Variation of optical bandwidth in defected ternary photonic crystal under different polarisation conditions

Arpan Deyasi*
Department of Electronics and Communication Engineering,
RCCI Institute of Information Technology,
Kolkata-700015, India
Email: deyasi_arpan@yahoo.co.in
*Corresponding author

A. Sarkar
Department of Electronics and Communication Engineering,
KGEC,
Nadia-741235, India
Email: icce16@gmail.com

Abstract: Photonic bandwidth of defected one-dimensional ternary photonic crystal is analytically calculated under both types of oblique incidences. Both P and S type polarised incidences on the structure are considered in order to compute transmittivity of the proposed Butterworth type bandpass filter, and passband spectrum is kept at 1,550 nm by suitably choosing structural parameters and defect density. Defect is kept within feasible limit, and ripple in the desired passband region is tailored by its controlled variation. Width of passband as function of defect density, angle of incidence and dimension of constituent layers is computed, and critical dimension for the sandwiched layer is predicted over which the structure will behave as equivalent binary one. For closely-spaced signal transmission, this narrow bandpass filter will work as excellent candidate to improve SNR.

Keywords: optical bandwidth; transmittivity; polarised condition; defect density; ternary crystal; ripple factor.

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Biographical notes: Arpan Deyasi is currently working as an Assistant Professor in the Department of ECE in RCCIT, Kolkata, INDIA. He has 12 years of professional experience in academics and industry. He received BSc (Hons), BTech, and MTech from the University of Calcutta. He is working in the area of semiconductor nanostructure and semiconductor photonics. He has published more than 100 research papers in peer-reviewed journals and conferences. His major teaching subjects are solid state device, electromagnetics and photonics. He is a member of IEEE Electron Device Society, IE(I), Optical Society of India, IETE, ISTE, etc.
A. Sarkar is currently serving as an Associate Professor of the ECE Department in KGEC, West Bengal. He had earlier served JGEC as a Lecturer of ECE Department for ten years. He received his MTech in VLSI and Microelectronics from Jadavpur University. He completed his PhD from Jadavpur University in 2013. His current research interest span around study of short channel effects of sub 100 nm MOSFETs and nano device modelling. He is a senior member of IEEE and Executive Committee member of Electron Device Society, Kolkata Section. He has authored five books, three contributed book chapters, 52 peer-reviewed journals and 21 conference papers.

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1 Introduction

Multilayered optical structure which can effectively control the electromagnetic wave propagation is termed as photonic crystal, thanks to the theoretical work of Loudon (1970) two decades ago, followed by verification and physical implementation by Yablonovitch (1987). The restriction of propagation of light in certain spectrum and permission in other frequency ranges is owing to the formation of electromagnetic bandgap (Fogel et al., 1998), and this novel property tailors the behaviour of the structure as photonic filter (Mao et al., 2008). Photonic bandgap is originated due to the difference of refractive indices of the constituent materials and dimensions of the layers inside the periodic organisation (Maity et al., 2013), and its optical filter property can easily be derived once transmittivity is computed as a function of incident wavelength spectrum (Limpert et al., 2004; Xu and Shi, 2010). As a result, the structure behaves like bandpass filter (Biswas and Deyasi, 2015; D’Orazio et al., 2003; Chen et al., 1996). This optical device is already used to construct optical transmitter (Altug and Vučković, 2005), sensor (Liu and Salemink, 2012), receiver (Reininger et al., 2012), fiber (Belhadj et al., 2006), waveguide (Andreani et al., 2003), and also used for communication applications (Liu and Fan, 2013; Shinya et al., 2005).

