Design of Channel Filter based on Asymmetric One-Dimensional Defective Photonic Crystal for Broadband Responses

Asmar Aming and Ratchapak Chitaree

Abstract— **A study of the asymmetric geometry based on a one-dimensional defective photonic crystal is reported. A common structure in the form of $(HL)^4L(HL)^4$ is numerically investigated to be suitable for channel filters with broadband responses. The transmission characteristics, analysed by the Transfer Matrix Method (TMM), of the proposed structure in UV, VIS and IR ranges are clearly illustrated. A number of interesting features on the defect modes such as transmittance level, filtering frequency and the number of modes are observed when the defect layer thickness is adjusted. The results show a promising potential of the designed channel filter for various applications including the optical communication.**

Index Terms— **One-dimensional defective photonic crystal, Asymmetric photonic crystal, channel filter, Transfer Matrix Method (TMM), defect mode**

I. Introduction

Optical filter is a device for selectively transmitting light in a particular range of wavelengths while the other is blocked. Its widespread uses are found in various areas of interest such as nanotechnology [1-2], astronomy [3] and communication [4-7]. Designing is the first step in making an effective channel filter in many applications. Up to now, there are an increasing number of designed and developed filters to cover operating wavelengths from ultraviolet (UV) to terahertz (THz) wavelengths [4-14].

The one-dimensional photonic crystal (1D-PC) first introduced by Yablonovitch [15] and Sanjeev [16] has become a structure of choice to design a filter with good characteristics. 1D-PC is an artificial layered material with periodicity of different refractive indices and thicknesses [17]. 1D-PC can guide the flow of light passing through its structure. Principally, the existence of the photonic band gap (PBG) in PC prohibits a certain wavelength that falls within the PBG. Due to a simple structure, 1D-PC is the best candidate for a channel filter design with particular specifications. Different dielectric, metal, semiconductor and organic materials have been investigated numerically to explore their potentials as 1D-PC based bandpass filters [18-22]. By a theoretical design, 1D-PC uses the effect of interference to effectively transmit light over a desirable range of wavelength. For example, a transmission filter made of Si/SiO_2 photonic crystal was numerically and experimentally shown to work in IR range [7]. The binary structure on metallic-dielectric photonic crystal was studied and fabricated as a bandpass filter to cover applications in UV range [14] and the design of transmission band using Ta_2O_5 and SiO_2 photonic crystal was also developed to use in the communication [5]. Note that, these applications are realized by using pure PC structure. For more controllable features of 1D-PC based channel filter, the doping of some materials into the pure PC, changing the thickness of the layer or removing a layer from it, called defective PC has been increasingly studied. The localized or defect mode within the PBG corresponds to the resonant transmittance peak due to the change of the interference behavior of the light [23]. The introduction of the defect in the design of 1D-PC structure leads to various applications such as splitter and optical filters [2,24]. So far, the effort to extend for even more interesting applications is continually studied.

In this study, a common and simple design for channel filter is proposed based on the defective PC. A novel narrow band-pass filter at normal incidence over broadband range are designed and numerically investigated through Transfer Matrix Method (TMM). Based on a common structural configuration of $(HL)^4L((HL)^4$ design in which a defect layer is introduced into a periodic layered structure, a defect mode is found to appear at desired wavelengths in ultraviolet (UV), visible (VIS) and near infrared (IR) ranges. The designed filter as a channel filter exhibits a high transmission performance, sharp edge and good rejection of the undesired sideband. By just changing the combination of materials based on the designed structure, the operating wavelength of a channel filter can be tuned conveniently to cover the range of wavelengths in UV, VIS and IR. The properties of the proposed channel filter in terms of transmission and bandwidth are also investigated in this study.

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II. Mathematical Modelling

A. Transfer Matrix Method (TMM) [17]

A numerical method so called Transfer Matrix Method (TMM) is widely used to solve the amplitude of the light propagating inside 1D-PC. Consider a general defective photonic crystal structure, $air/(HL)^m D(HL)^m/air$, in which H represents the layer of high refractive index and L represents low refractive index materials and D is the defect layer.

