Temperature sensor and monochromatic filter based on one-dimensional photonic crystal containing Si and SiO_2 with a defect layer of liquid crystal

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In this article, we have proposed a temperature sensor and monochromatic filter based on one-dimensional photonic crystal (1DPC) containing Si and SiO_2 layers with liquid crystal (LC) as a defect layer i.e. $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ structure. By applying the transfer matrix method (TMM), we have studied transmission properties of the $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ structure. The tunable transmission characteristics of the periodic structure $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ are investigated with the variation of temperature of the LC layer as well as the incident angle of the electromagnetic wave. The calculated transmission peak of defect mode lies in photonic band gap (PBG) region of the 1DPC, and the transmission peak of the defect mode shifts with the temperature variation of the LC. The transmittance of defect mode peak in PBG region of the 1DPC has analyzed with the variation of temperature, and suggested a temperature sensor as well as a monochromatic filter based on the $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$structure.

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1. Introduction

Photonic Crystals (PCs) are periodically composition of dielectric materials in one dimension (1D), two dimension (2D) and three dimensions (3D). Such PCs are very interesting to investigate because such periodic layered optical media have special characteristics, which can be used in the optical devices [1-4]. PCs control the electromagnetic wave propagation inside the periodic dielectric materials and due to having a regular arrangement of dielectrics, such PCs yields a special domain of frequencies called photonic band gap (PBG) [5-7]. In such PCs, the electromagnetic wave can't propagate inside PBG region of the PCs, which is a novel property of the PCs. Hence, such periodic materials or PCs can be used in optical devices to control the propagation of electromagnetic wave [8-10].

Liquid crystals (LCs) are novel organic materials, which have a transitional segment between liquids and solids. LC has the flow characteristics like liquid and crystalline characteristics like solid. LC is extraordinary and highly birefringent material, and applicable in tunable optical devices [11-13]. The refractive indices of LC have extraordinary (n_e) and ordinary refractive indices (n_o) and these refractive indices are electric fields and temperature dependent. Hence, the tunable transmission of one-dimensional photonic crystal (1DPC) with liquid crystal as a defect layer can be achieved by varying temperature dependent optical parameters of LC like refractive index, director angle and incident angle etc. Such tunable transmission properties of the 1DPC with LC defect layer can be used in many tunable optical devices like optical filters, bistable switches, multichannel filters etc. Busch et al. proposed that the optical tunability of PBG regions can be achieved by coating the inverse opal with LC, and verified it experimentally by Yoshino et al. [14,15]. As discussed above, LC has electric field and temperature dependent optical parameter and these optical properties of LC can be tuned by the variation of electric field and the temperature. The optical transmissions of PCs can be tuned by controlling the optical parameters of LC as a defect layer in PCs [16-21]. The photonic crystals with infiltrated holes with LC are also a method to attain the tunable optical transmissions characteristics of PCs [22]. LCs are birefringent and nonlinear optical materials and they have remarkable optical characteristics which can be used in the novel optical devices [23, 24] like all-optical switching in PC, and moderated transmissions of the electromagnetic wave in the PC. Mohamed et al. investigated the effect of LC director orientation angle and temperature on the transmissions of 1DPC with LC as a defect layer. Similarly, the optical properties of 1DPC with LC as a defect layer was investigated by Entezar et al. and they have demonstrated that the tunability of PCs could be achieved by regulating the optical parameter of LC [25-29]. Authors had also discussed the bi-stable characteristics of PC, which was dependent upon the functioning temperature and examined the influence of temperature on the optical transmission properties of the PC.

In this work, we have studied the temperature-dependent tunable optical transmission characteristics of one-dimensional photonic crystal (1DPC) composed of Si and SiO_2 layer with a defect layer of liquid crystal (LC) like E7. The 1DPC with a LC defect layer is composed structure which is represented as $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$. The defect layer LC is the E7 liquid crystal mixture, which is the composition of four liquid crystals; 5CB, 7CB, 8OCB, and 5CT [30]. The transmission characteristics of 1DPC with defect layer E7 mixture have studied using the transfer matrix method (TMM). The optical parameters of the E7 LC are temperature dependent, and hence the optical transmission characteristics of 1DPC can be easily tuned by the variation of the temperature. Further, we have also investigated the transmittance of defect mode peak wavelength with the variation of temperature for a particular angle of incidence. The transmittance of the periodic structure $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ affects with the variation of temperature because the optical parameters of LC depends upon the temperature. So we have proposed temperature sensor and monochromatic filter based on the periodic structure $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ with defect layer of LC.

