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Photonic crystal based add/drop optical filter with flat-top response

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In this paper, an all-optic add/drop filter, having nearly squared flat top spectral characteristic, is designed using 1D photonic crystal with defects. Estimated defects are incorporated here into the Photonic band gap (PBG) structure through proper extension in dielectric layers of specific unit cells. Performance of the flat top filter is analyzed using transfer matrix method. The analysis reveals that the distribution of the introduced defects controls the transmission characteristics of the structure. To achieve flat top response, the general condition regarding distribution of defects within the PhC is derived. Analysis is also carried out to ensure the optimum design for ripple free pass band. Width of the flat top pass band is further tailored to support shifts of signal wavelength in an allotted channel within its permissible limit, which is 14 *nm* as specified by ITU-T Recommendation G.694.2 for a coarse wavelength division multiplexing (CWDM) system.

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1. Introduction

Photonic crystals (PhCs) are essentially dielectric periodic structures [1] that possess a great potential in controlling light propagation. They appear to be very promising in realizing novel photonic devices for various applications in integrated optical communication systems. In the last decade, research interest has therefore, been intensified on such devices [2-13]. Specifically, important roles of filters in channel selection for wavelength multiplexed systems [14-18], make optical filters based on PhCs a subject of special interest.

In optical coarse wavelength division multiplexing (CWDM), it is desirable to have a compact optical filter with unity gain squared pass band. Such response ensures signal fidelity that increases the tolerance for shifts in signal wavelength. Such filter should also be characterized with side lobe-free stop bands. A variety of such optical filters, viz. thin-film filters [14], arrayed waveguide grating (AWG) filters [15], and photonic band gap (PBG) micro cavity waveguide filters [16-18] have been developed. However, thin film-filters cannot be integrated with active optical devices in photonic integrated circuits. AWGs are of complex structures and do not favor flat-top pass band tailoring due to high insertion loss associated with it. PBG micro cavity waveguides, on the other hand, are suitable for integration. But they make use of anomalous dispersion (AD) mirrors employing PBG micro cavities with inherent radiation loss.

In this paper, we propose PhC based side lobe-free filter, characterized with unity transmittance and nearly squared pass band. A transfer matrix formulation for the structure is made to compute spectral characteristics of the filter. The filter design involves introduction of defects in the PBG structure through extensions of dielectric layers in selective unit cells. The defect regions divide the periodic structure into a number of segments. A detailed derivation ensures proper choice of the optical paths offered by these segments to achieve a flat top ripple free response. Variation in roll-off and 3-dB band width of the pass band with refractive index contrast of the dielectric pair is also investigated. The model can further be modified to offer a full-width of 14 *nm* at half maximum of the pass band to brace the tolerable limit of shift in carrier signal wavelengths, allocated for CWDM systems, as specified by ITU-T Recommendation G.694.2.

2. Theory and modelling

2.1 General theory for PBG structure with defects

We consider a 1D PBG structure that extends along z-direction and is composed of N number of unit cells (as shown in Fig. 1). Each unit cell is formed by a pair of non-magnetic dielectric materials with refractive indices n_1, n_2 and of thickness l_1, l_2 respectively. In order to tune the center of photonic band gap about the free space wavelength ($\lambda_0 = 2\pi c/\omega_o$), individual dielectric layer in each unit cell should provide an optical path of length $\lambda_0/4$.

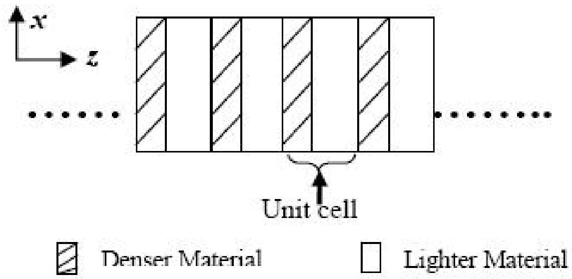

Fig. 1. Schematic presentation of 1D PBG structure.

Light is assumed to incident on the structure along z direction. A general form of transfer matrix is formulated to estimate the transmittivity of the 1D PBG structure. Complex amplitudes (A_m and C_m) of the forward and backward waves formed on either sides of the m^{th} unit cell can be expressed in terms of refractive indices of dielectric layer using Transfer matrix (T matrix) approach. They are related through T matrix as

$$\begin{bmatrix} A_{m-1} \\ C_{m-1} \end{bmatrix} = \begin{bmatrix} T_1 \end{bmatrix} \begin{bmatrix} A_m \\ C_m \end{bmatrix} \tag{1}$$

where T_1 is a 2 X 2 matrix with elements

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

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

with $a_{12} = n_2 - n_1$, $b_{12} = n_2 + n_1$, $c_{12} = 2n_1$, $d_{12} = 2n_2$, and $\theta_1 = k_{m-1}l_1$, $\theta_2 = k_m l_2$, $k_{m-1} = n_1 \frac{\omega}{c}$ and $k_m = n_2 \frac{\omega}{c}$.