Work on effect of polarised incidence and magnitude of incident angles (Winn et al., 1998) is carried out a decade ago on one-dimensional photonic crystal. Dispersion property (Khankaev and Steel, 2009) of magnetic photonic crystal (TPhC) is calculated a few years ago for optical confinement. Transmission spectrum of fractal photonic crystal (Xu et al., 2010) is investigated for optical waveguiding. Sawtooth profiles for refractive indices (Morozov et al., 2013) of the materials are recently considered by theoretical workers for exact analytical solution for transmittivity. Nonreciprocal effect inside ternary magnetised plasma photonic crystals for propagating waves is calculated by Arakani (2014). Wanga et al. (2014) made some fundamental studies on ternary structure, and OLED is constructed (Pradana and Gerken, 2015). Optimisation approach for filter design (Hassan et al., 2015) is recently available in literature, and reflectance of TPhC is obtained for metal-dielectric interface (Pandey et al., 2016).

In the present paper, transmittivity and bandwidth of ternary photonic crystal is calculated for oblique incidences (both s-polarised and p-polarised) in presence of point
defects inside the structure. SiO$_2$/air/TiO$_2$ structure is considered for simulation purpose, as it is practically possible to fabricate for the purpose of optical device. If defect density is within tolerable limit, then narrow bandpass filter is generated, and variation of bandwidth is also reported for different structural parameters. Results show that intentional introduction of defect is very key for design of the device with required Butterworth characteristics.

2 Mathematical modelling

Computation of reflectivities can be made for a two layer system under oblique incidence as

\[
\begin{align*}
|r_{21}|^2 &= \frac{n_1 \cos \theta_2 - n_2 \cos \theta_1}{n_1 \cos \theta_2 + n_2 \cos \theta_1} \quad (1) \\
|r_{21}|^2 &= \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \quad (2)
\end{align*}
\]

Assuming the phase of the propagating e.m wave as constant, propagation matrix is given by

\[
P_{n,n} = \begin{pmatrix}
\exp[jk_{n,n}d_{m,n}] & 0 \\
0 & -\exp[jk_{n,n}d_{m,n}]
\end{pmatrix}
\]

(3)

where $d_{m,n}$ is the dimension of $m^{th}/n^{th}$ layer, $k_{m,n}$ is the propagation vector.

We consider ‘$f$’ is normalised defect density. Propagation matrix in presence of point defect is obtained as

\[
P_{n,n} = \begin{pmatrix}
\exp[jk_{n,n}d_{m,n}]f & 0 \\
0 & -\exp[jk_{n,n}d_{m,n}]f
\end{pmatrix}
\]

(4)

Transfer matrix for the elementary cell in presence of defect in first layer and third layer

\[
M_{\text{defect}} = M_{\text{defect}}^T M_{1} M_{2} M_{3} P_{\text{defect}}
\]

(5)

whereas in absence of defect,

\[
M_{\text{defect}} = M_{1}^T P_{1} M_{2}^T P_{2} M_{3}^T P_{3}
\]

(6)

‘$M$’ is the transfer matrix between the adjacent layers, given by

\[
M_{mn}^T = \frac{1}{r_{m,n}} \begin{pmatrix}
1 & r_{m,n} \\
r_{m,n} & 1
\end{pmatrix}
\]

(7)

Considering ‘$N$’ no. of elementary cells, transfer matrix for the system is given by

\[
M_{\text{tot}} = M_{\text{defect}}^N
\]

(8)

From equation (8), value of $M_{11}$ can be substituted to calculate transmittivity as
3 Results and discussions

Using equation (1), transmittivity is calculated as a function of wavelength keeping the central wavelength of passband at 1.55 µm. Structural parameters and incidence angle are chosen in such a way that ripple can be minimised at passband. Simulation is carried out for both types of polarisations in presence of point defect.

**Figure 1** Transmittivity profile with wavelength for different angle of incidence with (a) 2% defect density for s-polarised incident wave (b) 4% defect density for s-polarised incident wave

Bandwidth is calculated from the knowledge of transmission coefficient at passband for different polarisation angles and also for different defect densities. It is calculated as the difference of the adjacent notches around the central passband in wavelength scale.

