Design of a novel optical sensor for the detection of waterborne bacteria based on a photonic crystal with an ultra-high sensitivity

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Abstract
Today, detecting processes of waterborne bacteria in drinking water is a global challenge because these bacteria can lead to dangerous diseases to the human body. In this paper, we have developed a new sensor for the detection of waterborne bacteria based on a one-dimensional defective binary photonic crystal. The defect layer is taken as a water sample located in the middle of the photonic crystal structure. A resonant peak is then created within the photonic bandgap. The sensing mechanism of the proposed detector is based on the refractive index difference between pure water and waterborne bacteria samples. This index change leads to a shift in the resonant peak position in the transmission spectrum. The effects of many parameters, such as incident angle, defect layer thickness, thicknesses of periodic layers and the number of periods on the sensitivity are investigated. At the optimum conditions, the proposed sensor exhibits a sensitivity of 3639.53 nm/RIU which is ultra-high compared with recently published biosensor papers. It also showed a high-quality factor (7521.26), high figure of merit (8977.98 RIU⁻¹) and low detection limit (1.77 × 10⁻⁵ RIU). The proposed design could distinguish between the different types of waterborne bacteria although the minute difference between their refractive indices. In addition to that, it has a simple design so that it can be easily fabricated.

Keywords Photonic crystal · Waterborne bacteria · Detector · Transmission spectrum · Sensitivity
1 Introduction

Several harmful bacteria found in contaminated water, such as *Escherichia coli*, *Vibrio cholera*, and *Shigella flexneri*, enter our bodies, causing diarrhoea, severe abdominal pain, hepatitis, typhoid, vomiting, and other symptoms (Craun et al. 2006; Liu and Lay 2007). Furthermore, the severity of the infection is particularly sensitive in children and the elderly. The World Health Organization is also concerned about the untimely deaths caused by waterborne germs around the world (Clark et al. 2003). To detect various types of bacteria present in drinking water, various technologies such as polymerase chain reaction (PCR), and enzyme-linked immunosorbent assay (ELISA) are now used. The aforementioned approaches entail long procedures that take many hours to complete the test and obtain a report. As a result, developing a highly sensitive and real-time detector for watery bacteria identification is important. Various waterborne bacteria have a substantial variation in refractive index value compared to clean water, therefore this characteristic is a good option for sensing applications. Refractive indices of pure water, *V. cholera, E. Coli* and *S. flexneri* are 1.333, 1.365, 1.388 and 1.422, respectively (Liu et al. 2014).

Photonic crystals (PCs) and electromagnetic wave propagation have been widely discussed during the last three decades at both the design and manufacturing stages (Doghmosh et al. 2021; Glushko 2021). In a PC, light propagation is controlled by several layers of dielectric materials with low and high refractive indices (Yu and Chang 2004). There is a very interesting region in the transmission spectrum of a PC called the photonic bandgap (PBG) region, which refers to the frequency range that is waves are not permitted to propagate through (Kang and Liu 2018; Revathy et al. 2019). The PBG is highly sensitive to external conditions, including temperature (Trabelsi et al. 2020), mechanical stress (Lee 2004), magnetic field (Xu et al. 2019), electric field (Haurylau et al. 2006), pressure (Kim et al. 2014), and self-organization of multilayered stacks (Trabelsi 2019). Therefore, PCs are considered significant devices for optical sensor applications, such as chemical sensors (Desimoni and Brunetti 2015), pressure sensors (Vijayashanthi and Robinson 2014), and biosensors (Panda et al. 2021). Many researchers have employed the index of refraction as a parameter to develop optical biosensor devices using PCs, especially as urea concentration sensor (Sharma and Sharan 2015) a blood glucose sensor (Banerjee 2019), and a blood sensor (Gharsallah et al. 2018). Such optical biosensor devices have high sensitivity and quick response time for small variations in the sample refractive index.

The sensitivity of an optical liquid sensor based on a photonic crystal waveguide was investigated theoretically (Nacer and Aissat 2013). The sensing principle depends on the change of the effective refractive index of the waveguide induced by the analyte refractive index change (Nacer and Aissat 2013). The finite element approach was used to propose and analyze a D-shaped photonic crystal fiber with a square-lattice and a nanoscale gold layer (Wang et al. 2016). The proposed D-shaped photonic crystal fiber was employed in biological sensors due to the strong surface plasmon resonance effect between fiber core modes and surface plasmon polariton modes (Wang et al. 2016). A photonic crystal nanoring resonator was used to design and optimize a biosensor (Olyaee and Mohebzadeh-Bahabady 2015). The ring resonator was formed by two consecutive curves and is sandwiched by two waveguides.