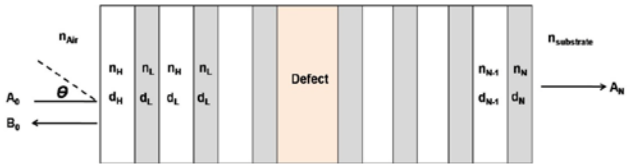

Fig. 1 One-dimensional photonic crystal (1D-PC) with defect

To compute the defect mode in the transmission spectrum, TMM for the system can be written as

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A_N \\ B_N \end{pmatrix}$$

$$M_{sys} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1}(M_H M_L)^m M_D (M_H M_L)^m D_0$$

Where $M_l = D_l P_l D_l^{-1}$ and m is the number of layers and l stands for H, L and D layers.

For TE wave

$$D_l = \begin{pmatrix} 1 & 1 \\ n_l \cos\theta_l & -n_l \cos\theta_l \end{pmatrix}$$

For TM wave

$$D_l = \begin{pmatrix} \cos\theta_l & \cos\theta_l \\ n_l & -n_l \end{pmatrix}$$

θ_l is the ray angle in the layer. Also, the propagation P_l matrix can be defined as

$$P_l = \begin{pmatrix} e^{i\delta_l} & 0 \\ 0 & e^{-i\delta_l} \end{pmatrix} \qquad ;\delta_l = \frac{2\pi d_l}{\lambda} n_l \cos\theta_l$$

B. Transmittance and Reflectance [17]

Using TMM method, the transmittance and reflectance of plane waves through a periodic layered structure, the incident light from medium 0, the reflection r and transmission t coefficients are

$$r = \left(\frac{B_0}{A_0}\right)_{B_s=0}$$

$$t = \left(\frac{A_s}{A_0}\right)_{B_s=0}$$

Using the matrix equation

$$r = \frac{M_{21}}{M_{11}}$$

$$t = \frac{1}{M_{11}}$$

Reflectance R is given by

$$R = |r|^2 = \left|\frac{M_{21}}{M_{11}}\right|^2$$

Providing that the medium 0 is lossless. Transmittance T is given by

$$T = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0} |t|^2 = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0} \left|\frac{1}{M_{11}}\right|^2$$

III. Result and Discussion

A defect layer in asymmetric geometry with a common structure of $air/(HL)^4 L(HL)^4/air$ are studied as channel filters to cover UV, VIS and IR regions. The proposed configuration of channel filter consists of a defect layer (with a refractive index of n_D) inserted into alternating layer of high (n_H) and low (n_L) refractive index materials as shown in Fig. 1. Note that a defect mode referred in the transmittance characteristics corresponds to a design wavelength (λ_0) for a channel filter. Each optical width of the layer is chosen to be a quarter-wavelength, i.e., $n_H d_H = n_L d_L = n_D d_D = \lambda_0/4$. The number of periodicity is optimized for $N = 4$. The substrate is air. This proposed filter was designed and calculated through transfer matrix method (TMM) only at normal incidence over UV, VIS and IR ranges. The transmission performances of the channel filter at each range of wavelengths in terms of high transmittance, tunable bandpass, photonic band gap (PBG) and band edges are investigated and discussed.

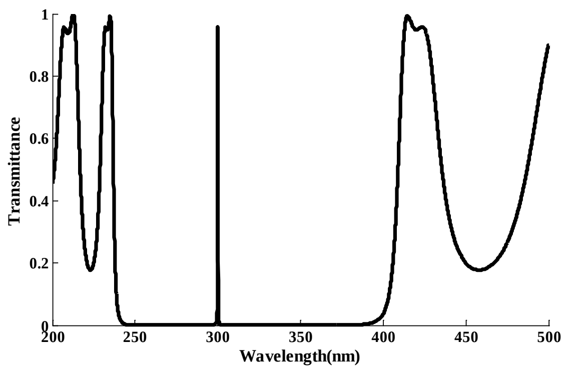

Fig. 2. Transmission spectrum of designed filter in UV range.

