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Comparing the Adjustability of Terahertz Temperature-Dependent Defect Mode with a One-Dimensional Photonic Crystal Containing PbSe, $Hg_{1-x}Cd_xTe$, and $Pb_{1-x}Sn_xTe$ Defects

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Abstract
In this study, the temperature-dependent properties of defect mode in a semiconductor-dielectric photonic crystal were separately investigated for three defects including PbSe, $Hg_{1-x}Cd_xTe$, and $Pb_{1-x}Sn_xTe$. Using the transfer matrix and based on the transmission spectrum, these investigations were conducted on the structure of $(Si/SiO_2)^N$ defect $(SiO_2/Si)^N$. With the temperature-dependent electric permittivity of defect layer, the defect mode would be adjustable to temperature. Given the defect loss, the intensity of defect mode would considerably decrease at higher temperatures for all three defects.

Keywords: One-Dimensional Photonic Crystal, Terahertz Defect Mode, Transmission Spectrum

Introduction

One of the main properties of a photonic crystal is its band gap which is similar to the electronic band gap in solids. An electromagnetic wave with a frequency in the range of photonic band gap cannot be propagated. If a defect layer is created in the structure of a photonic crystal, a defect mode will be generated inside the photonic band gap. The defect mode is detected in transmission spectrum, and there will be a transmission peak inside the gap. When the system does not have any loss, the maximum transmission is obtained. A defective photonic crystal can actually play the role of a transmission filter. The structure of a one-dimensional defective photonic crystal, indicated in Figure 1, is like $(HL)^N D(LH)^N$ in which $(HL)^N$ is the host photonic crystal and D is the defect layer. H and L refer to the forming layers with high and low refractive indices. In this study, they were considered H=Si and L=SiO_2.

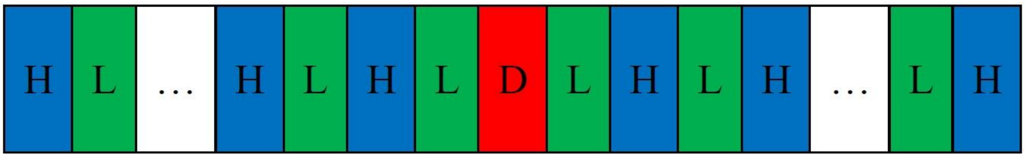

Figure 1: The Structure of a One-Dimensional Defective Photonic Crystal

Basic Equations and Calculation Methods

In terahertz frequency, the electric permittivity of the three abovementioned materials is a little complex and temperature-dependent. It is indicated with Drude's model:

$$\varepsilon_D(\omega,T) = \varepsilon'_D(\omega,T) - j\varepsilon''_D(\omega,T) = \varepsilon_\infty - \frac{[\omega_p(T)]^2}{\omega^2 - j\omega\gamma(T)} = \varepsilon_\infty - \frac{[\omega_p(T)]^2}{\omega^2+[\gamma(T)]^2} - \frac{[\omega_p(T)]^2\gamma(T)}{\omega^3+\omega[\gamma(T)]^2} \quad (1)$$

In Formula 1, ε_∞ refers to the electric permittivity at high higher frequencies. The temperature relationship in electric permittivity is well-indicated through damping factor ($\gamma(T)$) depending on temperature and plasma frequency ($\omega_p(T)$):

$$\omega_p(T) = 2\pi f_p(T) = \sqrt{\frac{\bar{N}(T)e^2}{\varepsilon_0 m^*}} \quad (2)$$

In which *N(T)* represents the intrinsic carrier density based on $\frac{1}{m^3}$. Moreover, m^*, e, ε_0, K_B, and T represent the effective mass of a free carrier, electric charge, vacuum permittivity, Boltzmann constant, and temperature in Kelvin, respectively.

The transfer matrix was used to calculate the transmission for the layer structure placed in air. *R* and *T* indicate reflectivity and transmission, respectively.

$$\bar{T} = |t|^2 = \left|\frac{1}{M_{11}}\right|^2 \quad (3) \qquad \bar{R} = |r|^2 = \left|\frac{M_{21}}{M_{11}}\right|^2 \quad (4)$$

M_{11} and M_{21} are two components of the general transmission matrix *M* in this structure.