In this work, a 1D defective binary PC is investigated for refractive index sensing of waterborne bacteria as real-time detection in the IR region. GaAs and TiN layers are used to achieve high contrast between the refractive index of the high index and low index adjacent layers for a binary PC. Based on the transfer matrix method, the
transmission spectrum of the proposed PC that comprising a water sample as a defect layer is investigated. Incident angle, defect layer thickness, thicknesses of periodic layers and the number of periods are studied to enhance the sensitivity of the proposed detector.

2 Design and theoretical aspects

A 1D binary defective PC is proposed for waterborne bacteria detection. The PC has the structure air/(AB)^N/Defect/(AB)^N/substrate. Layers A and B are GaAs and TiN with indices of refraction n_1 and n_2. The thicknesses of the layers are d_1 and d_2 taken according to the Bragg quarter-wave condition. The defect layer thickness is d_f and its index is n_f. The defect layer lies midway between two identical periods. N is the number of periods and the substrate is chosen as a crown glass with a refractive index n_s. Figure 1 shows a schematic diagram of the proposed binary defective PC.

Here, we have used the well-known transfer matrix method to study the transmittance through the PC. The transfer matrix method is appropriate and accurate for finite-size PBG structures with a defect layer (Yeh 1988). The characteristic transfer matrices are defined as (Doghmosh et al. 2021; Trabelsi et al. 2020)

\[
U_j = \begin{bmatrix}
\cos (\varphi_j) & -\frac{i \sin (\varphi_j)}{\beta_j} \\
-i \beta_j \sin (\varphi_j) & \cos (\varphi_j)
\end{bmatrix}
\]

(1)

\[\varphi_j = \frac{2\pi}{\lambda} n_j d_j \cos \theta_j\]

(2)

where \(n_j\) is the refractive index of the layer and \(d_j\) its thickness. \(\theta_j\) is the angle of incidence of the layer which is given in terms of the initial incidence angle \(\theta_0\) as (Doghmosh et al. 2021)

![Schematic diagram of a 1D binary PC having a water sample as a defect layer](image)

Fig. 1 Schematic diagram of a 1D binary PC having a water sample as a defect layer
where \( n_0 \) is the refractive index of the ambient medium and

\[
\beta_j = n_j \cos(\theta_j)
\]

for transverse electric (TE) wave.

The transfer matrix \( U_0 \) for one period consisting of two layers \( A \) and \( B \) can be written as \( U_0 = U_A U_B \). The full transfer matrix \( U \) of a defective binary PC can be expressed as

\[
U = (U_0)^N U_D (U_0)^N = \begin{bmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{bmatrix}
\]

where \( U_D \) is the transfer matrix of the defect layer and \( U_{ij} \) are the elements of the total transfer matrix \( U \). The transmission coefficient can be written in terms of the total transfer matrix elements as

\[
t = \frac{2 \beta_{in}}{(U_{11} + U_{12} \beta_s) \beta_{in} + (U_{21} + U_{22} \beta_s)}
\]

and the transmittance can have the form

\[
T = \frac{\beta_s}{\beta_{in}} |t|^2
\]

The reflection coefficient can be written as

\[
r = \frac{(U_{11} + U_{12} \beta_s) \beta_{in} - (U_{21} + U_{22} \beta_s)}{(U_{11} + U_{12} \beta_s) \beta_{in} + (U_{21} + U_{22} \beta_s)}
\]

and the reflectance can have the form

\[
R = |r|^2
\]

For transverse electric (TE) wave \( \beta_{in} = \cos(\theta_0) \) and \( \beta_s = n_s \cos(\theta_s) \). Based on the above theoretical equations, we can study the properties of the transmission spectra of the defective binary PC.