Figure 1 shows the transmittivity profile for different incidence angles with different defect densities when TM mode propagation is considered. In Figure 1(a), result is obtained for 2% value, whereas in Figure 1(b), it is calculated for 4% defect. It is observed that notch length for different incidence angles are asymmetric on either side of passband. From the plot, it is observed that with increasing angle of incidence, blueshift is observed in passband. Again, the notch length initially reduces with increasing angle which deteriorated filter quality; but at very high angle, filter performance is improved in terms of restriction of noise signal. Similar variation is observed for 4% defect states, as shown in Figure 1(b). This variation suggests the higher incidence angles are preferred for practical application.

But comparative study reveals the fact that with intentional introduction of higher defect density, filter performance is improved, which can be measured with increment of notch length in either side of desired passband. Therefore, it may be concluded that for s-polarised wave incidence, higher defect density within tolerable limit may be considered advantageous for optical filter design.
Figure 2 depicts the transmittivity profile for 2% defect density for different angle of incidence under TE mode propagation. It has been observed from the plot that with minute change of incidence angle, length of guardband varies, but the rejection probability of noise is better than that obtained under s-polarised condition. In this case, with increasing angle, red shift is observed for passband. But one point may be noted in this context that notch length in either side becomes asymmetric with increasing angle, i.e., filter performance is degraded. Also the amount of ripple is passband is higher than that obtained in Figure 1(a). Hence a trade-off is required.

**Figure 2** Transmittivity profile with wavelength for different angle of incidence with 2% defect density for p-polarised incidence wave

![Transmittivity profile](image)

**Figure 3** Bandwidth variation with (a) SiO$_2$ layer width for p-polarised incidence with different incident angle (b) TiO$_2$ layer width for s-polarised incidence with different incident angle

![Bandwidth variation](image)
Figure 3 exhibits the variation of bandwidth for constituent layer widths under different polarisation conditions. Figure 3(a) shows it for p-polarisation condition for different angle of incidences when SiO$_2$ layer dimension is varied; whereas in Figure 3(b), it is depicted for s-polarisation condition under TiO$_2$ layer width modulation. For both the cases, results are compared with that obtained in case of normal incidence. It is noted that for both the cases, result is obtained for 3% defect states. In both the cases, it is observed that bandwidth monotonically decreases with increasing dimension. Comparative study reveals that that the difference of bandwidths for different incident angles can clearly be distinguished in case of SiO$_2$ layer width variation than that of TiO$_2$.

Figure 4 shows the variation of bandwidth for different defect densities under p-polarisation condition. In Figure 4(a), it is noted down that for 1.5 µm thickness of SiO$_2$ layer, defect density lines for 3% and 4% makes a crossover. This suggests that higher defect density in ternary photonic crystal does not always reflect poor quality propagation. That’s why bandwidth is reduced with increasing defect density when dimension of the layer becomes higher than the critical value. But before the critical dimension, 4% defect gives higher bandwidth than the 3% defected structure which clearly makes importance and speaks in favour of intentional introduction of defects in the ternary PhC’s. In Figure 4(b), bandwidth is plotted by varying TiO$_2$ layer width. It is seen from the graph that bandwidth rapidly decreases with increase of layer width, and the rate is modified with change of defect density. But the rate of reduction is decreased once the layer width becomes wider.

4 Conclusions

Photonic bandpass filter is designed for optical communication with central wavelength of passband at 1,550 nm in such a way that minimum ripples is obtained in the desired spectrum. This is achieved by suitably choosing the constituent layer dimensions, i.e., length of the layers along the direction of wave propagation. Point defects are considered
in the otherwise perfect layers to make the results more realistic, as it is hardly possible to fabricate optical device with pure materials without any defect at the time of fabrication. Bandwidth variations are reported as a function of material widths and defect densities, which is very important for practically realisable filters as it gives the prediction for filter performance. Simulation work with consideration of defects is justified with the obtained result that bandwidth reduces with increasing defect, and hence accurate computation is required prior to fabrication. Findings help to conclude that appropriate defect incorporation provides better outcome than the ideal structure. It may be finally commented that depending on the simulation result, filter design is possible as per requirement, i.e., bandwidth and ripple in passband.

References