2. Theory and methodology

LC is highly birefringent material, which has dielectric permittivity in the tensor form [11]. The dielectric tensor $(\tilde{\varepsilon})$ of LC can be characterized in expressions of parallel ($\varepsilon_{\parallel}$) and perpendicular $(\varepsilon_{\perp})$ components of dielectric permittivity, and the dielectric anisotropy ($\varepsilon_a = \varepsilon_{\parallel} - \varepsilon_{\perp}$), which is given as [12, 28];

$$\tilde{\varepsilon} = \begin{pmatrix} \varepsilon_{\perp} + \varepsilon_a \sin^2\phi & 0 & \varepsilon_a \sin\phi\cos\phi \\ 0 & \varepsilon_{\perp} & 0 \\ \varepsilon_a \sin\phi\cos\phi & 0 & \varepsilon_{\perp} + \varepsilon_a \cos^2\phi \end{pmatrix} \quad (1)$$

From equation (1), the dielectric tensor of LC depends upon the optical parameters i.e. $\varepsilon_{\parallel}, \varepsilon_{\perp}$ and director orientation angle (ϕ) with respect to the z-axis (Fig. 1). The tensor dielectric of LC is diagonalized for orientation angle $\phi = 0^0$ and $\phi = 90^0$. Hence, the transfer matrix method (TMM) can be used to study the optical properties.

The optical parameters of LC, extraordinary (n_e) and ordinary (n_o) refractive indices, are temperature dependent, which is given below [31, 32]:

$$n_e(T) = A - BT + \frac{2(\Delta n)_o}{3}\left(1 - \frac{T}{T_C}\right)^{\beta} \quad (2)$$

$$n_o(T) = A - BT - \frac{(\Delta n)_o}{3}\left(1 - \frac{T}{T_C}\right)^{\beta} \quad (3)$$

where $A, B, (\Delta n)_0, \beta$ are the wavelength dependent parameter of LC and T_C is the clearing temperature of LC. The above constants are different for different LCs. In our calculation, we have considered E7 LC as a defect layer in 1DPC of Si/SiO_2 materials. All constant values for E7 LC are considered for 1.5 μm wavelength.

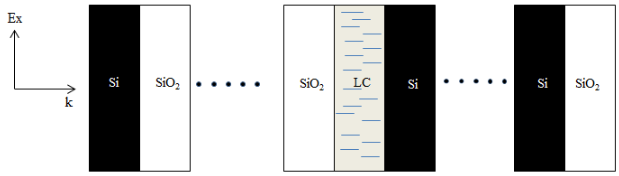

Fig. 1. Schematic diagram represents one-dimensional photonic crystal containing Si/SiO_2 materials with LC as a defect layer i.e. $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$

To study the temperature dependent optical properties of the 1DPC of Si/SiO_2 materials with LC as a defect layer, we have considered the periodic structure of Si and SiO_2 materials which is inserted LC as defect layer asymmetrically, $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$, which is shown in Fig. 1. The transmission properties of the $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ structure have studied using simple transfer matrix method (TMM). In TMM, the magnetic field and electric field in the same layer at two different locations can be related by characteristics matrix, which is given below [33];

$$M_{A,B} = \begin{bmatrix} \cos(k_{A,Bz} d_{A,B}) & \kappa_{12} \\ \kappa_{21} & \cos(k_{A,Bz} d_{A,B}) \end{bmatrix} \quad (4)$$

$$\text{where } \kappa_{12} = i\frac{\omega\mu_{A,B}}{ck_{A,B}}\sin(k_{A,Bz} d_{A,B}) \quad (5)$$

$$\text{and } \kappa_{21} = i\frac{ck_{A,B}}{\omega\mu_{A,B}}\sin(k_{A,Bz} d_{A,B}) \quad (6)$$

Again where $k_{Az} = \left[\left(\frac{\omega}{c}\right)^2 \varepsilon_A\mu_A - k_x^2\right]^{1/2}$ and $k_{Bz} = \left[\left(\frac{\omega}{c}\right)^2 \varepsilon_B\mu_B - k_x^2\right]^{1/2}$ are z-component of the wave vectors in the Si and SiO_2 layers and k_x is the x component of the wave vector.