### 3 Results and discussion

Layers A and B are considered as GaAs and TiN with indices of refraction \( n_1 = 3.36 \) and \( n_2 = 1.2887 \). The thicknesses of the layers are taken according to the Bragg quarter-wave condition where \( d_1 = 126.48 \) nm and \( d_2 = 329.78 \) nm. The number of periods is taken as \( N = 5 \) and the substrate is chosen as crown glass with a refractive index of 1.517. TE polarized light is used in this work.
3.1 Detection of waterborne bacteria

The wavelength range of the incident radiation is taken as 800–2600 nm. Normal incidence is first considered in which \( \theta_0 = 0 \). The transmission spectrum of the proposed binary PC without a defect layer can be seen in Fig. 2a. A PBG of width 1152.5 nm can be seen with left and right edges at wavelengths of 1298.7 nm and 2451.2 nm, respectively. Figure 2b illustrates the transmission spectrum through the structure when a pure water sample of thickness \( D = d_1 + d_2 \) is treated as a defect layer, where \( D = d_1 + d_2 \). The PBG expands to a width of 1276.3 nm where the left and right edges are at wavelengths of 1292.1 nm and 2568.4 nm, respectively. An enlarged view of the defect mode is plotted in Fig. 2c when the sample of pure water is treated as a defect layer. A defect mode can be observed at a resonance wavelength of 1924.2 nm. The full width at half maximum (FWHM) of the resonance peak is 0.14 nm where the wavelengths of

![Fig. 2](image)

**Fig. 2** Transmission spectra of a binary PC without a defect layer (a), with a pure water sample as a defect layer (b) and an enlarged view of the defect mode (c). The parameters of the three panels are \( \theta_0 = 0.0^\circ \), \( n_1 = 3.36 \), \( n_2 = 1.2887 \), \( d_1 = 126.48 \text{ nm} \), \( d_2 = 329.78 \text{ nm} \) and \( N = 5 \).
left and right edges at half maximum are at 1924.12 nm and 1924.26 nm. The quality factor (QF) is found to be 13,744.28 which is calculated using the relation \( QF = \frac{\lambda_{\text{peak}}}{\text{FWHM}} \).

Figure 3 shows the transmission spectra through the proposed PC at normal incidence for different water samples. It is found that the defect mode gets shifted towards longer wavelengths when a waterborne bacterium instead of pure water is used as a defect layer. This shift is due to the position-dependent refractive index of the defect layer and it is also understood by the condition of standing wave (Aly and Zaky 2019) given by

\[
\text{OPD} = m\lambda = n_{\text{eff}}K \tag{10}
\]

where \( \text{OPD} \), \( m \), \( n_{\text{eff}} \) and \( K \) are the optical path difference, integer, effective refractive index and geometric path difference, respectively. The waterborne bacteria samples have a higher index compared to the pure water sample. As \( n_{\text{eff}} \) increases, the wavelength position of resonant modes also increases to keep the optical path difference constant.

Table 1 presents the refractive indices of different water samples, defect mode positions of each and the sensitivity of the proposed binary PC to each sample, where the sensitivity can be calculated as \( \frac{\Delta \lambda}{\Delta n} \) where \( \Delta \lambda \) is the wavelength shift between the resonant peak position of pure water and bacteria samples and \( \Delta n \) is the refractive index change between them. The proposed detector displays an average sensitivity of about 579.61 nm/RIU at a normal incidence.
3.2 Effect of the incident angle

The transmission spectra at different incident angles are investigated. The angle of incidence was varied from 0° to 85°. Some of these results are presented in Tables 2 and 3 for the angles of incidence of 10° and 50°. From Tables 2 and 3, the average sensitivity increases from 590.51 nm/RIU to 851.27 nm/RIU as the incident angle changes from 10° to 50°. The results of all angles of incidence are presented in Table 4. The sensitivity exhibits a significant enhancement with the increase of the incident angle. When the incident angle increases beyond θ₀ = 85°, the defect mode is not observed. The sensitivity has its maximum value of 1194.2 nm/RIU at an incident angle of 85°. So, the optimum incident angle is θ₀ = 85°.

