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Transmission properties of one dimensional Photonic Crystals with defects

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Abstract: The transmission properties of one dimensional Photonic Crystals (PCs) with two defects having structures $(HL)^n$ $(D_1LD_2L)^m(HL)^{n,}$ where m is the stack number of the Photonic Quantum Well (PQW) have been theoretically investigated by the transfer matrix method. The thickness and temperature dependence of the defect modes have been studied by considering Si and air as the high and low refractive index materials with GaAs and InSb as the two defects. This paper is to analyze the defect modes in two different regions of PBG such as PBG1 (393 nm – 701 nm) and PBG2(1055 nm- 2016 nm) by varying the thickness of the defect layers and the temperature of each layer. It was found that the number of defect modes are increased by changing the thickness of the defect layers. Also the shift in the transmittance peak gets decreased. Due to temperature variation of each layer, the two defect peaks in the transmittance spectrum when m=1, shift by 0.14 nm/ K and 0.15 nm/K in PBG1. In PBG2 the defect peaks shift by 0.44 nm/K and 0.50 nm/K . The above shifts for other cases ($m \neq 1$) have also been studied.

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1. Introduction

Photonic Crystals (PCs) of periodic structures are a new class of artificial materials that allow one to manipulate the flow of light [1]. These photonic crystals lead to the formation of Photonic band gaps (PBGs), in which propagation of electromagnetic waves of certain wavelengths is prohibited in their transmission spectra. In recent years tunable PCs play a key role in a variety of optical and microwave applications [2-5]. The defect modes within the PBG have been found to bring about the tunability of the PC structure. The defect(s) can be introduced into PCs by changing the thickness of layer [6], another medium adding into the structure [7], removing a layer from it [8], or subjecting to temperature and hydrostatic pressure [9].

For a simple one dimensional (1D) PC, a popular application is to design narrowband transmission filters having the structure $(AB)^nC(AB)^n$, where $(AB)^{2n}$ is a defect free PC. Here A and B are the high and low index layers, respectively, C is a defect layer and n is the number of periods. In the transmission spectrum there exists a single transmission peak inside the PBG. Based on the photonic Quantum Well (PQW) the 1D PC can also exhibit multichannel filtering properties [10]. It has the structure $(AB)^n(CD)^m(AB)^n$ where n and m are the stack numbers of the two PCs made of (AB) and (CD) bilayers, instead of using a single defect layer C in a defective PC. The central part $(CD)^m$, plays the role of PQW and the number of peaks in the transmission spectrum is just equal to m. In this work, tunable multichannel transmission filters working in the two different regions of PBG by changing the thickness of each defect layer and varying the temperature of each layer are investigated. We first consider a 1D PC containing defects by changing the thickness of the defect layer. We design a structure of $(HL)^n(D_1LD_2L)^m(HL)^n$ where H and L stand for the media with high and low indices of refraction respectively. We choose Si for layer H, air for layer L, GaAs for layer D_1 and InSb for layer D_2. The refractive index of air is independent of temperature. But the refractive indices of Si, GaAs and InSb layers are temperature dependent.

2. Theoretical Model

In this work, we consider a defect free PC having a structure of $(HL)^{2n}$ and a defective PC with a structure $(HL)^n(D_1LD_2L)^m(HL)^n$, in which H and L are respectively the higher and lower refractive index layers and D_1 and D_2 are the defect layers. The structure is shown in Fig 1.