The total transmission coefficient of periodic structure for the incident electromagnetic wave is given below;

$$t = \frac{2p_0}{(p_0 M_{22} + p_s M_{11}) - (p_0 p_s M_{12} + M_{21})} \quad (7)$$

The transmittance of the 1DPC with LC defect layer can be written as;

$$T = \frac{p_s}{p_0}|t|^2 \quad (8)$$

3. Results and discussion

3.1. Transmission properties of $(Si|SiO_2)^6$ and $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ periodic structure with wavelength

In this section, we have studied the optical properties of one-dimensional periodic structure composed with Si and SiO_2 (i) without defect layer of LC i.e. $(Si|SiO_2)^6$ and (ii) with defect layer LC i.e. $(Si|SiO_2)^3|LC|(Si|SiO_2)$. As discussed above section, LC is temperature dependent dielectric parameter for both extraordinary (n_e) and ordinary (n_o) refractive indices of the E7 LC mixture. For E7 LC, we have considered the extraordinary (n_e) and ordinary (n_o) refractive indices, which are represented by Eqs. (2) and (3). The constant presented in the Eqs. (2) and (3) are A = 1.7230, B = 5.24×10^{-4}, $(\Delta n)_o$= 0.3485, β = 0.2542 at 1.5 μm wavelength and T_C=330 K. For the calculation of optical properties of 1DPC with and without LC defect, we have taken the thickness of Si, SiO_2 and LC layer are 40 nm, 91 nm and 100 nm respectively. The refractive indices of Si and SiO_2 layers are 3.4 and 1.5 respectively. The average refractive index of E7 LC at a given temperature is considered in the calculation, which is given by;

$$n_{avg} = \frac{2n_o + n_e}{3} \quad (9)$$

The transmission properties of $(Si|SiO_2)^6$ and $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ are represented by solid and dash lines respectively, as shown in Fig. 2. The one-dimensional periodic structure of Si and SiO_2 without LC defect layer produces a PBG region between 423-786 nm i.e. PBG have width of 363 nm. On the other hand, a sharp the defect mode wavelength peak appears in the PBG region due to the presence of defect layer LC in the periodic structure. The transmittance of the defect mode wavelength peak 566 nm is found to be 82.4% and the PBG region increases with range of 405-874 nm. The defect mode transmittance peak in obtained PBG region is tunable with the variation of temperature of LC and the incident angle of the electromagnetic wave.

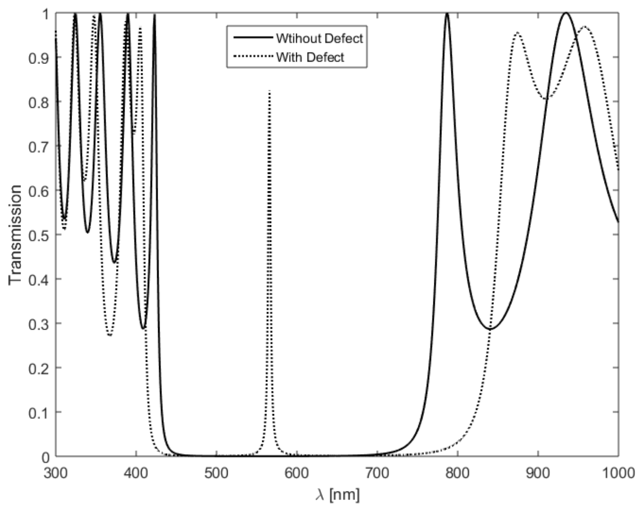

Fig. 2. Transmission properties of periodic structure (i) with LC defect layer $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$(Dash) and (ii) without LC defect layer (Solid) $(Si|SiO_2)^6$

3.2. Temperature dependent transmission characteristic of $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ with wavelength

For the temperature sensor and the monochromatic filter devices, we have studied the temperature dependent transmission properties of $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ at 200 K, 400 K and 800 K as shown in Fig 3. From Fig. 3, we conclude that the defect mode peak wavelength has obtained in the PBG region is tunable with the variation of temperature. From the Eqs. (2) and (3), the dielectric parameters (n_e, n_o) of liquid crystal mixture varies with the temperature, and hence the transmission properties of $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ periodic structure is tunable with changing the refractive index of LC by temperature.