Table 2 Defect mode position and sensitivity of waterborne bacteria at an incidence angle of θ₀ = 10°

| Defect layer     | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
|------------------|------------------|-------------------------------|-----------------------|----------------------|
| Pure water       | 1.333            | 1912.14                       | –                     | –                    |
| *Vibrio cholera* | 1.365            | 1931.1                        | 18.96                 | 592.5                |
| *E. coli*        | 1.388            | 1944.63                       | 32.49                 | 590.72               |
| *Shigella flexneri* | 1.422         | 1964.5                        | 52.36                 | 588.31               |

Average sensitivity = 590.51 nm/RIU

Table 3 Defect mode position and the sensitivity of waterborne bacteria at an incidence angle of θ₀ = 50°

| Defect layer     | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
|------------------|------------------|-------------------------------|-----------------------|----------------------|
| Pure water       | 1.333            | 1653.35                       | –                     | –                    |
| *Vibrio cholera* | 1.365            | 1680.73                       | 27.38                 | 855.62               |
| *E. coli*        | 1.388            | 1700.2                        | 46.85                 | 851.81               |
| *Shigella flexneri* | 1.422         | 1728.68                       | 75.33                 | 846.4                |

Average sensitivity = 851.27 nm/RIU

Table 4 Effect of the incident angle on the sensitivity of waterborne bacteria at d = 1D and N = 5

| Incident angle (degree) | Average sensitivity (nm/RIU) |
|-------------------------|------------------------------|
| 0                       | 579.61                       |
| 10                      | 590.51                       |
| 20                      | 621.59                       |
| 30                      | 674.23                       |
| 40                      | 751.44                       |
| 50                      | 851.27                       |
| 60                      | 966.36                       |
| 70                      | 1082.13                      |
| 80                      | 1170.51                      |
| 85                      | 1194.2                       |

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The variation of sensitivity as a function of the incident angle is shown in Fig. 4 (red points). The relation between the sensitivity \( S \) and the incident angle \( \theta_0 \) can be fitted according to the following relation which is shown as a black curve in Fig. 4.

\[
S(\theta_0) = 578.741 + 1.169\theta_0 - 0.00553\theta_0^2 + 0.00316\theta_0^3 - 2.65 \times 10^{-5}\theta_0^4
\]  
(11)

The fitting Eq. (11) is useful to predict the sensitivity of waterborne bacteria detector at any value of the incident angle located between \( \theta_0 = 0.0^\circ \) and \( \theta_0 = 85^\circ \). As shown in Fig. 4, the matching between the data and the fitting equation curve is perfect.

### 3.3 Effect of the defect layer thickness

In this subsection, the transmission spectra at different thicknesses of the defect layer are also investigated. The defect layer thickness is varied from 1 to 13D in a step of 2D. The results of the thicknesses of 3D and 9D as presented in Tables 5 and 6. The sensitivity improved from 965.1 to 1276.68 nm/RIU and the defect mode shifts to a higher wavelength region as the defect layer thickness increases from 3 to 9D. These results agree with many papers (Aly et al. 2020). All the results are shown in Table 7. The sensitivity increases rapidly from 579.61 to 1354.82 nm/RIU when the defect layer thicknesses increase from 1 to 13D. By increasing the defect layer thickness beyond \( d_f = 13D \), an ignorable sensitivity enhancement is noticed. Thus, the optimum defect layer thickness is considered as \( d_f = 13D \). This behavior can be attributed to the interactions between electromagnetic waves and water samples. Increasing the geometrical
path of the radiation in the defect layer leads to more interactions between electromagnetic waves and water samples. Hence, the sensitivity can be considerably improved (Aly et al. 2020).

The variation of the sensitivity as a function of the defect layer thickness is shown in Fig. 5 (red points). The relation between the sensitivity of the binary PC and the defect layer thickness \(d_f\) can be fitted by the following relation

\[
S(d_f) = 267.37 + 0.8042d_f - 2.75 \times 10^{-4}d_f^2 + 4.515 \times 10^{-8}d_f^3 - 2.77 \times 10^{-12}d_f^4
\]

which is shown as a black curve in Fig. 5. The fitting Eq. (12) is useful for predicting the sensitivity of waterborne bacteria detector at any value of the defect layer thickness located between \(d_f = 1D\) and \(d_f = 13D\). As shown in Fig. 5, the matching between the data and the fitting equation curve is perfect.