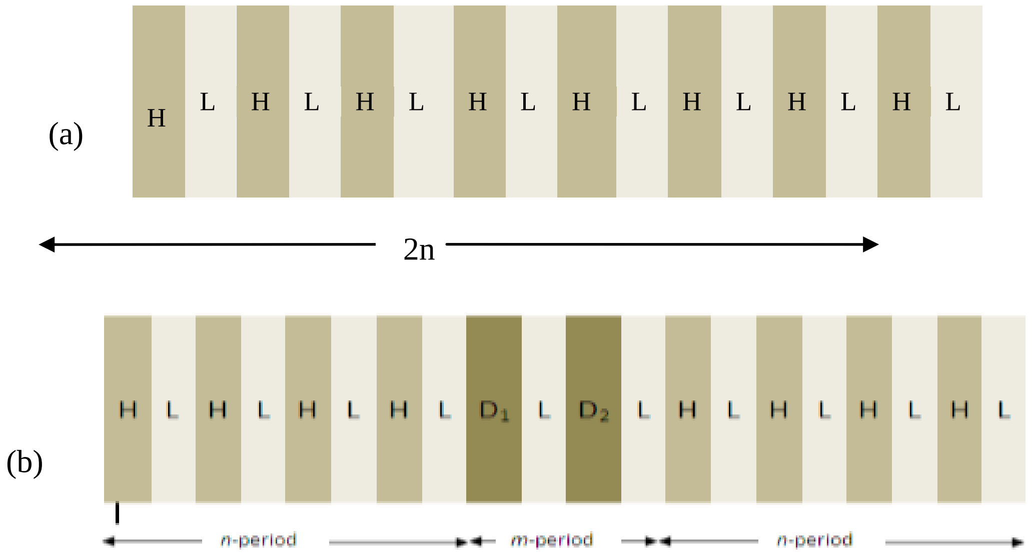


Fig 1 (a). Defect free PC with a structure $(HL)^{2n}$ (b). A defective PC -$(HL)^n(D_1LD_2L)^m(HL)^n$

To compute the defect mode in the transmission spectra, we employ the transfer matrix method (TMM) [11]. Each layer of PC has its own transfer matrix and the overall transfer matrix of the system is the product of the individual transfer matrices.

According to TMM, each single layer has a transfer matrix given by

$$M_l = \begin{pmatrix} \cos\delta_l & \frac{-i}{n_l}\sin\delta_l \\ -in_l\sin\delta_l & \cos\delta_l \end{pmatrix} \qquad (1)$$

where l represents either H,L,D_1 or D_2 layer.

The phase δ_l is expressed as

$$\delta_l = k_l d_l = \frac{2\pi d_l}{\lambda} n_l \qquad (2)$$

n_l = refractive index of the layer
d_l = thickness of the layer
k_l = wave vector

For the entire structure of Air/$(HL)^{2n}$/Air, the total transfer matrix is given by

$$T = (M_H M_L)^{2n} \qquad (3)$$

where the matrix elements can be obtained in terms of the elements of the single-period matrix.

The transmission coefficient for tunneling through such a structure is given by

$$t = \frac{4}{(T_{11}+T_{22})^2 + (T_{12}+T_{21})^2} \qquad (4)$$

where T_{ij} are the elements of the matrix T.
The characteristics matrix for a defective PC by taking n=2 and m=2 is

$$S = (M_H M_L)^2 (D_1 L D_2 L)^2 (M_H M_L)^2 \qquad (5)$$

3. Results and Discussion

Consider a defect free PC $(HL)^4$ to have a PBG in two different regions by assigning the thickness of the high and low index layers as shown in Table 1. Here, Silicon and air are chosen as the higher and lower refractive index materials. The refractive index of Si is 3.45 and air is 1.

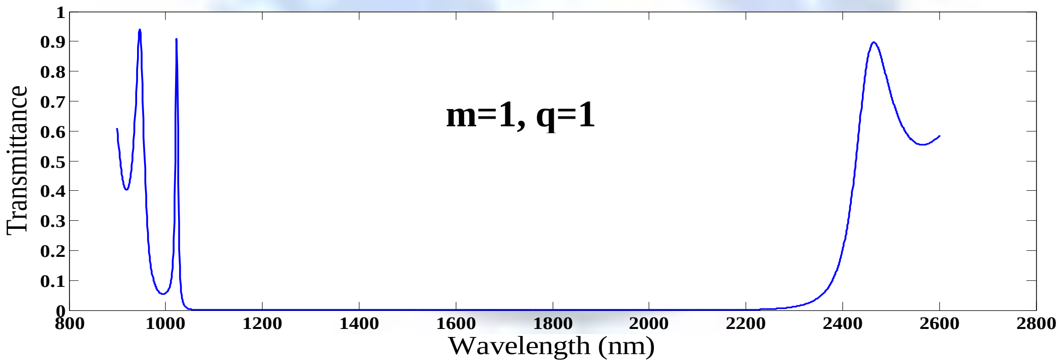
Table 1. PBG region for different thicknesses