A. Design of Ultraviolet (UV) filter

Based on the asymmetric PC structure, *air/(HL)^{4}D(HL)^4/air*, the proposed channel filter in UV range is selected as the layers of two different materials TiO_2 (n_H = 2.8) and MgF_2 (n_L = 1.4). A defect layer of MgF_2 (n_D = 1.4) is introduced into PC structure. With each layer of quarter-wavelength thickness, the proposed structure, $(TiO_2/MgF_2)^4MgF_2\ (TiO_2/MgF_2)^4$, is calculated at the design wavelength λ_0 = 300 nm. The designed PBG is calculated to be between 240-400 nm and the defect mode locates at the design wavelength within the UV range. Fig 2. shows the transmission spectrum of the designed filter. To achieve a maximum intensity of the defect mode, it is recommended to select a high contrast of the refractive index materials. Refractive index of the defect layer is chosen to close to the low refractive index material so as to maximize the transmittance of the defect mode. In this study, MgF_2 is a suitable material for this purpose because of its low absorption in the UV range. In addition, the proposed channel filter can be tuned to a desired wavelength by changing the thickness of the defect layer. The position of defect mode is shifted to a longer wavelength as the thickness of defect layer increases. On the contrary, the decrease of the defect layer thickness causes to lower the designed wavelength. The relation is clearly shown in Fig. 3. The periodicity of the structure, N = 4, gives rise to a sharp edge and high transmission. Although the increase of the periodicity has influenced on sharp edges, this inevitably causes the decrease of the transmittance level of UV channel filter.

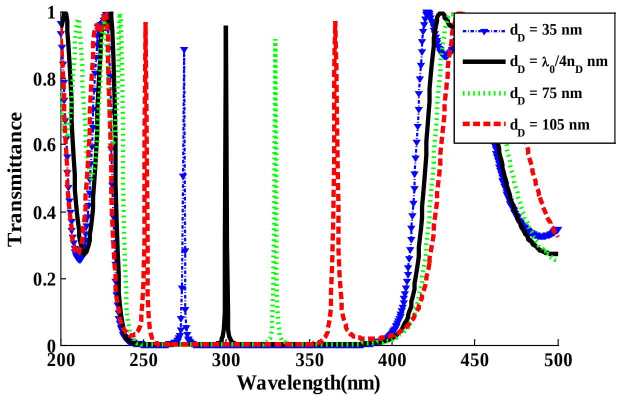

Fig. 3. Transmission spectra of designed filter based on asymmetric defective PC of *air/(TiO$_2$/MgF$_2$)^4 MgF$_2$ (TiO$_2$/MgF$_2$)^4/air* at normal incidence in UV range.

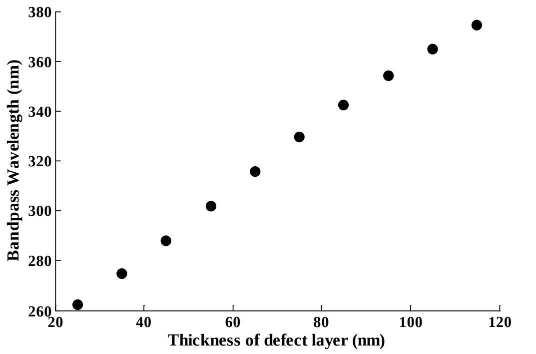

Fig. 4. The variation of channel wavelengths of a single defect mode with different thicknesses of defect layer based on asymmetric defective PC of *air/(TiO$_2$/MgF$_2$)^4 MgF$_2$ (TiO$_2$/MgF$_2$)^4/air* at normal incidence in UV range.

The simulation result shows that the thickness change of the defect layer significantly affects a spectral transmission of the proposed UV filter. Two defect modes apparently occur when the defect layer width has been changed twice as thick as an original value. A defect mode near the band edge of the long wavelength finally disappears if the thickness keeps increasing. However, this clearly points out that the channel filter based on the proposed structure can work as either a single or multi-channel operation depending on the adjustment of the defect layer thickness.

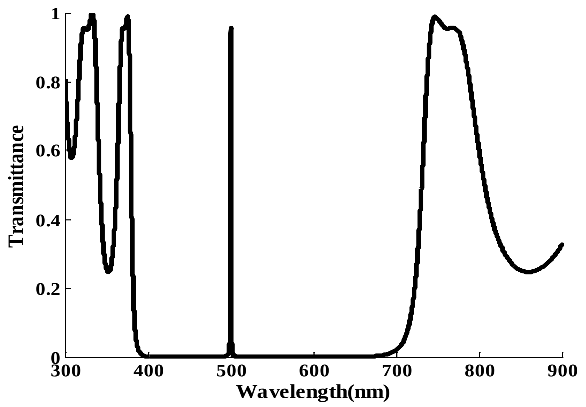

Fig. 5. Transmission spectrum of a designed filter in a visible range.

