown in Fig. 1. It extends along *z*-direction and comprises of *N* unit cells, formed by alternating arrangements of two non-magnetic dielectric materials of widths L_1, L_2 and refractive indices n_1, n_2 ($n_1 > n_2$). A *p*-polarized electromagnetic wave associated with light is assumed to propagate in the *xz* plane and to be incident on the structure along *z*- direction.

The complex amplitudes (A_m and C_m) of the forward and backward waves formed at the m^{th} interface between layers of higher and lower refractive index medium are described by the relations:

$$C_{m-1} = \frac{a_{12}}{b_{12}} A_{m-1} + \frac{d_{12}}{b_{12}} C_m e^{i\theta_2} \quad (1)$$

and

$$A_m e^{-i\theta_2} = \frac{c_{12}}{b_{12}} A_{m-1} - \frac{a_{12}}{b_{12}} C_m e^{i\theta_2} \quad (2)$$

where $a_{12} = n_2 - n_1$, $b_{12} = n_2 + n_1$, $c_{12} = 2n_1$, $d_{12} = 2n_2$, with $\theta_1 = k_{m-1} L_1$, $\theta_2 = k_m L_2$, $k_{m-1} = n_1 \frac{\omega}{c}$ and $k_m = n_2 \frac{\omega}{c}$.

Waves at the interface between rarer to denser dielectric layers can have similar descriptions.

Thus, amplitudes of the waves on either sides of the n^{th} unit cell can be related as

$$\begin{bmatrix} A_{n-1} \\ C_{n-1} \end{bmatrix} = T_1 * \begin{bmatrix} A_n \\ C_n \end{bmatrix} \quad (3)$$

where T_1 is a 2 X 2 matrix, popularly known as transfer matrix (*T* matrix) , with elements

$$T_{11} = T_{22}^* = \frac{1}{c_{12} d_{12}} \left(b_{12}^2 e^{-i(\theta_2 + \theta_1)} - a_{12}^2 e^{i(\theta_2 - \theta_1)} \right)$$ and

$$T_{12} = T_{21}^* = \frac{a_{12} b_{12}}{c_{12} d_{12}} \left(e^{i(\theta_2 + \theta_1)} - e^{-i(\theta_2 - \theta_1)} \right).$$

Introduction of defect, through interruption in periodicity of the crystal, incorporates additional phase which is proportional to the optical path offered by the defect region. The additional phase shift disturbs the 'in phase' relationship for a specific wavelength undergoing Bragg reflection at the interfaces, and thereby, gives rise to sharp transmission peak within the photonic band gap. The location of this transmission peak can be tuned by altering length of the defect region, while the refractive index contrast between the dielectric materials governs its bandwidth. In this paper, such defects are created in specific unit cells by extending the width of its denser dielectric layer as indicated in Fig.1.

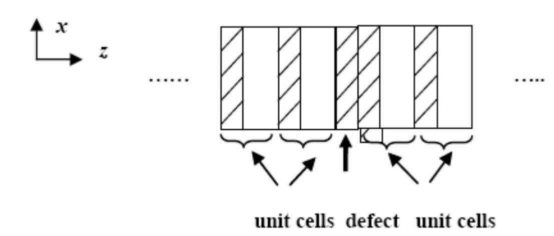

Fig.1. A schematic PBG structure with defect; the red layers represent denser medium while the others lighter one.

A phase shift θ_j, thus introduced in the j^{th} unit cell, can be mathematically realized by multiplying *T* matrix of that unit cell with a diagonal matrix T_{θ_j} , where

$$T_{\theta_j} = \begin{bmatrix} e^{j\theta_j} & 0 \\ 0 & e^{-j\theta_j} \end{bmatrix} \quad (4)$$

Following the same principle, several defects can be incorporated in a PhC to open multiple transmission windows.

Using transfer matrix method, forward and backward waves for the entire PBG structure with defects can be expressed in a form similar to eq.(3), where the resultant matrix represents product of all the 2 X 2 matrices for individual unit cells.