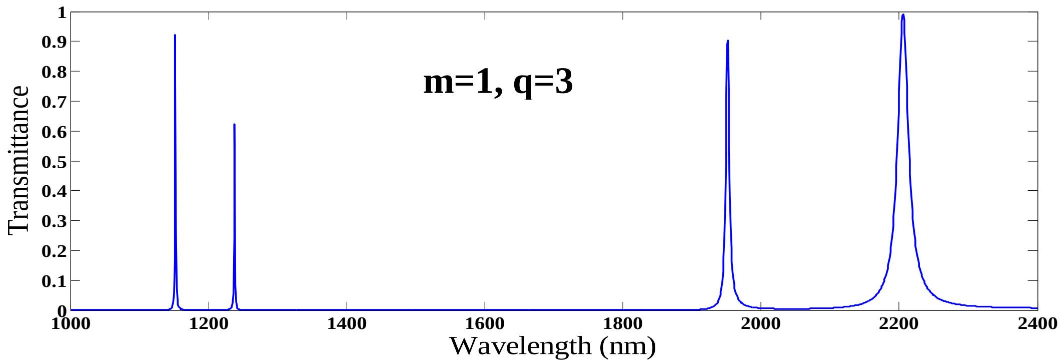
Label	Thickness of High and low index Layers		Band Gap region	Width
	d_h	d_l		
PBG1	45 nm	90 nm	393 nm – 701 nm	308 nm
PBG2	100 nm	350 nm	1055 nm - 2016 nm	961 nm

The analysis of the defect modes for different band gap regions labeled as PBG1 and PBG2 is given next . The thickness of the defect layers are calculated from $d_l = \frac{q\lambda_0}{4n_l}$ where l represents GaAs and InSb respectively and q is an optical constant coefficient with a design wavelength of λ_0= 600 nm for region PBG1 and λ_0= 1550 nm for region PBG2. We assume that the whole structure is immersed in air. Here D_1 is taken to be GaAs with refractive index 3.32 (n_{GaAs}) and D_2 is taken to be InSb with refractive index 4.418 (n_{InSb}).

3.1. Thickness dependence of defect modes :

The wavelength shifts for an increase in thickness of the defect layer GaAs and InSb by changing the value of q for the structure $(HL)^2(D_1LD_2L)^m(HL)^2$ where m=1,2,3 is considered. The defect modes shift towards the lower wavelength region with the increasing thickness of the defect layers. No defect modes appear within the PBG for q=1 in both PBG1 and PBG2. In the case of q = 3 & 4 by increasing the thicknesses of the defect layers, 2m defect modes appear within the PBG. The transmittance peaks appear very much closer in lower wavelength region for q= 4, when compared to the other values of q. No defect modes appear within the PBG when m=1 and q=1 as shown in Figure 2 (a). The wavelength dependent transmittance of the structure where m=1,2,3 in PBG2 by changing the value of q is studied, for different thickness as shown in Figure 2. It shows that there are 2m transmittance peaks for each defect appearing within the PBG.