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \quad (5)$$

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$$M = D_A^{-1}(D_H P_H D_H^{-1} D_L P_L D_L^{-1})^N (D_D P_D D_D^{-1})(D_L P_L D_L^{-1} D_H P_H D_H^{-1})^N D_A$$
(6)

In this equation, the emission matrix in layer *i*, P_i(i=H,L,D), is indicated as follows:

$$M = \begin{pmatrix} \exp(ik_i d_i) & 0 \\ 0 & \exp(-ik_i d_i) \end{pmatrix} \quad (7)$$

In which $k_i=k_0 n_i=k_0\sqrt{\varepsilon}$ and d_i represent the wave number and thickness in layer *i*. Moreover, $k_0=\frac{\omega}{c}$ is the wave number of free space, and $D_q(q=A,H,L,D)$ is the dynamic matrix in material *q*.

$$D_q = \begin{pmatrix} 1 & 1 \\ \sqrt{\varepsilon_q} & \sqrt{\varepsilon_q} \end{pmatrix} \quad (8)$$

Results and Discussion

First, consider a case in which the photonic crystal is not defective while H=Si and L=SiO_2. The refraction coefficients Si and SiO_2 are equal to 3.3 and 2.25, respectively. The transmission spectrum was calculated in between 4 and 7 terahertz (42.86 to 75 micrometer) and indicated in Figure 2. It should be mentioned that the widths of layers Si and SiO_2 were equal to 5 micrometers, and the number of cells on each side were considered to be 20 (N=20, $d_H=d_L=5\mu m$).
Figure 2 indicates a photonic band gap in terahertz range. Its band edges on left and right are f_L= 4.77 and f_R=6.02, respectively. The magnitude of the photonic gap band is equal to f_R-f_L= 1.25 (THZ), and the frequency center is $f_c=\frac{(f_R+f_L)}{2}=5.395(\mathrm{THZ})$

A) PbSe

Considering PbSe to be the defect layer in Figure 2, ε'_D and ε''_D can be drawn in frequency for 5 different temperatures. The defect layer is 10 micrometer wide.

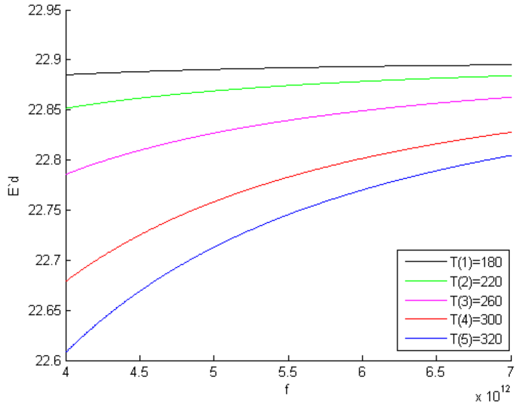
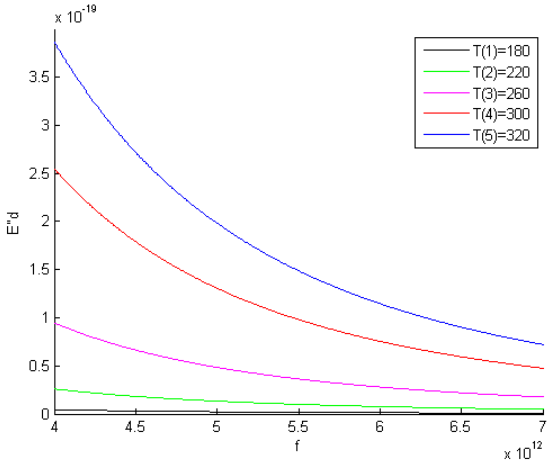
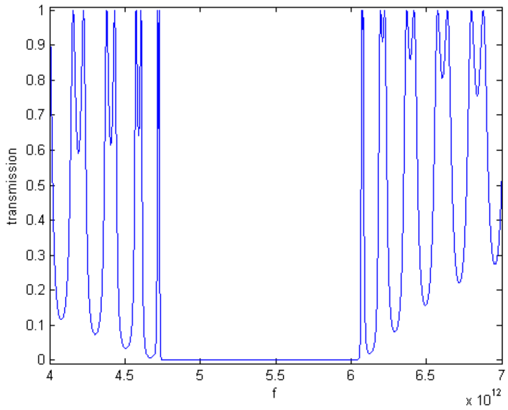


