

Photonic Crystal for Gas Sensing Application



Shreerupa Biswas, Shampa Guin and Nikhil R. Das

Abstract In this paper, 1D Photonic Crystal structure, consisting of alternate layers of silicon and air, is theoretically studied for gas sensing application. With one of the air layers replaced by a different gas layer, the resulting defect mode can be utilized for sensing a particular gas, from the transmittance curve, calculated by Transfer matrix method. Very small refractive index variation, $\Delta n = 1.5 \times 10^{-5}$ and a sensitivity = 979 nm/RIU is found by this sensor.

Keywords 1D photonic crystal · Photonic bandgap · Gas sensor

1 Introduction

Photonic crystals [1] are periodic dielectric structures which are designed to control the propagation of electromagnetic waves. A semiconductor cannot support electrons of energy lying in the electronic bandgap. Similarly, a photonic crystal cannot support photons lying in the photonic bandgap. Those wavelengths that are not able to pass through the structure is called Photonic bandgap. Three types of photonic crystals structures are studied according to their periodicity, those are one-dimensional-, two-dimensional-, and three-dimensional photonic crystal structures [2].

S. Biswas (✉) · S. Guin · N. R. Das (✉)
Institute of Radio Physics & Electronics, University of Calcutta,
92, A.P.C. Road, Kolkata 700009, West Bengal, India
e-mail: shreerupabiswas@gmail.com

N. R. Das
e-mail: nrd@ieee.org

S. Guin
e-mail: shampaphysics@gmail.com

© Springer Nature Singapore Pte Ltd. 2019
U. Biswas et al. (eds.), *Advances in Computer, Communication and Control*, Lecture Notes in Networks and Systems 41, https://doi.org/10.1007/978-981-13-3122-0_46

Consider that first layer is Si (silicon) which has permittivity ϵ_1 , permeability μ_1 , thickness d_1 , and refractive index n_1 and second layer is air layer which has permittivity ϵ_2 permeability μ_2 , thickness d_2 , and refractive index n_2 .

The transverse component of E and H field inside the Structure from the Maxwell's equation, for TE polarization is given by

$$E = A \cdot e^{i(\omega t - kd)} + B \cdot e^{i(\omega t + kd)} \tag{1}$$

$$H = \frac{1}{\eta} (A \cdot e^{i(\omega t - kd)} - B \cdot e^{i(\omega t + kd)}), \tag{2}$$

where k = wave number and η = intrinsic impedance are

$$k_L = \omega \sqrt{(\epsilon_0 \mu_0 \epsilon_L \mu_L)} \tag{3}$$

$$\eta_L = \sqrt{(\epsilon_0 \mu_0 / \epsilon_L \mu_L)} \tag{4}$$

L is the total number of periodic layers inside the photonic crystal structure.

We can found a relation between the electromagnetic field components E_L and H_L inside the structure and the electromagnetic field components E_1 and H_1 in the air in matrix form using the transfer matrix method.

$$\begin{pmatrix} E_1 \\ H_1 \end{pmatrix} = M_1 M_2 \dots M_{L-1} M_L \begin{pmatrix} E_L \\ H_L \end{pmatrix} \tag{5}$$

M_L is the characteristic matrix of L th layer

$$M_L = \begin{pmatrix} \cos(k_L d_L) & j\eta_1 \sin(k_L d_L) \\ \frac{j}{\eta_L} \sin(k_L d_L) & \cos(k_L d_L) \end{pmatrix} \tag{6}$$

If we consider the angle of incident light (θ_L) then the characteristic matrix of L th layer can be written as

$$M_L = \begin{pmatrix} \cos(\delta_L) & j\gamma_L \sin(\delta_L) \\ \frac{j}{\gamma_L} \sin(\delta_L) & \cos(\delta_L) \end{pmatrix} \tag{7}$$