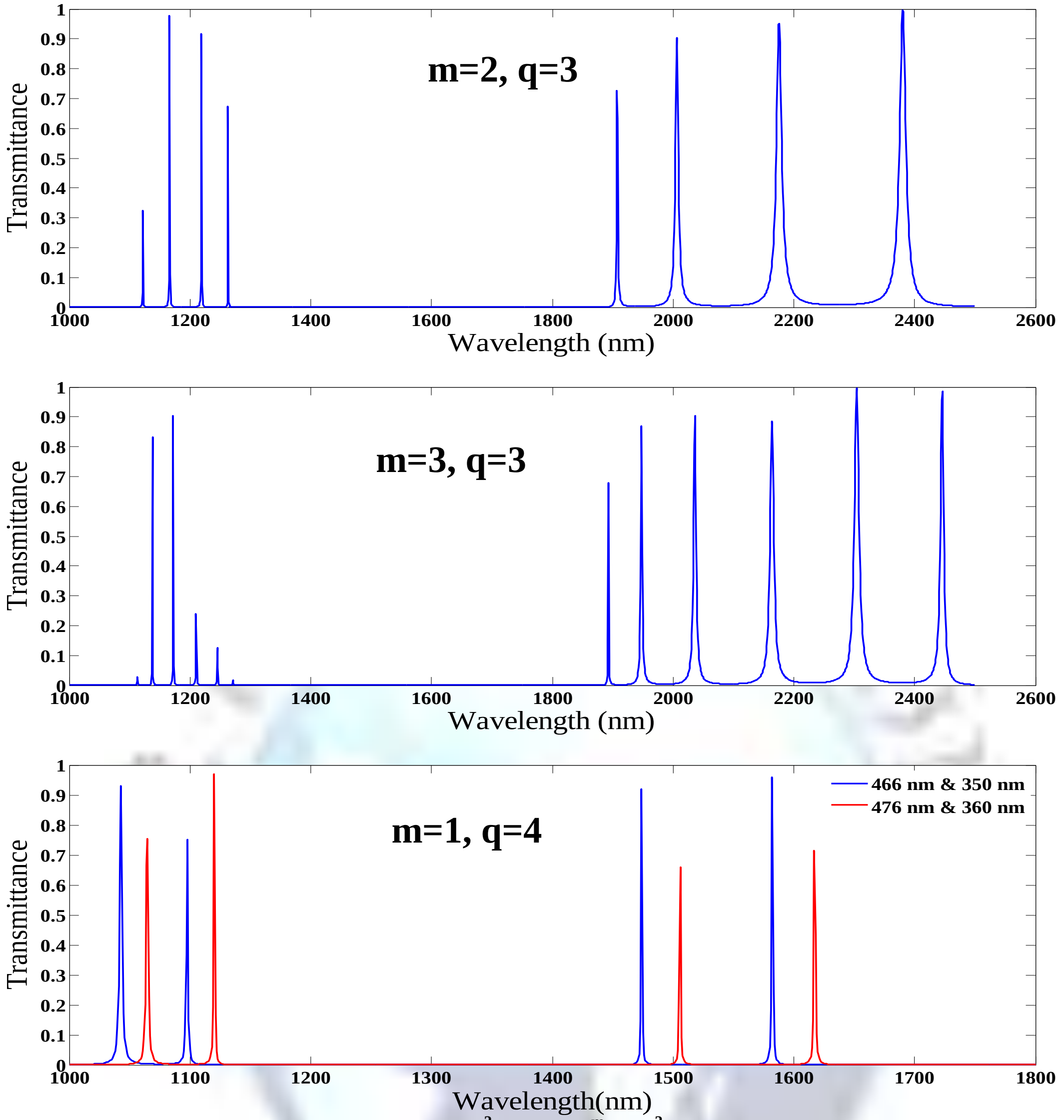


Fig 2. Transmittance spectra for the structure of $(HL)^2(D_1LD_2L)^m(HL)^2$ for different thicknesses of the defect layers when (a) m=1, q=1 , b) m=1, q=3 (c) m=2, q=3 (d) m=3, q=3 (e) m=1, q=4

When the thicknesses of the defect layers increased by 10 nm, as calculated from the expression $d_l = \frac{q\lambda_0}{4n_l}$, the photonic Band gap increases for various value of q. The shift in transmittance peak decreases for the first defect (GaAs) and approximately the same for the second defect (InSb) in both the region of PBG1 and PBG2 when the value of q=2. Similarily the shift in transmittance peak decreases when q=3 and q=4. For m=1 and q=3, there are two transmittance peaks for each defect. The first and second peak due to GaAs defect are located at 431 nm and 467 nm whose thickness is 135 nm and 706 nm and 810 nm due to InSb defect when the thickness is d_{GaAs}= 135 nm and d_{InSb} = 105 nm. If we increase the thickness of the defect layers by 10 nm, the first and second peak are located at 460 nm and 504 nm due to GaAs defect and 746 nm and 853 nm due to InSb defect. From this, we infer that by increasing the thickness of the defect layers by 10 nm, the transmittance peak shifts by 29 nm and 37 nm due to GaAs defect and 40 nm and 43 nm due to InSb defect towards the higher wavelength region as shown in Fig 3 (a). Similarily , the transmittance peak shifts by 20 nm and 26 nm due to GaAs defect and by 29 nm and 36 nm due to InSb defect towards the higher wavelength region for m=1 and q=4 as shown in Fig 3 (b) , when we increase the thickness of the two defect layers by 10 nm. Similarily , the transmittance peak shifts by 49 nm and 49 nm due to GaAs defect and by 64 nm and 71 nm due to InSb defect towards the higher wavelength region for m=2 and q=2 as shown in Fig 3 (c), when we increase the thickness of the two defect layers by 10 nm.