Figure 2: A) ε''_D Diagram for 5 Different Temperatures



B) ε'_D Diagram for 5 Different Temperatures



C) Transmission Spectrum of the Non-Defective Photonic Crystal

The transmission spectrums pertaining to 5 different temperatures can be seen in Figure 3. If temperature is increased, the position of defect mode shifts to the right. Moreover, the peak has decreased with increase in temperature.

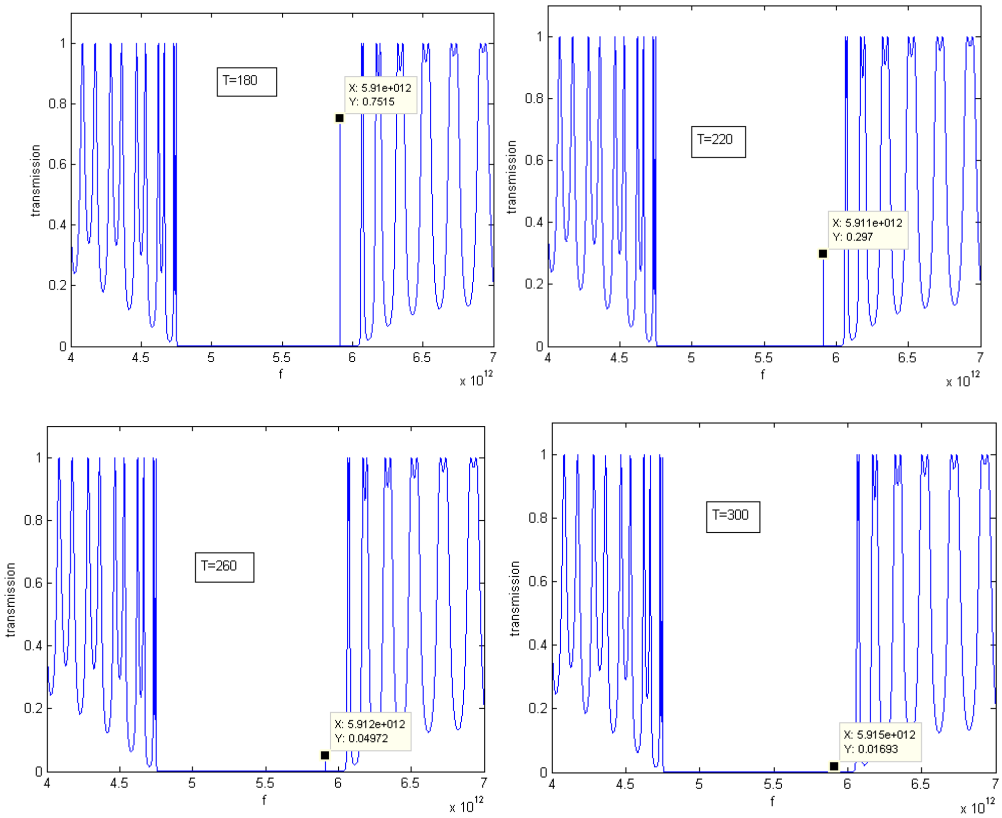


Figure 3: The Transmission Spectrums of PbSe-Defective Photonic Crystal for Different Temperatures

B) $Pb_{1-x}Sn_xTe$

In $Pb_{1-x}Sn_xTe$, the value of x was put 0.32, then ε'_D and ε''_D were drawn for 3 different temperatures in frequency in Figure 4. The defect layer was considered as wide as host layers (5 micrometers). The transmission spectrums pertaining to 3 different temperatures can be seen in Figure 5.