B. Design of Visible (VIS) filter

Asymmetric one-dimensional defective photonic crystal structure based on *air/(HL)^{4}D(HL)^4/air* is also used for a channel filter in the visible range. H is taken to be *Ti* (n_H = 2.7) and L is taken to be *Al* (n_L = 1.2). To achieve a high transmission, a defect layer is chosen to be a low refractive index material of Al (n_D = 1.2). So, the designed filter is $(Ti/Al)^4Al(Ti/Al)^4$. Each layer thickness is set to be a quarter-wavelength. For normal incidence, the result shows that the PBG is 400 – 700 nm and the defect mode locates at a design wavelength, λ_0 = 500 nm (Fig. 5).

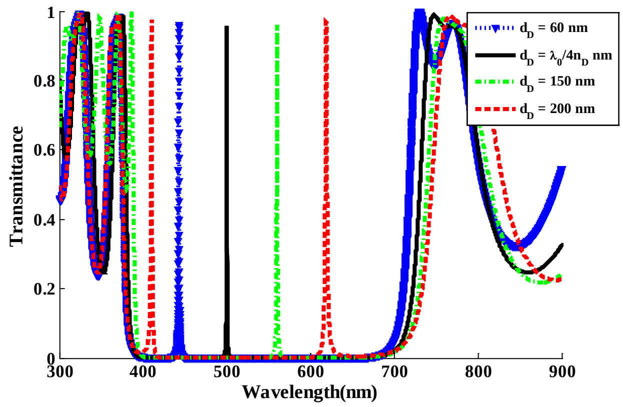

Fig. 6. Transmission spectra of designed filter based on asymmetric defective PC of *air/(Ti/Al)^{4}Al(Ti/Al)^4/air* at normal incidence in visible range.

Fig. 6 clearly shows that by increasing the thickness of defect layer the channel is shifted towards the longer wavelength, whereas the shift to the shorter wavelength occurs as the thickness decreases. The increase of the periodicity is again found to decrease the transmission of the design wavelength. Therefore, the periodicity of N = 4 is the optimum condition for the performance of the channel filter. From Fig. 6, the result shows that two defect modes are found within the PBG if the width of defect layer is twice as thick as the original quarter-wavelength. One of the two defect modes whose position near the band edge of the long wavelength disappears according to the increment of the thickness of defect layer. This illustrates that the variation of defect layer thickness can be used to obtain either a single channel filter or multi-channel filter.

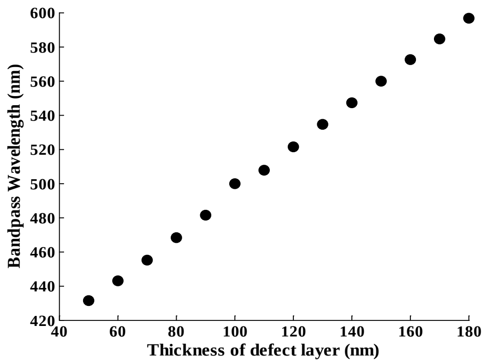

Fig 7. The variation of channel wavelengths of a single defect mode with different thicknesses of defect layer based on asymmetric defective PC of *air/(Ti/Al)*^{4}*Al(Ti/Al)*^{4}*/air* at normal incidence in visible range.

C. Design of Infrared (IR) filter

IR bandpass filter is again designed with asymmetric geometry of *air/(HL)*^{4}*D(HL)*^{4}*/air* where H is GaAs (n_H = 3.41), L is LiF (n_L = 1.36) and D is LiF (n_D = 1.36). The design wavelength was chosen to be λ_0 = 1060 nm. The transmittance of the designed filter, *(GaAs/LiF)*^{4}*LiF(GaAs/LiF)*^{4} , at normal incidence shows that a high transmittance of the defect mode can be achieved when its refractive index is close to the low refractive index material.

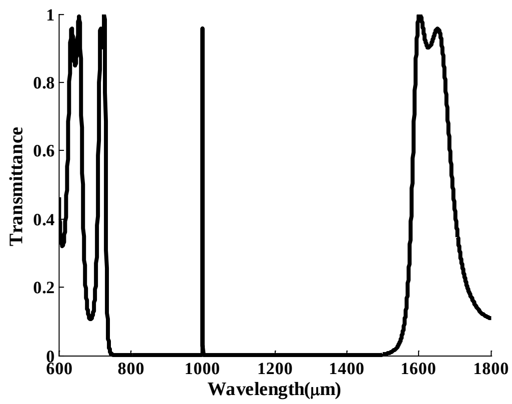

Fig. 8. Transmission spectrum of designed filter in infrared range.