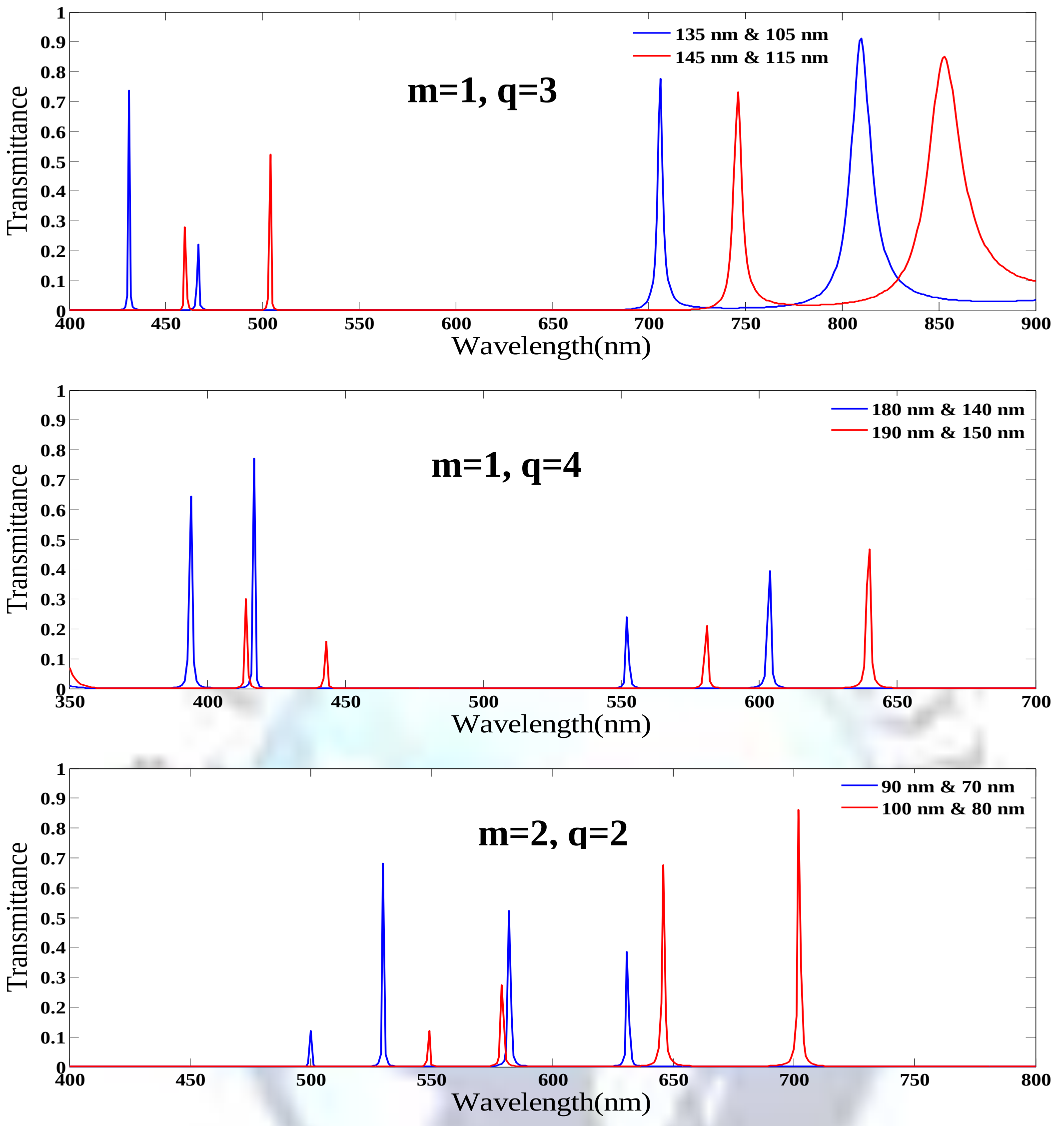


Fig 3. Transmittance spectra for the structure of $(HL)^2(D_1LD_2L)^m(HL)^2$ for different thicknesses of the defect layers when (a) m=1, q=3 , b) m=1, q=4 (c) m=2, q=2 in PBG1