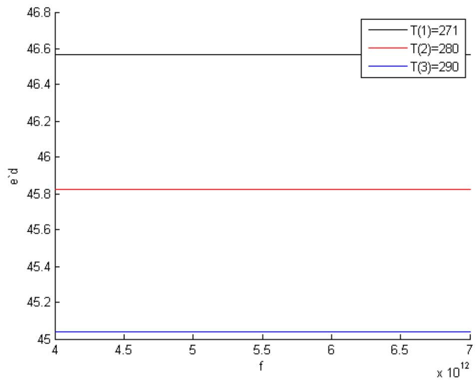
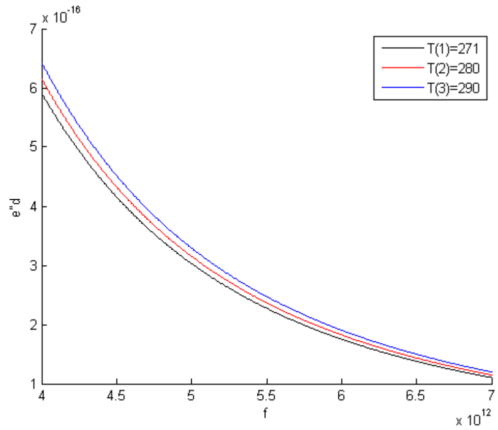


Figure 4: A) ε'_D Diagram for 3 Different Temperatures



B) ε''_D Diagram for 3 Different Temperatures

Given the transmission spectrum, it is obvious that the sensitivity of $Pb_{1-x}Sn_xTe$ to temperature is much more than PbSe. Moreover, the changes in frequency is equal to 0.039 terahertz for $Pb_{1-x}Sn_xTe$, whereas, it was 0.05 for PbSe.

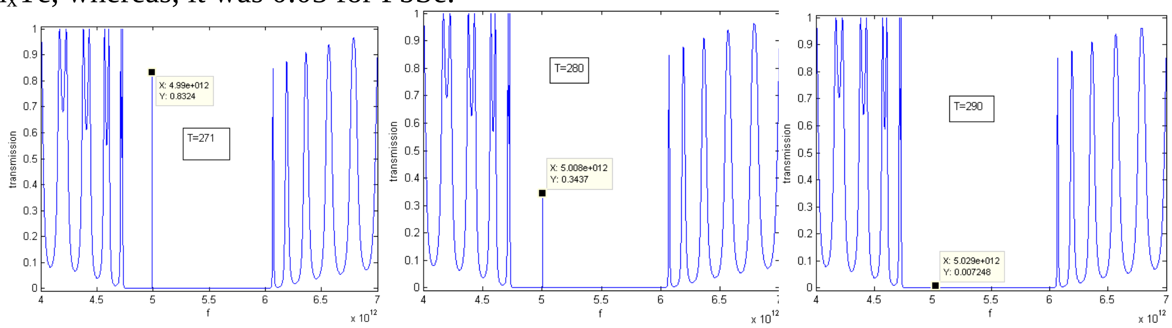


Figure 5: The Transmission Spectrums of One-Dimensional Photonic Crystal with the $Pb_{1-x}Sn_xTe$ Defect Layer for 3 Different Temperatures

C) $Hg_{1-x}Cd_xTe$

In the photonic crystal with $Hg_{1-x}Cd_xTe$ defect layer, the value of x was considered equal to 0.18. The real and imaginary diagrams of electric permittivity were drawn in frequency for different temperatures in Figure 6. In this case, the defect layer was 10 micrometers wide while the host layers were 5 micrometers wide, and there were 22 cells. Given the figure, it is obvious that ε'_D and ε''_D were weakly dependent on frequency at lower temperatures. In fact, $Hg_{1-x}Cd_xTe$, like PbSe, behaves like a dielectric with low loss. Moreover, if temperature increases, the amplitudes of ε'_D decreases, whereas that of ε''_D increases.