### 3.4 Effect of GaAs layer thickness

The transmission spectra at different values of the GaAs layer thickness are also studied. Tables 8 and 9 show some of these results for two values of the GaAs thickness. The thickness was changed from 126.48 to 200 nm. An improvement of the sensitivity from 619.89 to 723.13 nm/RIU can be seen as the GaAs layer thickness increases from 140 to 180 nm. All the results are presented in Table 10. The sensitivity is improved with an increase in the GaAs layer thickness. Increasing the GaAs layer thickness beyond 200 nm, no defect mode can be observed. The sensitivity has a maximum value of 766.78 nm/RIU at a GaAs layer thickness of 200 nm. The optimum thickness of the GaAs layer is taken as \(d_1 = 200\) nm.

### Table 6: Defect mode position and sensitivity of waterborne bacteria at a thickness of defect layer of 9D

| Defect layer | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
|--------------|-----------------|-------------------------------|-----------------------|----------------------|
| Pure water   | 1.333           | 2268.43                       | –                     | –                    |
| *Vibrio cholera* | 1.365     | 2309.97                       | 41.54                 | 1298.12              |
| *E. coli*   | 1.388           | 2338.9                        | 70.47                 | 1281.27              |
| *Shigella flexneri* | 1.422   | 2379.74                       | 111.31                | 1250.67              |

Average sensitivity = 1276.68 nm/RIU

### Table 7: Effect of the defect layer thickness on the sensitivity of waterborne bacteria at \(\theta_0 = 0^\circ\) and \(N = 5\)

| Defect layer thickness (nm) | Average sensitivity (nm/RIU) |
|----------------------------|------------------------------|
| 1D                         | 579.61                       |
| 3D                         | 965.1                        |
| 5D                         | 1122.92                      |
| 7D                         | 1213.13                      |
| 9D                         | 1276.68                      |
| 11D                        | 1318.97                      |
| 13D                        | 1354.82                      |
Fig. 5  Sensitivity versus the defect layer thickness of a binary PC for TE wave at $n_1 = 3.36$, $n_2 = 1.2887$, $\theta_0 = 0^\circ$, $d_1 = 126.48 \text{ nm}$, $d_2 = 329.78 \text{ nm}$ and $N = 5$. (Color figure online)

Table 8  Defect mode position and sensitivity of waterborne bacteria at a thickness of GaAs layer $d_1 = 140$ nm

| Defect layer         | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
|----------------------|------------------|-------------------------------|----------------------|---------------------|
| Pure water           | 1.333            | 1998.92                       | –                    | –                   |
| Vibrio cholera       | 1.365            | 2018.81                       | 19.89                | 621.56              |
| E. coli              | 1.388            | 2033.01                       | 34.09                | 619.81              |
| Shigella flexneri    | 1.422            | 2053.95                       | 55.03                | 618.31              |

Average sensitivity = 619.89 nm/RIU

Table 9  Defect mode position and sensitivity of waterborne bacteria at a thickness of GaAs layer $d_1 = 180$ nm

| Defect layer         | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
|----------------------|------------------|-------------------------------|----------------------|---------------------|
| Pure water           | 1.333            | 2215.94                       | –                    | –                   |
| Vibrio cholera       | 1.365            | 2239.1                        | 23.16                | 723.75              |
| E. coli              | 1.388            | 2255.74                       | 39.8                 | 723.63              |
| Shigella flexneri    | 1.422            | 2280.2                        | 64.26                | 722.02              |

Average sensitivity = 723.13 nm/RIU

Table 10  Effect of the GaAs layer thickness on the sensitivity of waterborne bacteria at $\theta_0 = 0^\circ$, $d_1 = 1D$, $d_2 = 329.78$ nm and $N = 5$

| Thickness of GaAs layer (nm) | Average sensitivity (nm/RIU) |
|------------------------------|------------------------------|
| 126.48                       | 579.61                       |
| 140                           | 619.89                       |
| 160                           | 674.75                       |
| 180                           | 723.13                       |
| 200                           | 766.78                       |
The relation between the sensitivity of the waterborne bacteria detector and the GaAs layer thickness can be fitted by the following equation

\[
S(d_1) = 522.67 - 6.776d_1 + 0.106d_1^2 - 4.8 \times 10^{-4}d_1^3 + 7.63 \times 10^{-7}d_1^4
\]  

(13)

The fitting equation of the sensitivity as a function of the GaAs layer thickness (black curve) along with the data presented in Table 10 (red points) are shown in Fig. 6. The matching between the data and the fitting equation is excellent.