Assuming that the incident wave is normalized (i.e. A_1 =1) and suffers no further reflection after coming out of the structure (i.e. C_N = 0), the resultant T-matrix can finally be formulated as [14]

$$T = \begin{pmatrix} \frac{1}{t} & \frac{r^*}{t^*} \\ \frac{r}{t} & \frac{1}{t^*} \end{pmatrix} \quad (5)$$

where r^* and t^* are complex conjugate of reflection (r) and transmission (t) coefficients for the PhC. From eq.(5), transmittivity of the PBG structure can be readily determined as

$$T_p = \left(\frac{n_2}{n_1} \right) \left(t.t^* \right) \quad (6)$$

Its value can be modulated by selectively introducing defects in the PhC.

3. Results and discussion

In this paper, we consider a PBG structure with ten 2-layer unit cells with n_1 and n_2 taken as 3.5 and 1.5 [as in Ref. 14] to illustrate our results. In order to place the band gap center close to free space wavelength ($\lambda_0 = 2\pi c/\omega_o$), each dielectric layer of a unit cell should provide an optical path of $\lambda_0/4$. The choice of λ_0 as 1550 *nm* leads to widths of respective dielectric layers of the structure as 111 *nm* and 258 *nm*.

To tailor the transmission characteristic of a PhC for specific applications, we incorporate defects through extension of dielectric layers in selective unit cells. As mentioned earlier, such extension introduces additional phase shift proportional to defect length. Fig. 2 shows that incorporation of a defect corresponding to a 90^o phase shift (Φ) at the central interface of the structure opens up a narrow transmission window at λ_0. It also indicates that modulation of length of the defect region results in windows appearing at different wavelengths within the stop band. However, insertion of the defect at any interface other than central one results in drastic fall in its transmiittivity.

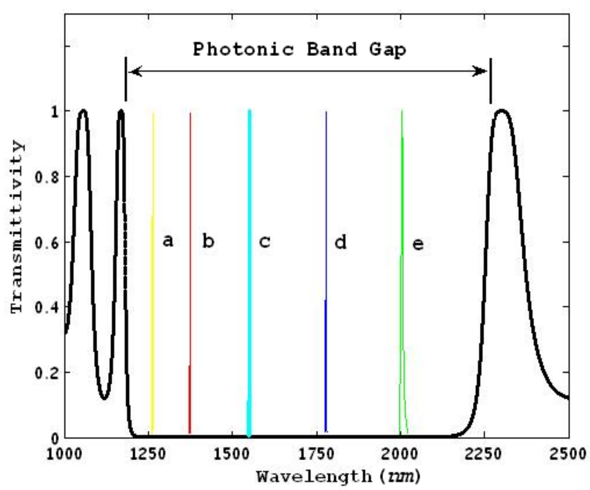

Fig. 2. Transmittivity vs. wavelength of transmission window for length of defect region equivalent to additional phase (Φ): (a) Φ =30^0 (yellow), (b) 60^0 (red), (c) 90^0 (cyan), (d) 120^0 (blue) and (e) 150^0 (green); the defect is introduced at the central interface in a 10-period 1D PBG structure with n_1=3.5, n_2=1.5 and λ_o = 1550 nm .

A variation in refractive index contrast of the dielectric layers, on the other hand, is found to modulatethe bandwidth of transmission windows. As evident from Fig. 3, higher values of refractive index contrast yield narrower windows.

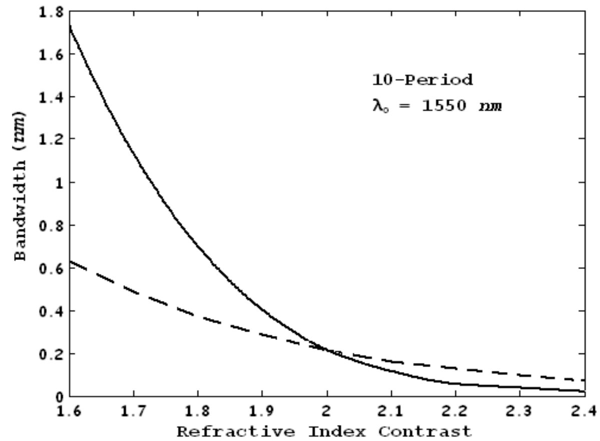

Fig. 3. Bandwidth of transmission window vs. refractive index contrast of dielectric materials with: n_2=1.5, n_1 is varied (solid) and n_1=3.5, n_2 is varied (broken).