δ_L and γ_L being the matrix parameters and depending on the incident angle θ_L of light, the optical constants and the layer thickness are expressed as,

$$\delta_L = k_L d_L \cos(\theta_L) \tag{8}$$

$$\gamma_L = \eta_L / \cos \theta_L \text{ (TE mode)} \tag{9}$$

By considering the characteristic matrix of each layer, we can obtain the transmission matrix of the whole structure, where p is the number of periods,

$$\prod_1^p (M_p) = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{10}$$

$$M_p = M_1 \times M_2 \tag{11}$$

The transmittance t is defined as the ratio of the fluxes of the transmitted wave to the flux of the incident wave.

$$t = \frac{2\eta_i^{-1}}{(m_{11} + m_{12}\eta_s^{-1})\eta_i^{-1} + (m_{21} + \eta_s^{-1}m_{22})} \tag{12}$$

Here η_i and η_s are the intrinsic impedance of the first and last medium of the structure which is given as,

$$\eta_s = \begin{cases} \frac{\eta_s \cos \theta_s}{Z_0} \text{ TE mode} \\ \frac{\cos \theta_s}{\eta_s Z_0} \text{ TM mode} \end{cases} \tag{13}$$

where

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \tag{14}$$

Hence the transmittance T spectrums can be obtained by using the expressions

$$T = |t|^2 \tag{15}$$

The sensitivity of this sensor is given by the following expression:

$$S = \Delta\lambda / \Delta n \text{ (nm/RIU)} \tag{16}$$

3 Results and Discussion

The analysis using the transfer matrix approach uses four periodic layers of silicon and air on each side of the defect layer.

Different lengths of defect layer are studied to get defect mode within 1.55 μm range, assuming a thickness of Si layer of $d_{\text{Si}} = 540 \text{ nm}$ and thickness of Air layer of $d_{\text{Air}} = 440 \text{ nm}$, as shown in Fig. 2. For a normal incident of light, defect mode appears within the photonic bandgap, depending on the length of the defect layer. The wavelength of defect mode shifts when cavity length increases from 700 to 900 nm.

The wavelength shifting is linear with the length of the defect layer as shown in Fig. 3. This shift of the wavelength within the photonic bandgap also depends on the thickness of the Si layer (d_{Si}).

When light incident on the structure at an angle other than normal incidence, defect mode shifts in lower wavelength value as shown in Fig. 4. It may also be noted from Fig. 4 that the photonic bandgap increases with increase in incident angle of light which is clear from Fig. 5.

Figure 6a, b shows the transmission characteristics of 1D photonic crystal in the presence of different gases such as Helium (He), Hydrogen (H_2), Carbon dioxide (CO_2), Methane (CH_4), Argon (Ar), Neon (Ne), and Sulfur dioxide (SO_2) in the defect layer. The shift in wavelength peak-position is measured taking air as reference. It may be seen from the figure that the peak-position shifts to lower wavelengths for

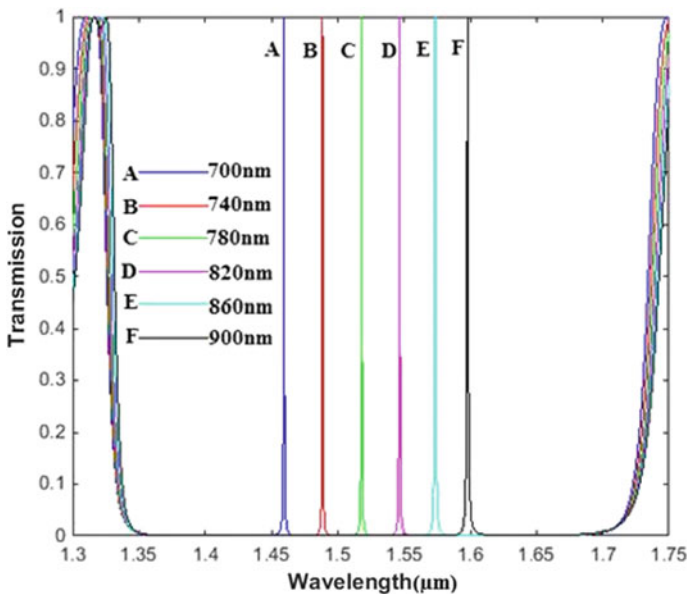


Fig. 2 Transmission spectrum of 1D photonic crystal for different defect layers thickness. Si layer thickness $d_{\text{Si}} = 540 \text{ nm}$ and air layer thickness $d_{\text{Air}} = 440 \text{ nm}$