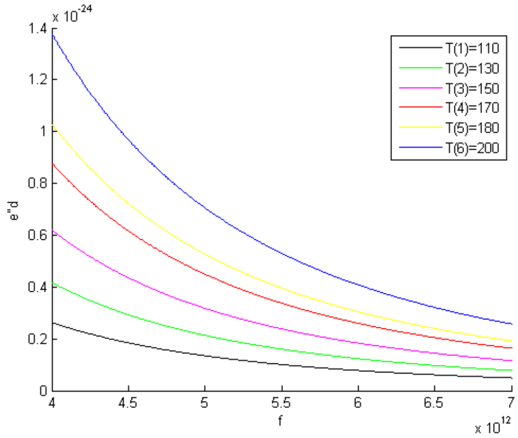
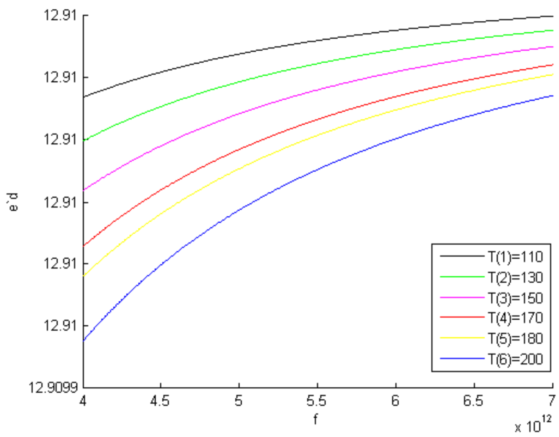


Figure 6: A) ε'_D Diagram for Different Temperatures



B)ε''_D Diagram for Different Temperatures

Figure 7 indicates the transmission spectrums for different temperatures. According to this figure, if temperature increases, the peak height of defect approaches zero. In fact, the sensitivity of $Hg_{1-x}Cd_xTe$ to the temperature is more than PbSe and less than $Pb_{1-x}Sn_xTe$. However, unlike the two other materials, the position of defect mode does not change when the temperature changes. In fact, the transmission changes were drawn for these three materials in temperature in Figure 8 which confirms this fact.