Fig. 3 also indicates that width of the resulting window is more sensitive to variation in refractive index of the denser material. Therefore, in order to incorporate an estimated disturbance in the PBG structure, we prefer to modulate width of the denser layer only.

Fig. 4 relates wavelength of the desired transmission peak to the required length of defect region. The corresponding phase shifts thus introduced are also shown.

Thus, Figs. 3 and 4 can provide guidelines to have desirable transmission characteristics from a PhC with single defect.

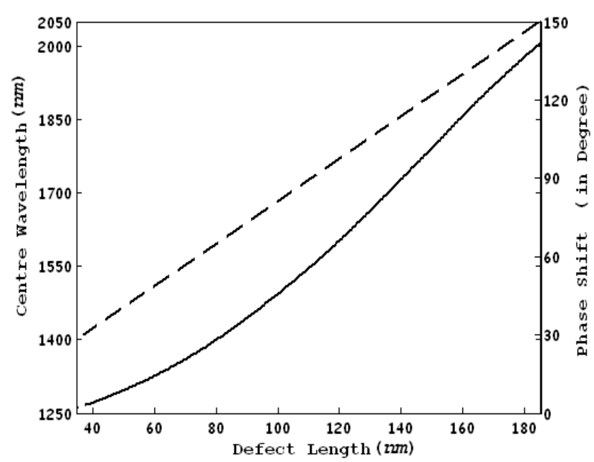

Fig. 4. Variation of centre wavelength of transmission window (solid) and corresponding phase shifts introduced (broken) with extension of dielectric layer width at the central interface of a 1D PBG structure.

In the same manner, a number of defects introduced symmetrically into a PBG structure gives rise to equal number of transmission windows within its stop band. The periodicity in distribution of defects controls the separation between transmission peaks. In this communication each defect is introduced by simply doubling the thickness of denser layer in specific unit cell and thus, corresponds to an additional 90^{o} phase shift.

Incorporation of such defects allows the windows to be opened symmetrically about the free space wavelength λ_0. Defect regions of other lengths result in asymmetric windows at wavelengths apart from λ_0, and therefore, make the structure unusable for specific application. Fig. 5 presents transmission characteristics for a 15-period PBG structure, within which 2 defects are incorporated at an interval of 5 unit cells. The resulting structure yields two transmission windows, with a spacing of 12 *nm*, appearing symmetrically about 1550 *nm*. It therefore comes out to be suitable for filtering CWDM channels. Other features of this basic model are summarized in Table I.

The inter-channel spacing i.e., separation between the transmission peaks is sensitive to variation in refractive index of each dielectric layer of the PhC. The dependence of channel spacing only on refractive index of the denser layer is presented in Fig.5, as the width of this layer is changed to introduce defects. The figure shows the variations for PhCs with 2- defects incorporated at a period of 3- and 4- unit cells. It indicates that inter-channel spacing can be primarily tuned by modulating number of periods between defect regions, while its exact tuning depends on a proper choice of material pair. Once the material pair and defect interval are fixed by the specified channel separation, total number of unit cells and thereby, total length of the resulting PhC can be readily determined. However, through an estimated shift in λ_0, the set of windows having desired width and spacing can be translated to a specified location, with all their features retained.

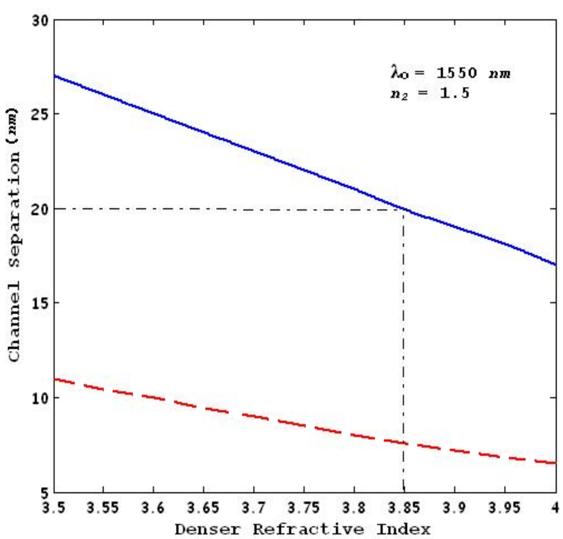

Fig. 5. Interchannel separation vs. denser layer refractive index for a 2-channel PBG filter with two defects separated by: 4 unit cells (solid) and 5 unit cells (broken).