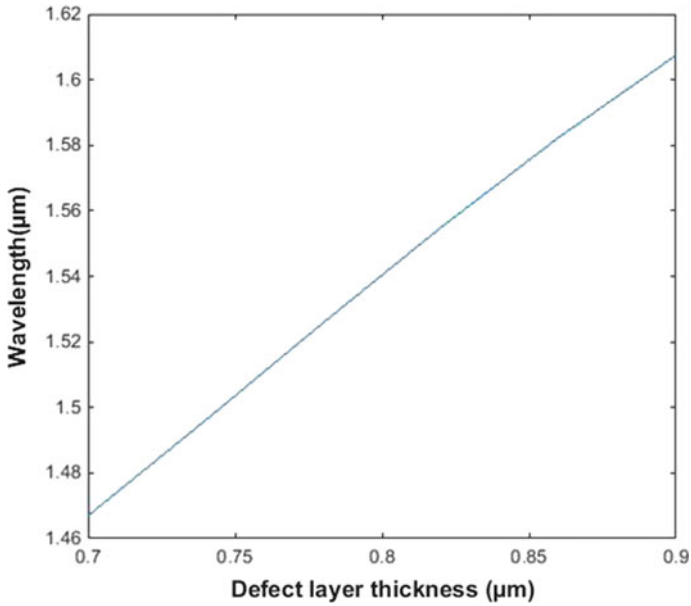


Fig. 3 Wavelength of defect layer as a function of defect layers thickness for $d_{Si} = 540$ nm, $d_{Air} = 440$ nm where cavity length changes from 700 to 900 nm

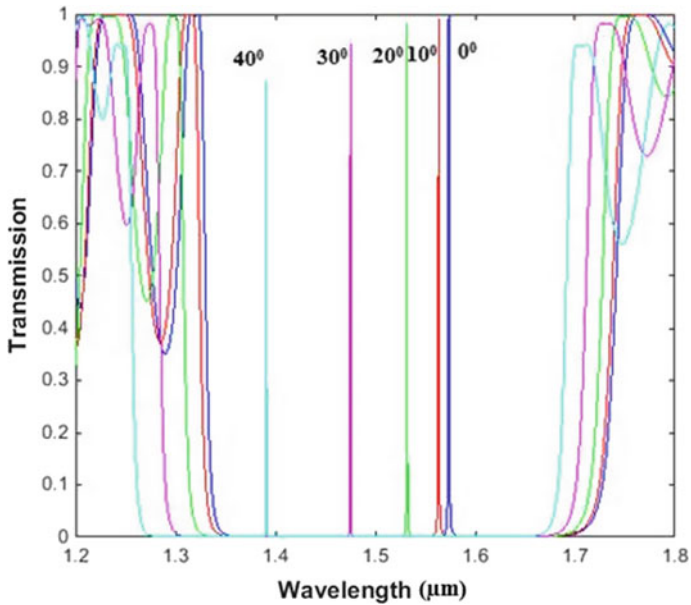


Fig. 4 Transmission spectrum for different incident angle of light for Si layer thickness $d_{Si} = 540$ nm and air layer thickness $d_{Air} = 440$ nm