### 3.5 Effect of the TiN layer thickness

The dependence of the sensitivity on the TiN layer thickness is also investigated. Tables 11 and 12 show the average sensitivity improves from 587.26 to 604.83 nm/RIU when the TiN layer thickness grows from 340 to 380 nm. The sensitivity variation with the increase of the TiN layer thickness is shown in Table 13. The defect mode can’t be seen after a TiN layer thickness of 400 nm. The sensitivity has a maximum value of 613.54 nm/RIU at a TiN layer thickness of 400 nm. The relation between the sensitivity of the waterborne bacteria detector and the thickness of TiN layer \(d_2\) can be fitted by the following equation

\[
S(d_2) = -101659 + 1120.58d_2 - 4.6d_2^2 + 8.4 \times 10^{-4}d_2^3 - 5.727 \times 10^{-6}d_2^4
\]  

(14)

---

**Table 11** Defect mode position and sensitivity of waterborne bacteria at a thickness of TiN layer \(d_1 = 340\) nm

| Defect layer          | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
|-----------------------|------------------|--------------------------------|-----------------------|----------------------|
| Pure water            | 1.333            | 1961.9                         | –                     | –                    |
| *Vibrio cholera*      | 1.365            | 1980.68                        | 18.78                 | 586.87               |
| *E. coli*             | 1.388            | 1994.43                        | 32.53                 | 591.45               |
| *Shigella flexneri*   | 1.422            | 2013.83                        | 51.93                 | 583.48               |

Average sensitivity = 587.26 nm/RIU

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**Fig. 6** Sensitivity versus the GaAs layer thickness of a binary PC for TE wave at \(n_1 = 3.36, n_2 = 1.2887, \theta_0 = 0^\circ, \) \(d_3 = 329.78\) nm \(d_1 = 1D\) and \(N = 5\). (Color figure online)
The fitting Eq. (14) is useful to predict the sensitivity of the proposed detector at any value of TiN layer thickness in the considered range. The fitting equation of the sensitivity as a function of the TiN thickness (black curve) along with the data (red points) is shown in Fig. 7.

### 3.6 Effect of the number of periods

In this part, the effect of the number of periods on the sensitivity is discussed. From Tables 14 and 15, the sensitivity decreases from 584.87 nm/RIU to 579.58 nm/RIU as the number of periods increases from N = 3–6. On the whole, the growth of the number of periods leads to a little shrinkage of the sensitivity as shown in Table 16. When the number of periods is taken less than N = 3, the PBG is not observed. Therefore, N = 3 is considered as the optimum number of periods when treating the proposed structure as an optical biosensor. The relation between the sensitivity and the number of periods (N) can be fitted by the following equation

$$S(N) = 683.16 - 71.131N + 18.08N^2 - 2.01N^3 + 0.0821N^4$$ (15)

The fitting equation of the sensitivity as a function of the number of periods (black curve) along with the data (red points) is shown in Fig. 8.

### 3.7 Optimization of waterborne bacteria detector

The resonant peaks of the proposed defective binary PC are shown in Fig. 9 when the pure water and waterborne bacteria samples are treated as defect layers at the optimized conditions. When the pure water is taken as a defect layer, the resonant peak position is found at
2408.25 nm. It is found that the defect mode gets shifted towards longer wavelengths when waterborne bacteria are used as defect layers instead of pure water. The new wavelength positions of the resonant peaks are found at 2526.45, 2608.81 and 2726.72 nm for the samples of *V. cholera*, *E. coli* and *S. flexneri*, respectively. The sensitivity is calculated and found as 3693.75, 3646.54 and 3578.31 nm/RIU for the samples of *V. cholera*, *E. coli* and