Exploiting the above features, such PBG structures can be tailored to serve as add/drop filters in a MUX-DEMUX for a multi-channel optical communication link. In the following, we aim to design a filter that satisfies the ITU-T recommendation (G.694.2). The PhC is to be designed such that the channels lie entirely within its photonic band gap, while individual channel wavelengths correspond to centers of the introduced windows. The free space wavelength for the structure is to set at the middle of the channel wavelengths. Therefore, in order to add/drop the ITU-T recommended channels 1551 *nm* and 1571 *nm*, design of filter is based on λ_0 translated to 1561 *nm* from 1550 *nm* as considered in the previous model. To support the channels with a spacing of 20 *nm*, two defects must be introduced properly. Refractive index of the denser material and number of unit cells between the defects, that provides the required channel spacing, can be derived from Fig. 5. It results in the refractive index as 3.85 and interval between the defects as 4 unit cells for the 2-channel system. In other filter with different channel spacing or /and higher number of channels, design criteria may involve modification of refractive indices for both the materials in the PhC.

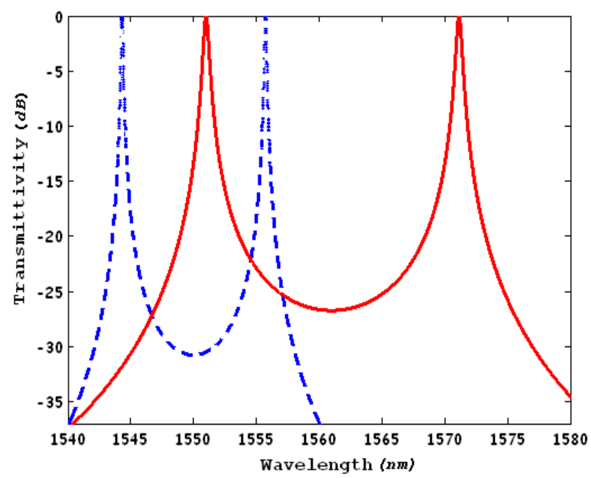

Fig. 6. Transmission characteristics of a photonic crystal based filter supporting CWDM channels: a typical model (broken) and a model satisfying ITU-T Recommendation (solid).

Transmission characteristic of the resulting PhC based filter for filtering ITU-T recommended channels is presented in Fig. 6, along with that for a typical structure filtering CWDM channels as discussed earlier. Other features of ITU-T recommended channels and the design parameters of the filter supporting those channels are summarized in Table I.

Table 1. Parameters of add/drop filters for a 2-channel DEMUX based on 1D PBG with defects.

Parameters	Filters supporting CWDM channels	
	A typical model	Model satisfying ITU-T Recommendation
Channel wavelengths (*nm*)	1544 , 1556	1551, 1571
Channel spacing (*nm*)	12	20
Channel width (*nm*)	0. 3	0. 5
Stop band attenuation (*dB*)	-30	-26.7
Free space wavelength (*nm*)	1550	1561
n_1	3.5	3.85
n_2	1.5	1.5
L_1 (*nm*)	110.7	101
L_2 (*nm*)	258.3	258.3
No. of unit cells	15	12
Defect Length (*nm*)	110.7	101
Width of the entire structure (*μm*)	5.8	4.5

In order to demultiplex the dropped channels, the signal obtained from above add/drop filter output is then split into a number of branches, schematically shown in Fig.7. PhCs with single defect incorporated at their central interface, are employed in all branches.

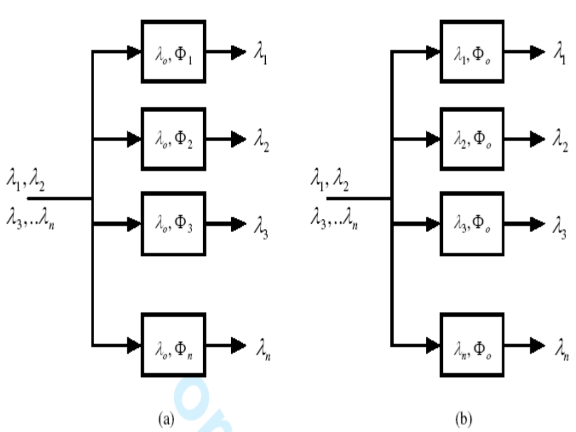

Fig. 7. Schematic illustration of the DEMUX based on PhCs with single defect. In different branches, in scheme (a) defect length varies with identical λ_0; (b) λ_0 varies with identical defect.