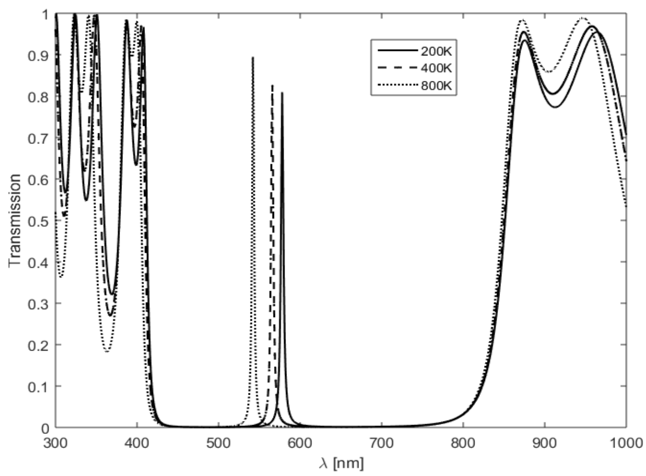

Fig. 3. Transmission properties of $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ versus wavelength at 200K, 400K, and 800K temperature

The transmission of the defect mode wavelength peaks in the PBG region increases with temperature increases but it shifts toward the lower wavelength region.

The optical properties of considered periodic structure $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ for temperature 200 K, 400 K and 800 K at 30^o incident angle are shown in Fig. 4. The transmittance of defect mode peaks 555 nm, 542 nm, and 516 nm wavelengths is found to be 70.62%, 72.4%, 77.32%, respectively. The shifting of defect mode peak wavelengths also affects by the incident angle. The transmittance defect mode wavelength peaks are relatively lower compared to normal incidence, and the transmittance peaks are also shifted to relatively lower wavelength.

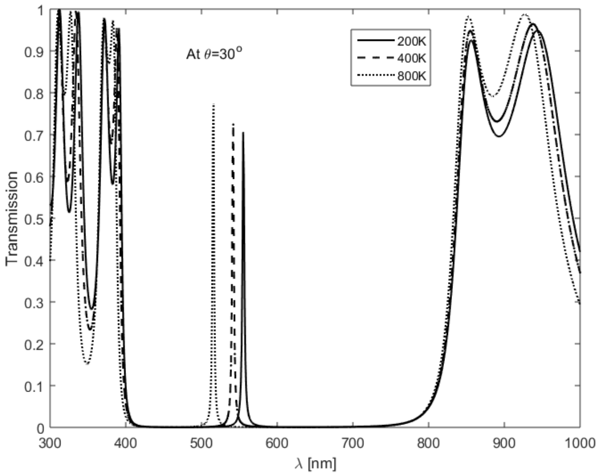

Fig. 4. Transmission properties of $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ versus wavelength at 200 K, 400 K and 800 K temperature for 30^o incident angle

The transmittances of defect mode wavelengths in the PBG region are found to be relatively lower in comparison to the incident angle 0^o. The variation of transmission peak characteristic of the periodic structure has found the same nature at higher incident angle i.e. the peak of the defect mode wavelength is shifted to lower wavelength with low transmission. The detail calculations of transmission properties of periodic structure $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ for 200 K, 400 K and 800 K at a higher incident angle have been tabulated in Table 1:

Table 1

Parameter	Temperature		
Incident angle (θ^o)	200K	400K	800K
	Wavelength of transmission peak of defect mode		
0	578nm	566nm	542nm
30	555nm	542nm	516nm
60	504nm	487nm	454nm
85	477nm	457nm	418nm
	Transmittance peak of defect mode		
0	80.95%	82.45%	89.47%
30	70.62%	72.4o%	77.32%
60	41.63%	43.79%	50.68%
85	6.00%	4.80%	9.30%

3.3. Variation of wavelength and transmittance peak with incident angle

In Figs. 5 and 6, the variation of defect mode wavelength peak with incident angle and temperature has been studied. From the Figs. 5 and 6, we conclude that the increment in temperature affect the position of defect mode wavelength i.e. peak shifted to lower wavelength with higher temperature but the PBG regions remain the same. In Fig. 6, we also conclude that incident angle of electromagnetic wave affect the transmission and position of defect mode peak wavelength with changes in PBG regions i.e. defect mode wavelengths is shifted to lower wavelength with lower transmissions and PBG regions are also changed with incident angle.