PhC-based filter design starts with opening a transmission window in photonic band gap of the structure. In order to introduce the window, the denser dielectric layer of specific unit cell in the periodic structure is extended so that it offers additional optical path and puts in estimated phase shifts into the propagating light waves. This approach suggests an efficient mean to distribute defects in PBG structure. The location and bandwidth of the window can be precisely controlled by the amount of additional phase introduced and the nature of the dielectric materials. A phase shift of θ_j, introduced in the j^{th} unit cell, can be realized mathematically by multiplying T matrix of the corresponding unit cell with a diagonal matrix $T_{\theta j}$ with elements exp ($\pm i\theta_j$). In similar manner, insertion of multiple defect regions into the structure may result in precisely controlled multiple transmission windows.

T matrix of the entire structure can be obtained by multiplying T matrices of all individual unit cells. Assuming that the incident wave is normalized (i.e. A_1 =1), and suffers no further reflection after the terminal N^{th} unit cell (i.e. C_N = 0), resultant T-matrix can finally be formulated as

$$T = \begin{pmatrix} \frac{1}{t} & \frac{r^*}{t^*} \\ \frac{r}{t} & \frac{1}{t^*} \end{pmatrix} \tag{2}$$

where r^* and t^* are complex conjugate of the reflection (r) and transmission (t) coefficients of light wave for the phase shifted PBG structure. From equ (2), transmittivity of the PBG structure can be readily determined as

$$T_p = \left(\frac{n_2}{n_1}\right)\left(t.t^*\right) \tag{3}$$

2.2 Modelling for flat top response

PBG structures with defects can be employed for filtering of wavelength channels in Multiplexer-Demultiplxer (MUX-DEMUX) of a CWDM system. However, the bandwidth of transmission windows obtained by following the above scheme is insufficient to accommodate the tolerable shifts in channel wavelength. For system designers, it is desirable to have a band pass filter with nearly squared pass band with unity transmittivity to cope with such shift in carrier signal wavelength.

In order to have a flat-top transmission window, a number of identical defects, each introducing 90^o phase shift, are incorporated into the structure dividing it into a no. of symmetrical sections. Thus, (N-1) defects divide the structure into N symmetrical sections such that $L_1 = L_N$, $L_2 = L_{N-1}$, and so on, where L_N is length of optical path offered by the N^{th} segment. Design of filter involving only two defects is described below.

2.3 All optic filters with two defects

In this case, we introduce two defects, symmetrically into the PBG structure dividing it into three separate segments as shown in Fig. 2.

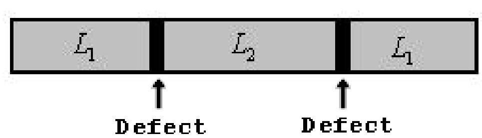

Fig. 2. Schematic presentation of 1D PBG structure with two defects.

Let us consider that T_A is transfer matrix for the single segment offering optical path L_1 and T_B is that for segment with optical path L_2. Elements of these matrices can be estimated using equ (1). Resultant T matrix (T_R) for the filter structure can, therefore, be expressed as

$$T_R = [T_A] * \begin{bmatrix} i & 0 \\ 0 & -i \end{bmatrix} * [T_B] * \begin{bmatrix} i & 0 \\ 0 & -i \end{bmatrix} * [T_A] \quad (4)$$

For simplicity, if we assume the contrast in refractive indices for the dielectric materials to be insignificant, the transfer matrices take the form

$$T_A = \begin{bmatrix} e^{-iL_1} & 0 \\ 0 & e^{iL_1} \end{bmatrix} \;\&\; T_B = \begin{bmatrix} e^{-iL_2} & 0 \\ 0 & e^{iL_2} \end{bmatrix}.$$

The transfer matrix for the entire structure is finally obtained as

$$T_R = \begin{bmatrix} e^{-i(2L_1+L_2)} & 0 \\ 0 & e^{i(2L_1+L_2)} \end{bmatrix},$$

from which its transmittivity can be estimated using equ (2) and equ(3).

A detailed derivation shows that to attain unity flat top transmission, the length of filter segments must fulfill the following condition

$$\gamma = \left| {L_2}/{L_1} \right| = 2 \quad . \quad (5)$$

3. Results and discussion

To compute the transmission spectrum of 1D PBG structure with defects, we take free space wavelength (λ_o) as 1550 *nm*, the most important wavelength for optical communication, and each of the two incorporated phase shifts as 90^o. As for the materials for PBG structure, we choose silicon (n_1 =3.45) and silicon dioxide (n_2 = 1.445), leading to a quite significant refractive index contrast. In deriving the condition for unity flat top transmission, the index contrast was assumed to be insignificant for the sake of simplicity. However, the condition remains the same irrespective of the value of the index contrast. In case of significant index contrast, as is taken by the choice of materials, the bandwidth of the window, and also the range of wavelength over which its flatness occur, gets modified only.