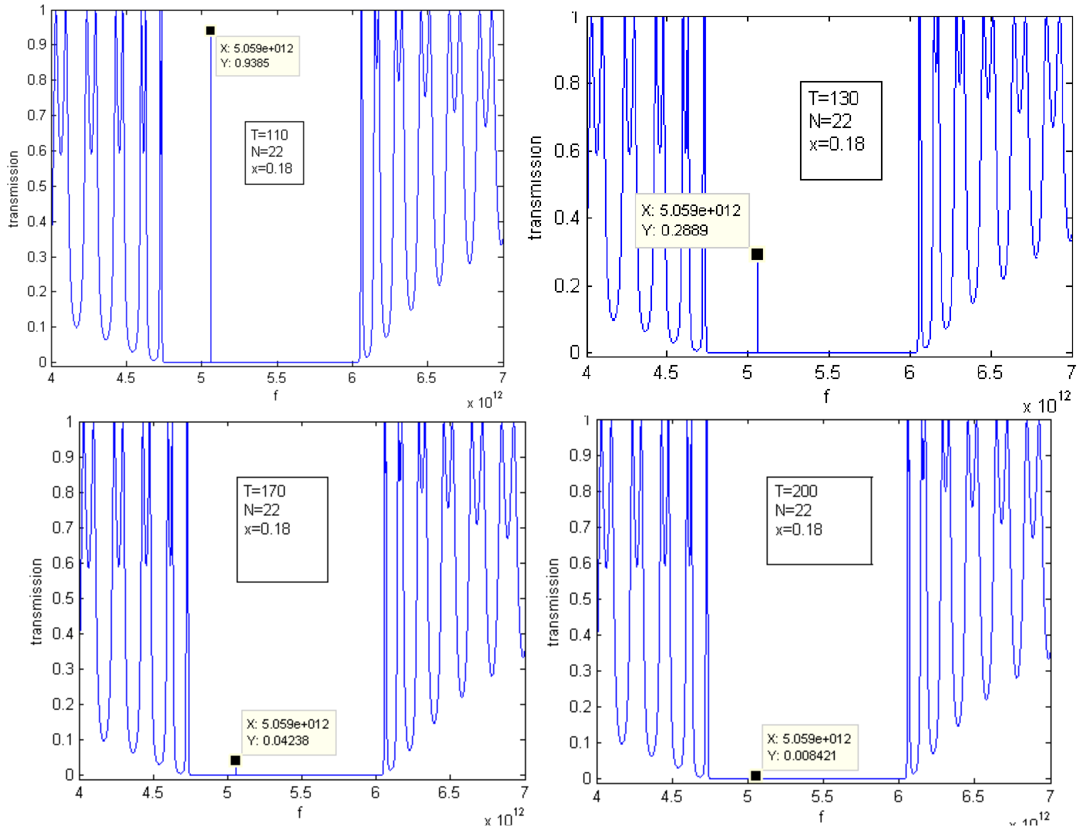


Figure 7: The Transmission Spectrums of One-Dimensional Photonic Crystal with $Hg_{1-x}Cd_xTe$ Defect for Different Temperatures

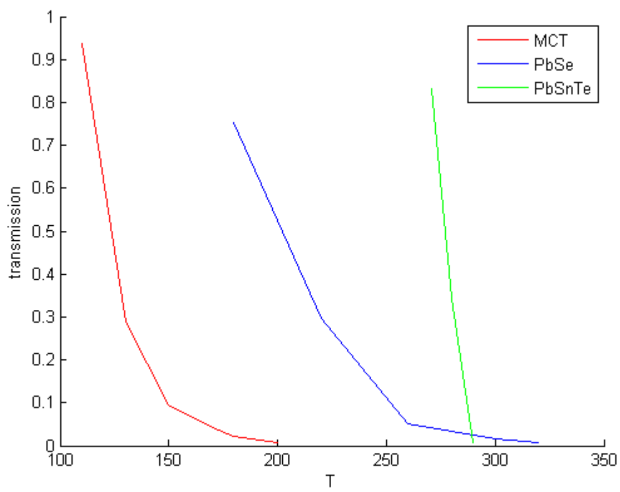


Figure 8: Transmission Changes with Temperature

Conclusion

In the defective one-dimensional photonic crystal, the adjustability of defect mode in terahertz range with temperature was obtained for three different defect materials. In each case, the defect peak approached towards zero after increasing the temperature. Regarding $Pb_{1-x}Sn_xTe$ and PbSe, the position of defect mode changed after increasing the temperature. However, it did not change for $Hg_{1-x}Cd_xTe$. For all three materials, the real and imaginary parts of electric permittivity were weakly dependent on frequency at low temperatures; therefore, they acted like a weak dielectric with low loss. Moreover, the sensitivity of $Pb_{1-x}Sn_xTe$ to temperature was higher than the two other materials, a property which is very useful in light filters.

References

[1] J. D. Joannaploouls, S. G. johnson, "Photonic Crystals: Molding the Flow of Light", Second Edition, Princeton University (2007)

[2] K. Sakoda, “Optical Properties of Photonic Crystals”, Springer, Verlag, New York, (2001)

[3] H. Ch. Hung, Ch. J. Wu, Sh. J. Chang. 2011. Terahertz temperature-dependent defect mode in a semiconductor-dielectric photonic crystal. Applied Physics , 110:093110.

[4] J. Liu, P. Han, G. Qiao, J. Yang. 2011. Properties of PC filters in one-dimensional photonic crystals containing defects. Journal of Intense Pulsed Lasers And Applications in Advanced Physics, 1: 69-72.

[5] P. Yeh.2005. Optical Waves in Layered Media. Wiley, NewYork. 124, pp.