3.2. Temperature dependence of defect modes :

The analysis of the defect modes for different band gap regions labeled as PBG1, and PBG2 at different temperatures are given below. The temperature dependence of photonic crystals includes two factors. The first is that the thickness of the constituent layers are temperature dependence due to thermal expansion. The second is that the index of refraction of each layer can be varied as the temperature changes because of the thermo-optical effect [12]. Due to thermal expansion, the thickness d of each layer is written as

$$d(T) = d(1+\alpha\Delta T) \qquad (6)$$

where α is the thermal expansion coefficient and ΔT indicates the variation of the temperature. For air, we have taken $\alpha_{air} = \frac{\gamma}{3}$ where γ is the coefficient of volume expansion of air [13]. The thermal expansion coefficient α of Si, GaAs and InSb are $2.6\text{x}10^{-6}$/K,$5\text{x}10^{-6}$/K and $4.7\text{x}10^{-6}$/K respectively [14,15]. The value of γ is $3.67 \text{ x } 10^{-3}$/K. For the thermo-optical effect, the temperature dependence of index of refraction n of each layer is [16]

$$n(T)=n_0+\beta\Delta T \qquad (7)$$

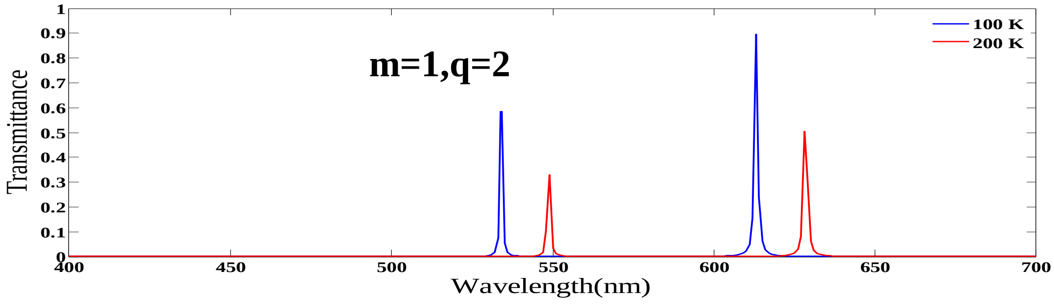
where β is the thermo-optic coefficient. The thermo-optic coefficient of Si, GaAs and InSb are 166x10^{-6}/K, 250x10^{-6}/K and 560x10^{-6}/K respectively [14,15]

By implementing equations (6) and (7), the wavelength shifts in the transmittance spectra for an increase of 100 K for the structure $(HL)^2(D_1LD_2L)^m(HL)^2$ where m=1,2,3 at two different temperatures (ΔT=100 K and 200 K) were obtained. The shift of transmittance peak per 100 K in different PBG regions for q = 4 as shown in Table 2 and the defect mode of the transmittance shifts towards the higher wavelength region. There is no defect mode within the PBG for q=1 in both the regions PBG1 and PBG2. When we increases the thickness of the defect layers by changing q, the transmittance peak shifts towards the lower wavelength region and there appear 2m defect modes within the PBG when q=3 and q=4.

In PBG1, the first peak is located at 534 nm due to GaAs defect and the second at 613 nm due to InSb defect when ΔT= 100 K. Similarily the first peak is located at 549 nm due to GaAs defect and the second peak is located at 628 nm due to InSb defect when ΔT= 200 K. It shows that the transmittance peak shifts towards the higher wavelength region by 14 nm due to GaAs defect and 15 nm due to InSb defect as the temperature increases by 100 K when m= 1 and q=2 in region PBG1 as shown in Fig 4 (a). Similarily, the transmittance peak shifts by 9 nm and 10 nm due to GaAs defect and 22 nm and 25 nm due to InSb defect when m=1 and q=3 in PBG1 as shown in Fig 4 (b). Similarily, the transmittance peak shifts by 8 nm and 8 nm due to GaAs defect and 12 nm and 12 nm due to InSb defect when m=1 and q=4 in PBG1 as shown in Fig 4 (c).

Table 2. Location of the transmission peak for different thicknesses of the defect layers by changing q according to $d_l = \frac{q\lambda_0}{4n_l}$ at different temperatures (ΔT=100 K,200 K) for the structure $(HL)^2(D_1LD_2L)^m(HL)^2$ where m=1,2,3 and q = 4.