To make the individual channels available at outputs of respective branches, we may adopt either of the following schemes. The PhCs may be characterized with an identical λ_0, but defect length in different branches varies to open the transmission window selectively at the wavelength to be supported by the channel. With the help of variation as presented in Fig.4, the defect length required for this purpose may be estimated. Alternatively, λ_0 for PhC in each branch is set at the corresponding wavelength to be taken out, where all the defects are to be introduced simply by doubling the denser dielectric layer of the specific unit cell. Thus the entire MUX-DEMUX module can be achieved using only PhCs with defects, and therefore, can be realized in an integrated form.

4. Conclusion

Transmission characteristics of PhCs were tailored by introducing defects through proper extension in width of selective dielectric layers. The defects give rise to narrow transmission windows at desired locations with precisely controlled width, isolation and spacing. We thus simulated PhCs with such defects, which serve as optical filters and are useful in realizing MUX-DEMUXs suitable for CWDM system. The general methodology to design PBG structures for filtering multiple channels with specified channel spacing has been described. The proposed method is validated for two ITU-T recommended channels, viz. 1551 *nm* and 1571 *nm*. A scheme to de-multiplex the channels using only PhCs with single defect is also proposed. The simplicity of the scheme in introducing defects in PBG structures is expected to yield less fabrication hazards in realizing above systems compared to other PhC-based MUX-DEMUXs [11], [12]. Structures proposed here are also expected to have better reproducibility. In addition, Si_{100} and SiO_2, having refractive indices closest to those used for simulation, may be the practical choice for material pair for above filter. The matured Si-based technology will also be helpful in realizing the structure in integrated form. We thus believe that this device concept would lead a way to implement simple integrated MUX-DEMUXs for CWDM systems.

References

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[2] B. Liu, A. Shakouri, P. Abraham, J.E. Bowers Applied Physics Lett., **76**, 282 (2000).
[3] S. J. McNab, N. Moll, and Y. A. Vlasov, Opt. Expr., **11**, 2927 (2003).
[4] Y. Sugimoto, Y. Tanaka, N. Ikeda, Y. Nakamura, K. Asakawa, K. Inoue, Opt. Expr., **12**, 1090 (2004).
[5] E. Chow, S. Y. Lin, J. R.Wendt, S. G. Johnson, J. D. Joannopoulos, Opt. Lett., **26**, 286 (2001).
[6] S. Y. Lin, E. Chow, J. Bur, S. G. Johnson, J. D. Joannopoulos, Opt. Lett., **27**, 1400 (2000).

[7] L. H. Frandsen, P. I. Borel, Y. X. Zhuang, A. Harpøth, M. Thorhauge, M. Kristensen, W. Bogaerts, P. Dumon, R. Baets, V. Wiaux, J. Wouters, S. Beckx, Opt. Lett., **29**, 1623 (2004).
[8] M. Thorhauge, L. H. Frandsen, P. I. Borel, Opt. Lett. **28**, 1525 (2003).
[9] B.-S. Song, S. Noda, T. Asano, Science **300**, 1537 (2003).
[10] L. Wu, M. Mazilu, T. Karle, T. F. Krauss, IEEE J. Quantum Electron. **38**(4), 915 (2002).
[11] M. Koshiba, J. Lightwave Technology. **19**(5), 1970 (2001).
[12] Tapio Niemi, Lars Hagedorn Frandsen, Kristian Knak Hede, Anders Harpøth, Peter Ingo Borel, Martin Kristensen, IEEE Photonics Technology Letters, **18**(1), 226 (2006).
[13] H. Kim, I. Park, B. O. S. Park, E. Lee, S. Lee, Opt. Expr., **12**, 5625 (2004).
[14] J. W. Haus, "Photonic band gap structures" in Nanometer Structures: Theory, Modeling and Simulation (Ed: A. Lakhtakia), Publisher City: New Delhi, Publisher Name: PHI, 2007, pp. 45

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