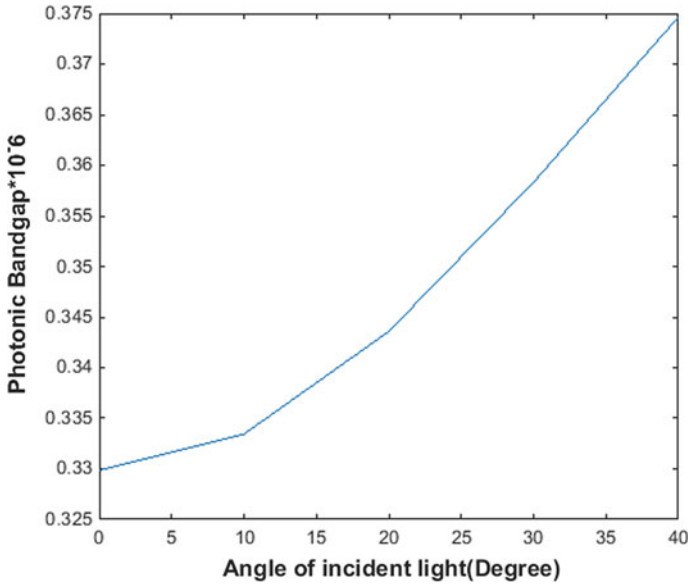


Fig. 5 Photonic bandgap for different incident angle of light for Si layer thickness = 540 nm and air layer thickness = 440 nm

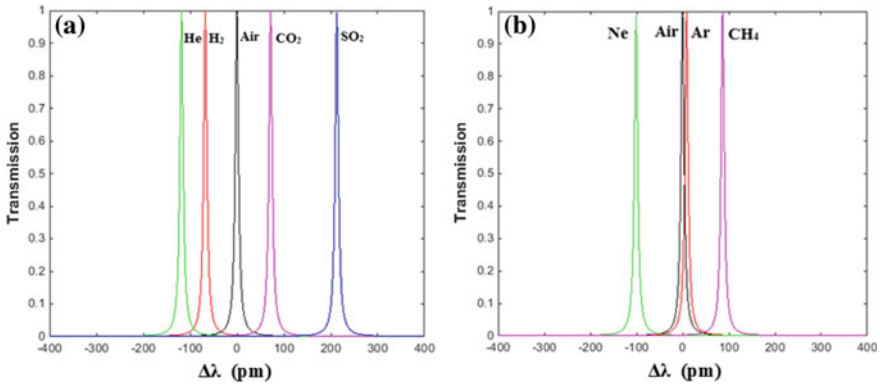


Fig. 6 Transmission spectrum for different gases with air as the reference medium $d_{\text{defect}} = 860 \text{ nm}$

gases having refractive indices less than air, while it shifts to higher wavelengths for gases having higher refractive indices. Thus, the result can be utilized for sensing of different gases.

To study the sensitivity of the device, different thicknesses of silicon and air layer are studied. Curve A, B, C, and D in Fig. 7 denote the corresponding results. Sensitivity, calculated from (16), for those designed structures are 440 nm/RIU, 550 nm/RIU, 654 nm/RIU, and 979 nm/RIU respectively.

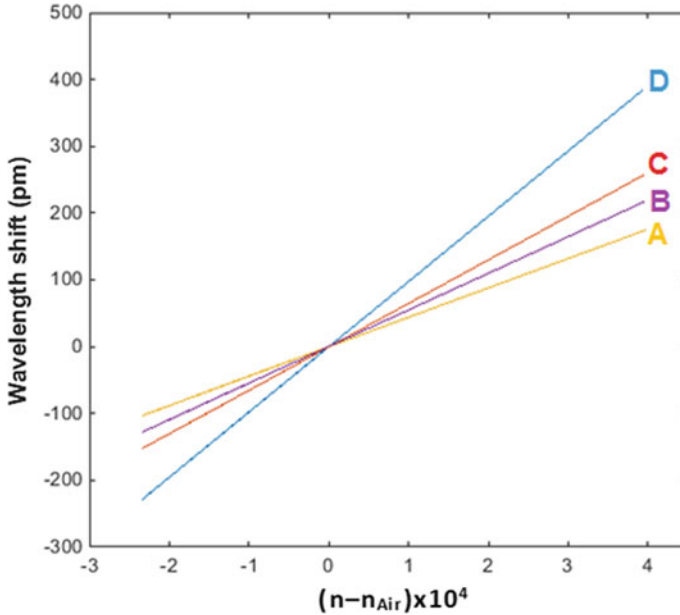


Fig. 7 Wavelength shift as a function of the refractive index change. A ($d_{Si} = 540$ nm, $d_{Air} = 440$ nm, $d_{defect} = 800$ nm), B ($d_{Si} = 380$ nm, $d_{Air} = 280$ nm, $d_{defect} = 700$ nm), C ($d_{Si} = 340$ nm, $d_{Air} = 620$ nm, $d_{defect} = 700$ nm), D ($d_{Si} = 160$ nm, $d_{Air} = 240$ nm, $d_{defect} = 700$ nm)