Region	Thickness (nm)		m	Temperature	Wavelength (nm)	
	d_{GaAs}	d_{InSb}			First Peak (λ_{GaAs})	Second Peak(λ_{InSb})
PBG1	180	140	1	100 K	401, 425	564, 616
				200 K	409, 433	576, 628
			2	100 K	393, 403, 421, 429	554, 571, 608, 632
				200 K	400, 410, 428, 436	565, 582, 620, 643
			3	100 K	391,397,403,419,425, 430	550, 561, 574, 605, 622, 638
				200 K	398,404,411,427,433, 437	562, 572, 585, 618, 634, 648
PBG2	466	350	1	100 K	1072, 1129	1507, 1617
				200 K	1109, 1166	1540, 1652
			2	100 K	1041, 1078, 1115, 1141	1477, 1528, 1595, 1657
				200 K	1070, 1111, 1150, 1176	1508, 1561,1630, 1692
			3	100 K	1031, 1054, 1080, 1108, 1130, 1145	1468, 1497, 1538, 1586, 1634, 1670
				200 K	1055, 1083, 1112, 1141, 1164, 1180	1499, 1528, 1571, 1620, 1668, 1704



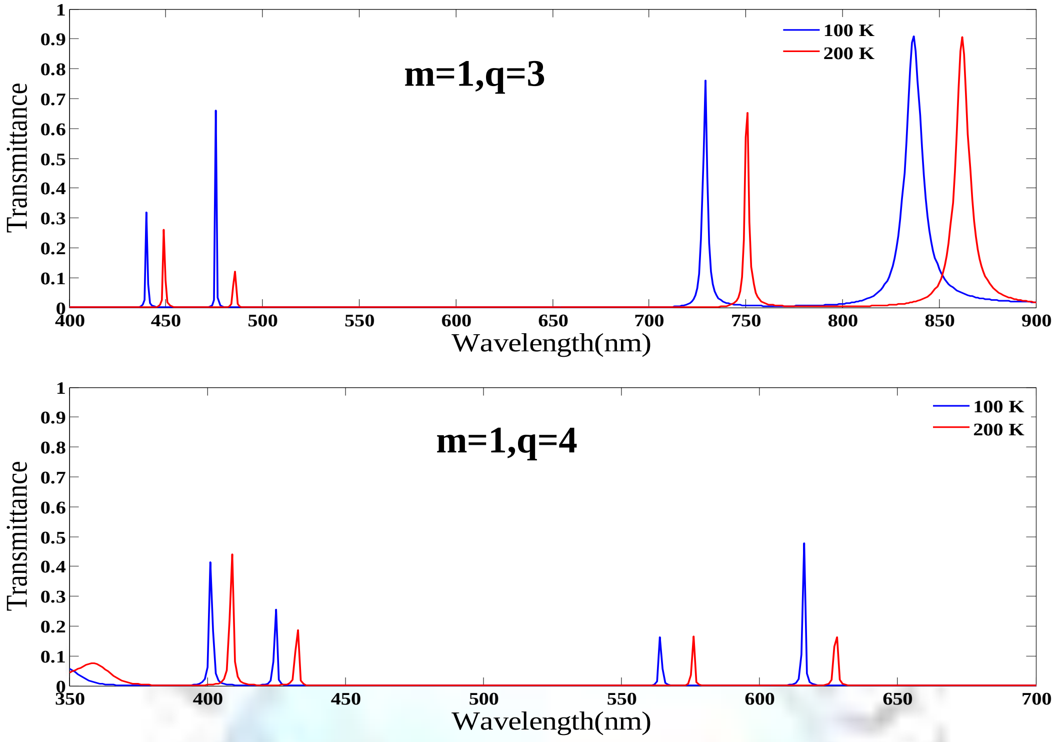


Fig 4. Transmittance spectra for the structure of $(HL)^2(D_1LD_2L)^m(HL)^2$ for different thicknesses of the defect layers (ΔT=100 K,200 K) in PBG1

The shift in transmittance peak for different values of m and q (ΔT=100 K,200 K) in PBG2 as shown in Fig 5.