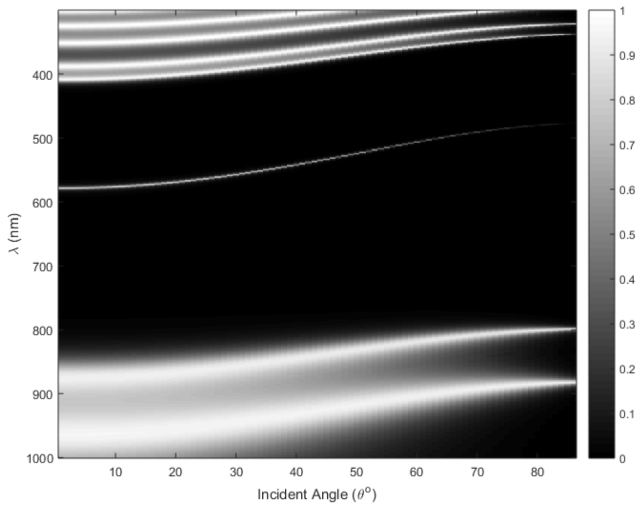

Fig. 5. Transmission properties of $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ with higher incident angle (θ^o)

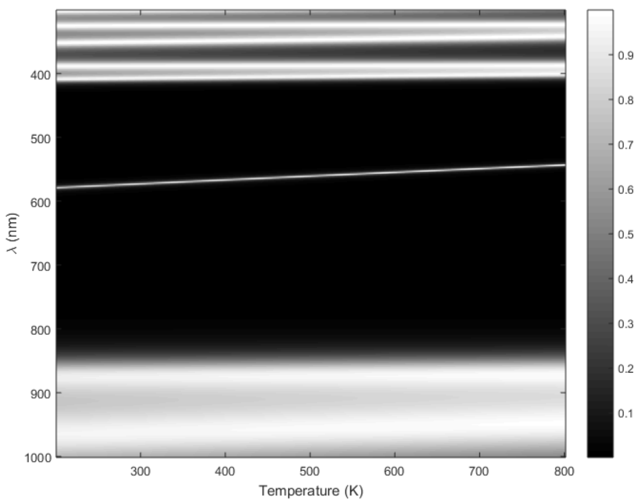

Fig. 6. Transmission properties of $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ with higher temperatures (K)

As discussed in above section, the optical properties of periodic structure $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ are dependent upon the temperature as well as the incident angle which is tabulated in the Table 1. It shows the variation of wavelength of the defect mode with different incident angles at 200 K, 400 K, and 800 K temperatures, which is shown in Fig. 7.

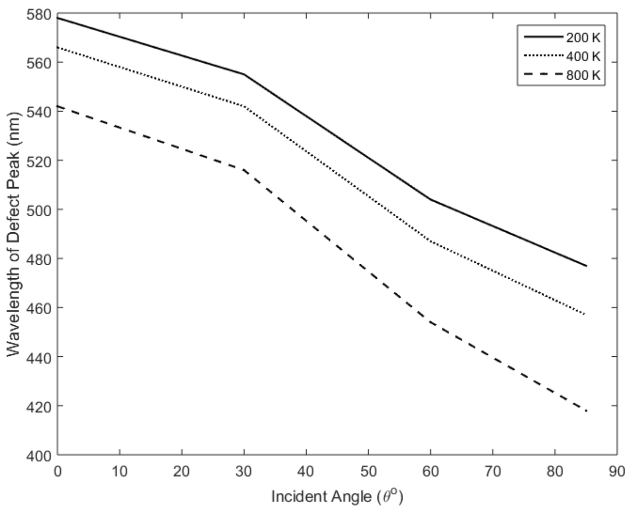

Fig. 7. Wavelength of the defect mode peak versus incident angle for 200 K, 400 K, and 800 K

It clearly shows that wavelength of the defect mode at 200 K is decreased with the increase incident angle i.e. wavelength of the defect mode is shifted to lower wavelength for 200 K temperature. Similar nature of wavelength of the defect mode for 400 K and 800 K temperatures is also found, and shows that transmission is also decreased with the increase incident angle. But the transmittance of defect mode peaks is increased with increase temperature and shifted towards the lower wavelength region.