There is a defect mode introduced within the PBG which is 800-1600 nm. A defect mode is shifted to the longer wavelength for increasing of the defect layer thickness. In contrast, the defect mode is shifted to the shorter wavelength with decreasing of the thickness of defect layer. The defect mode becomes weak or even disappears if the periodicity is greater than 4. So, the enhancement of the high transmittance for the designed filter is satisfied with the periodicity N = 4. This design wavelength is selected for near-infrared applications such as medical diagnostics, food quality control and optical communication.

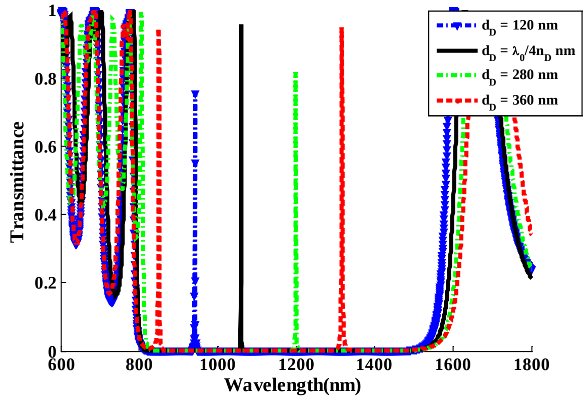

Fig. 9. Transmission spectra of designed filter based on asymmetric defective PC of *air/(GaAs/LiF)*^{4}*LiF(GaAs/LiF)*^{4}*/air* at normal incidence in infrared range.

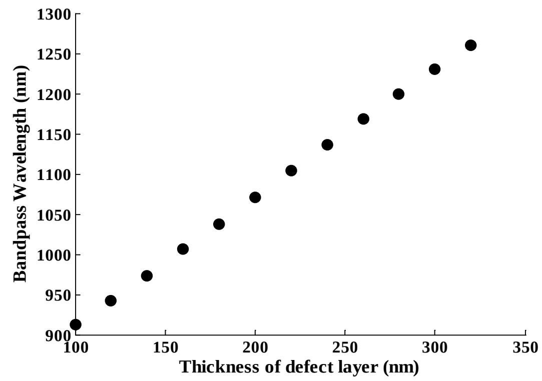

Fig 10. The variation of channel wavelengths of a single defect mode with different thicknesses of defect layer based on asymmetric defective PC of *air/(GaAs/LiF)*^{4}*LiF(GaAs/LiF)*^{4}*/air* at normal incidence in infrared range.

By increasing the width of the defect layer twice as thick as its original quarter-wavelength, two defect modes are observed within the PBG. When the thickness of defect layer increases, the first defect mode is shifted towards the longer wavelength. The defect mode disappears while the other defect mode near short wavelength remains. By varying the thickness of the defect layer, a design wavelength can be achieved. Therefore, this designed structure shows its function as a single or multi-channel filter, specially applied in DWDM applications. Note that the 1310 and 1550 nm are covered in this proposed structure.

IV. Conclusion

Using the Transfer matrix method (TMM), a narrow channel filter can be designed based on asymmetric defective photonic crystal (PC) of *air/(HL)*^{4}*L(HL)*^{4}*/air*. With the combination of appropriate materials and a quarter-wavelength width of the defect layer, a single defect mode occurs within the PBG at the design wavelength, within the ultraviolet (UV), visible (VIS) and infrared (IR) ranges. The position of defect mode can be shifted towards a longer wavelength as the defect layer thickness increases. The twice increment of the defect layer thickness with respect to the quarter-wavelength defect layer thickness leads to the introduction of two defect modes inside the PBG. The optimum periodicity, $N = 4$ in this study, numerically illustrates a high transmission of defect modes and sharp edges of the spectrum. Such designed filter is fully flexible to control the defect mode by changing the width of defect layer. The presence of either a single or two defect modes is utilized to design a single or multi-channel filter for various applications including the optical communication. Table 1 shows the summary of channel filter for UV, VIS and IR ranges based on the proposed asymmetric geometry structure, $air/(HL)^4L(HL)^4/air$.

TABLE I
SUMMARY OF THE DESIGNED FILTER

Range of wavelength (nm)	Photonic band gap (PBG) (nm)	The combination of materials based on $air/(HL)^4L(HL)^4/air$.
Ultraviolet	240 – 700	$(TiO_2/MgF_2)^4MgF_2(TiO_2/MgF)_2^4$
Visible	400-700	$(Ti/Al)^4Al(Ti/Al)^4$
Infrared	800-1600	$(GaAs/LiF)^4LiF(GaAs/LiF)$

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