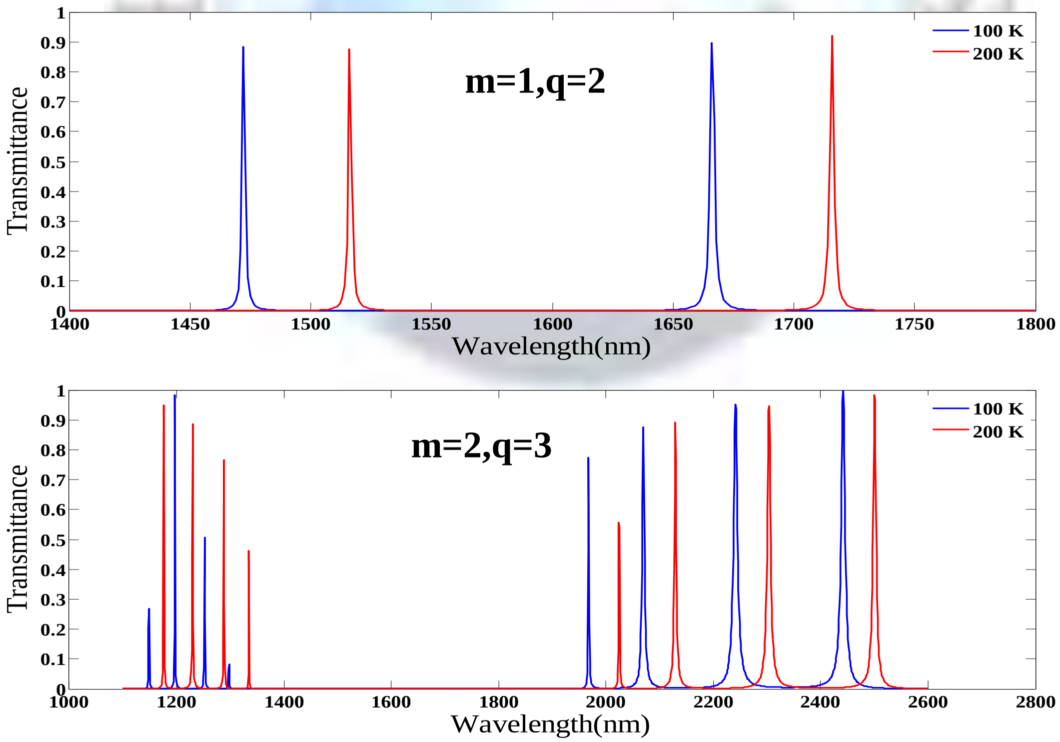


Fig 5. Transmittance spectra for the structure of $(HL)^2(D_1LD_2L)^m(HL)^2$ for different thicknesses of the defect layers (ΔT=100 K,200 K) in PBG2

Conclusion

The thickness and temperature dependences of defect modes in two different PBG regions of photonic crystals containing PQW have been investigated. There is no transmittance peak within the PBG when q=1. Transmittance peaks appear for higher value of q. Besides, the transmittance peak shifts towards the lower wavelength region when the thickness of the defect layers increases. Also, the separation between the peaks decrease. In temperature dependence, the shift of transmittance peak is between 14 nm /K and 15 nm/K in PBG1 and 41 nm/K – 46 nm/K in PBG2 due to GaAs defect. Due to InSb defect, the shift is between 14 nm/K – 15nm/K in PBG1 and 48 nm/K – 50nm/K in PBG2. It depends on the value of m when q=2. As we increase the thickness of the defect layers due to temperature dependence, the shift in transmittance peak due to GaAs defect is less as compared to InSb defect. But for q=3 , the shift in transmittance peak due to InSb defect is more as compared to the value of q=2. So, we can use the proposed structure as a temperature sensor. Alternatively, as a filter, the frequency may be tuned by external parameters such as temperature.

To our knowledge, this is the first work in which more than a single defect is used, and a systematic investigation of a defect modes within the PBG and their temperature dependence are investigated. Another novelty in the present work, a huge variation of defect modes with temperature has been investigated, enabling further research to exploit this in detectors with applications in metrology. The analysis of the defect modes provides useful information for the design of a narrowband transmission filter based on the one dimensional photonic crystals. The shifting feature in the transmittance peaks is akin to a tunable fabry-perot interferometer, which is used in optical spectrum analysis.

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