The variation of transmittance of the defect mode wavelength peaks with incident angle for 200 K, 400 K, and 800 K temperatures is shown in Fig. 8. From the Fig. 8, we conclude that the transmittance of the defect mode peak wavelength is decreased continuously with increase incident angle. This result is also clearly depicted in Table 1.

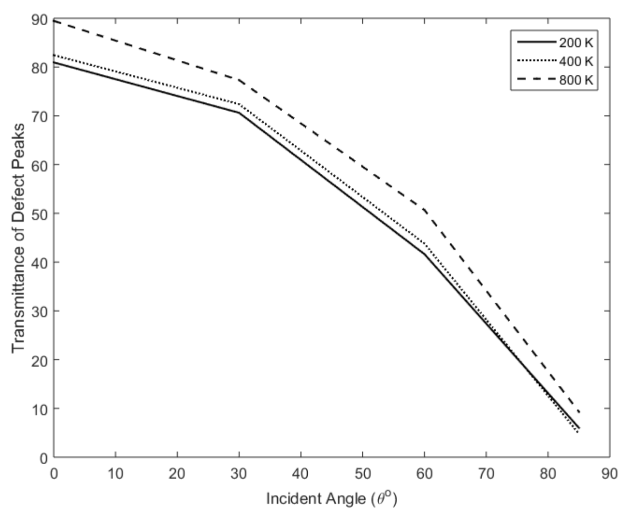

Fig. 8. Transmittance peak of the defect mode wavelength versus incident angle for 200K, 400K, and 800K

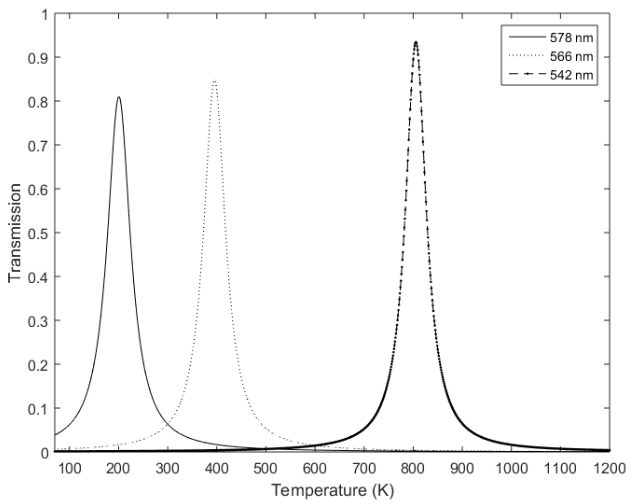

Fig. 9. Transmission peak of the defect mode at 578 nm, 566 nm, and 542 nm wavelength versus temperature

We have also studied the transmittance characteristics of the defect mode wavelength in view of temperature sensor application. In this regards, the transmission peak characteristics of the defect mode at 578 nm, 566 nm, 542 nm wavelength with temperature variation is shown in Fig. 9. The wavelength of the defect mode peaks for 542 nm has a high transmission with 89.47% at 800 K. The transmittance peaks for 566 nm and 578 nm at 200 K, 400K are decreased and become 82.45% and 80.95% respectively. The sharp transmission peak of the defect mode wavelength at a particular temperature leads to use for the temperature-sensing device.

4. Conclusion

In this paper, we investigated the optical properties of one-dimensional periodic structure containing Si/SiO_2 materials with E7 mixture of LC as a defect layer at the different temperatures and the incident angles. The optical parameters of the E7 LC mixture are the temperature dependent as well as the wavelength. Hence the optical properties of the periodic structure, $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$, with LC defect layer tuned by varying the temperature only. The wavelength of the defect mode peaks existed in the PBG region and highly affected by the variation of temperature. Such defect mode peak wavelength of the defect mode shifted to lower wavelength region having high transmittance for high temperature applied to the LC defect layer. Hence, we have suggested that the periodic structure with defect LC layer i.e. $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$ can be used as a temperature sensor. Besides this, such LC defect structure, $(Si|SiO_2)^3|LC|(Si|SiO_2)^3$, may be used as a temperature dependent monochromatic filter.

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