4 Conclusion

In this paper, a 1D photonic crystal structure as a gas sensor is studied. The sensor can sense the shift in wavelength of transmission spectra, using Transfer matrix method. The study shows that the defect mode inside the bandgap can shift in between the gap of the photonic bandgap if the length of the Si layer or the length of the defect layer or the angle of incidence of the light on the structure is changed. As a result, this structure is very sensitive to the refractive index change of gases which are present in the dry air. The sensitivity of this sensor will increase if we consider different designs of the device structure.

References

1. Joannopoulos, J.D., Steven, G., Johnson, C.: Photonic Crystals: Molding the Flow of Light. Princeton University Press, Princeton and Oxford (2008)
2. Steven, G., Johnson, Joannopoulos J.D.: Introduction to Photonic Crystals: Bloch's Theorem, Band Diagrams, and Gaps (But No Defects). MIT (2003)
3. Rayleigh, J.W.S.: On waves propagating along the plane surface of an elastic solid. J. Mol. Biol. 7(1), 4–11 (1885)

4. Yablonovitch, E.: Photonic band-gap structure: the face centered-cubic case employing non-spherical atoms. *Phys. Rev. Lett.* **67**(20), 2295–2298 (1991)
5. John, S.: Strong localization of photons in certain disordered dielectric superlattices. *Phys. Rev. Lett.* **58**(20), 2486–2489 (1987)
6. Chraim, F., Erol, Y.B., Pister, K.: Wireless gas leak detection and localization. *IEEE Trans. Industr. Inf.* **12**(2), 768–779 (2016)
7. Liu, X., Cheng, S., Liu, H.: C: a survey on gas sensing technology. *Sensors* **12**, 9635–9665 (2012)
8. Nam-Hee Park, T., Akamatsu, T., Itoh, C.: Calorimetric thermoelectric gas sensor for the detection of hydrogen, methane and mixed gases. *Sensors* **14**, 8350–8362 (2014)
9. Sünnner, T., Stichel, T., Kwon, S.-H.: C: photonic crystal cavity based gas sensor. *App. Phys. Lett.* **92**, 261112–261113 (2008)
10. Rshmat, M., Maulina, W., Rustami, E.: C: performance in real condition of photonic crystal sensor based NO₂ gas monitoring system. *Atmos. Environ.* **79**, 480–485 (2013)
11. Chen, T., Han, Z., Liu, J., Hong, Z.: Terahertz gas sensing based on a simple one-dimensional photonic crystal cavity with high-quality factors. *App. Optics.* **53**, 3454–3458 (2014)
12. Rahmata, M., Maulina, W., Isnaeni, C.: Development of a novel ozone gas sensor based on sol-gel fabricated photonic crystal. *Sensors Actuators A Phys.* **220**, 53–61 (2014)
13. Bouzidi, A., Bria, D., Akjouj, A., Pennec, Y.: C: A tiny gas-sensor system based on 1D photonic crystal. *App. Phys.* **48**(495102), 1–7 (2015)
14. Hamidia, S.M., Ramezania, R.: C: hydrogen gas sensor based on long-range surface plasmons in lossy palladium film placed on photonic crystal stack. *Opt. Mater.* **53**, 201–208 (2016)
15. Barkat, O.: theoretical investigation of transmission and dispersion properties of one dimension photonic crystal. *J. Electr. Electron. Eng.* **3**(2), 12–18 (2015)
16. Mohamed, M.S., EL-Okr, M.M., Mostafa, M.T.: Transmission and Dispersion Relation of One Dimensional Photonic Crystal Quantum Matter, vol. 5, pp. 1–6 (2016)