It is evident from Fig. 3 that for γ < 2, two transmission peaks appear symmetrically about λ_o, as usually expected for a PhC with two defect regions. Both peaks shift towards λ_o as γ approaches 2, and finally merge for γ exactly equal to 2 leading to flat top response with unity pass band. For γ > 2, we also get a single transmission peak, but it lacks unity transmittivity. Fig. 3 thus confirms that to have desirable filter response, the number of unit cells between two phase shift regions, i.e. the optical path length of different segments of the filter structure must satisfy our derived condition (5).

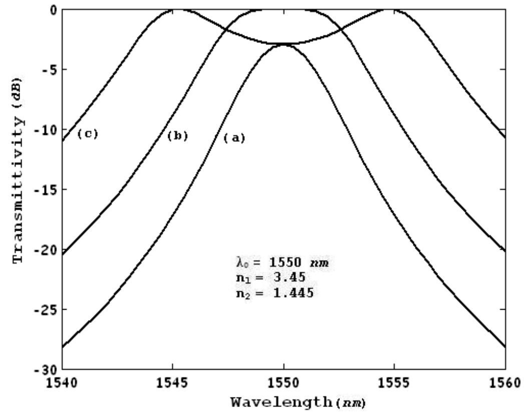

Fig. 3. Transmittivity vs. wavelength of transmission window in a 1D PBG structure with two defects for (a) γ>2 , (b) γ=2 and (c) γ<2; in all cases the length L_1 in terms of no. of unit cell is 3 with that for L_2 as (a) 7, (b) 6 and (c) 5.

3.1 Ripple factor

It is evident from Fig. 3 that for γ < 2, two very closely spaced peaks appear symmetrically about λ_o. Isolation between the peaks is so nominal that they can be treated as a wide single window with some ripple in its transmission characteristic.

To estimate the amount of ripple present, a ripple factor is defined as

$$R = \frac{T_{Max} - T_{Min}}{T_{Max} + T_{Min}}$$

where, T_{Max} corresponds to maximum transmittivity, which is obviously unity; T_{Min} is the minimum value of transmittivity, and therefore, can be taken as the measure of the dip.

The variation of ripple factor with the optical path length ratio γ is plotted in Fig. 4 for different value of refractive index of the denser layer, while keeping the lighter material unaltered.

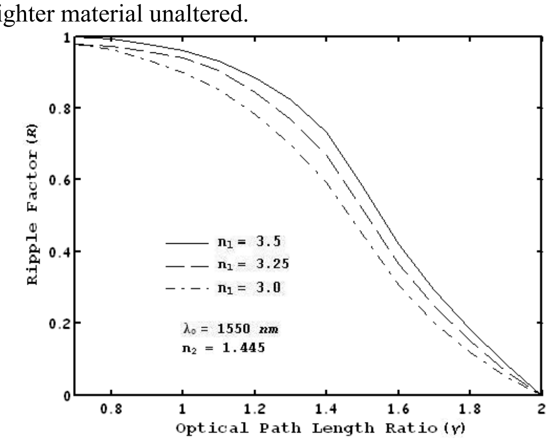

Fig. 4. Variation of ripple factor as a function of the optical length ratio γ, for different denser layer materials.

For a pair of materials, ripple rapidly increases as the ratio γ deviates from 2, its optimum value. The ripple also increases significantly with increase in refractive index contrast. The figure also shows that all the curves for different material pairs converge at γ = 2. It indicates that with γ = 2, i.e. with properly distributed defects, a PhC-based filter can provide flat-top ripple free transmission spectrum irrespective of the material pair used in it.

3.2 Bandwidth and roll off

The bandwidth and roll off of the pass band are two other important parameters that determine the performance of an optical filter. Extent of flatness of the pass band and roll off at the band edges can be controlled by refractive index contrast of the dielectric materials. To vary the index contrast, refractive index of denser layer only is altered here, as it affects the phase relationship by a greater extent, and thereby, makes the transmission spectrum more sensitive to its variation.

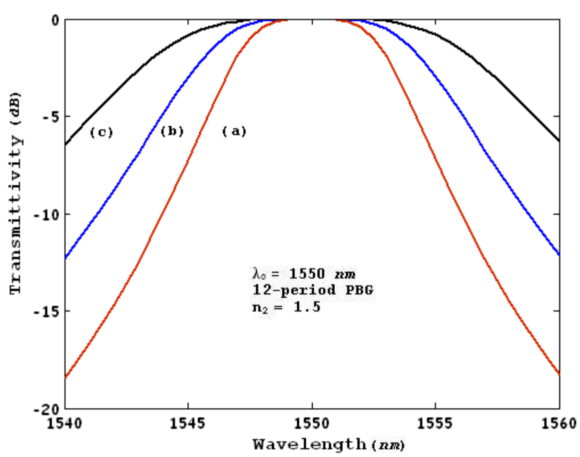

Fig. 5. Transmittivity vs. wavelength of transmission window for a PhC-based filter with n_2 taken as1.5 and n_1 as (a) 3.45, (b) 3.25, (c) 3.0.

Fig. 5 reveals that a higher refractive index contrast makes the edges of the pass band steeper, implying the filter to be more selective in nature. A higher index contrast further causes a reduction in width of the pass band. These features enable us to choose proper materials to have filters with desirable transmission spectra.

To employ such filter for channel selections in a CWDM add/drop multiplexing system, the full width at half maximum (FWHM) of the transmission peak must be sufficient to accommodate the allowable shift in carrier wavelength. As specified by ITU-T Recommendation G.694.2, source wavelength variation of ± (6 – 7) *nm* is permissible. Thus, the window opened should possess a FWHM of about 14 *nm.*

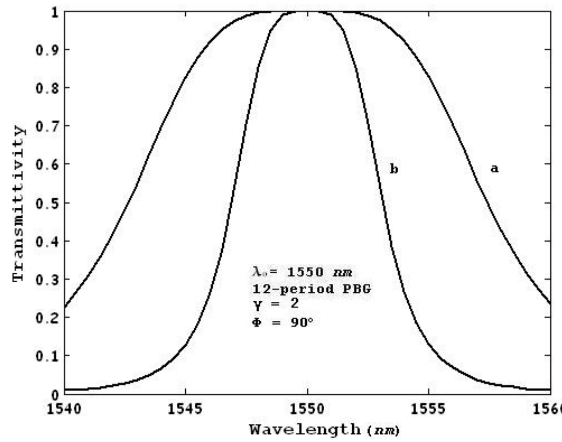

Fig. 6. Transmittivity vs. wavelength of transmission window for a phase-shifted PBG structure with different dielectric pairs: (a) n_1=3, n_2 =1.5 (b) n_1= 3.45, n_2=1.445

Fig. 6 presents the transmission spectrum for a filter that comprises of twelve unit cells with proper distribution of defects within it with the condition γ = 2 fulfilled. The filter thus designed with silicon and silicon dioxide as the dielectric materials can provide a FWHM of at most 7 *nm*. A demand of 14 *nm* FWHM can be satisfied by a material pair with refractive indices 3 and 1.5. The modified filter response is also presented in Fig.6. However, it is characterized with band edge roll–off and structure dimension almost comparable with those for micro cavity waveguide filter (FWHM of 13.6 *nm*) reported by Chyong-Hua Chen et. Al. [17] in 2007. But the most striking feature of our proposed model is that by virtue of its structure, it should be almost free from the inherent radiation loss present in the model referred above. The proposed structure also offers an improvement in FWHM value.

4. Conclusions

A band pass filter with flat top response is designed using photonic crystal with defects. A condition for squared pass band of the filter is derived. Simulated results also verify the derived condition through proper optimization in distribution of defects within the structure. The condition also assures ripple free flat top pass band for any pair of materials. The proposed filter with materials of refractive indices 3.0 and 1.5 provides a FWHM of 14 *nm* that can accommodate the channel in presence of carrier wavelength shift within permissible range specified by ITU-T Recommendation G.694.2. The closest choice of practical material for the above filter is *AlGaAs* with 8.4% aluminum as the denser material and SiO_2 as the lighter one. The proposed structure is expected to be almost free from inherent radiation loss present in other PhC based flat top band pass filter, and therefore, will be very useful for multiplexing-demultiplexing in 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, 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 Electronics. **38**, 915 (2002).
[11] M. Koshiba, J. Lightwave Technology. **19**, 1970 (2001).
[12] T. Niemi et al. IEEE Photonics Technology Letters, **18**, 226 (2006).
[13] H. Kim, I. Park, B. O. S. Park, E. Lee, S. Lee, Opt. Expr. **12**, 5625 (2004).
[14] P. Baumeister, Opt. Exp. **9**, 652 (2001).
[15] T. Kitoh, Y. Inoue, M. Itoh, M. Kotoku, Y. Hibino, Electron. Lett. **39**, 1116 (2003).
[16] J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith, and E. P. Ippen, Nature, **390**, 143 (1997).
[17] Chyong-Hua Chen, Yeshaiahu Fainman, IEEE J. of selected topic Quantum Electronics **13**, 261 (2007).
[18] A. S. Jugessur, P. Pottier, R. M. De La Rue, Electron. Lett. **39**, 367 (2003).

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