Fig. 7  Sensitivity versus the TiN layer thickness of a binary PC for TE wave at $n_1 = 3.36$, $n_2 = 1.2887$, $\theta_0 = 0^\circ$, $d_1 = 126.48$ nm, $d_2 = 1D$ and $N = 5$

| Table 14 | Defect mode position and sensitivity of waterborne bacteria at the number of periods $N = 3$ |
|----------|--------------------------------------------------------------------------------------------------|
| Defect layer | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
| Pure water | 1.333 | 1925.37 | – | – |
| *Vibrio cholera* | 1.365 | 1944.13 | 18.76 | 586.25 |
| *E. coli* | 1.388 | 1957.54 | 32.17 | 584.90 |
| *Shigella flexneri* | 1.422 | 1977.3 | 51.93 | 583.48 |
| Average sensitivity = 584.87 nm/RIU |

| Table 15 | Defect mode position and sensitivity of waterborne bacteria at the number of periods $N = 6$ |
|----------|--------------------------------------------------------------------------------------------------|
| Defect layer | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
| Pure water | 1.333 | 1924.16 | – | – |
| *Vibrio cholera* | 1.365 | 1942.76 | 18.6 | 581.25 |
| *E. coli* | 1.388 | 1956.04 | 31.88 | 579.63 |
| *Shigella flexneri* | 1.422 | 1975.59 | 51.43 | 577.86 |
| Average sensitivity = 579.58 nm/RIU |

| Table 16 | Effect of the number of periods on the sensitivity of waterborne bacteria at $\theta_0 = 0^\circ$, $d_1 = 126.48$ nm, $d_2 = 329.78$ nm and $d_f = 1D$ |
|----------|--------------------------------------------------------------------------------------------------|
| Number of periods (nm/RIU) | Average sensitivity |
| 3 | 584.87 |
| 4 | 580.31 |
| 5 | 579.61 |
| 6 | 579.58 |
| 7 | 579 |

The sensitivity is calculated and found as 3693.75, 3646.54 and 3578.31 nm/RIU for the samples of *V. cholera*, *E. coli* and *S. flexneri*, respectively.
S. flexneri, respectively. Table 17 presents the refractive indices of pure water and waterborne bacteria samples, defect mode positions of each and the sensitivity of the proposed binary PC to each sample. The relation between the resonant peak position of water samples ($\lambda_{\text{peak}}$) and the refractive index of the sample (n) can be fitted by the following equation

$$\lambda_{\text{peak}}(n) = -2358.79 + 3577.59n$$  \hspace{1cm} (16)

Figure 10 shows the resonant peak position variations as a function of the refractive index of different water samples. The position of the resonant peaks is linearly shifted to

![Figure 8](image_url) Sensitivity versus the number of periods of a binary PC for TE wave at $n_1 = 3.36$, $n_2 = 1.2887$, $d_1 = 126.48$ nm, $d_2 = 329.78$ nm, $\theta_0 = 0^\circ$, and $d_3 = 1D$. (Color figure online)

![Figure 9](image_url) Transmission spectra of a binary PC for different defect layers at $\theta_0 = 85^\circ$, $n_1 = 3.36$, $n_2 = 1.2887$, $d_1 = 200$ nm, $d_2 = 400$ nm, $d_3 = 13D$ and $N = 3$

**Table 17** Defect mode position and sensitivity of waterborne bacteria at the optimum parameters ($\theta_0 = 85^\circ$, $d_3 = 13D$, $d_1 = 200$ nm, $d_2 = 400$ nm and $N = 3$)

| Defect layer         | Refractive index | Position of resonant peak (nm) | Wavelength shift (nm) | Sensitivity (nm/RIU) |
|----------------------|------------------|--------------------------------|-----------------------|----------------------|
| Pure water           | 1.333            | 2408.25                        | –                     | –                    |
| Vibrio cholera       | 1.365            | 2526.45                        | 118.2                 | 3693.75              |
| E. coli              | 1.388            | 2608.81                        | 200.56                | 3646.54              |
| Shigella flexneri    | 1.422            | 2726.72                        | 318.47                | 3578.31              |

Average sensitivity = 3639.53 nm/RIU
a higher wavelength region as the refractive index of the defect layer increases. The black line in Fig. 10 represents the fitting equation and the red points are the simulation data.

To show the efficiency of the proposed detector, the performance parameters are examined such as the quality factor, figure of merit and detection limit. A high-quality factor of the sensor means that the defect mode has an extremely sharp bandwidth. The quality factor can be calculated as the ratio between the resonant peak position ($\lambda_{\text{peak}}$) and the full width at half maximum (FWHM) of that peak (Ding et al. 2017)

$$QF = \frac{\lambda_{\text{peak}}}{\text{FWHM}}$$  \hspace{1cm} (17)

The results demonstrate that the proposed detector has a high Q-factor of about 7521.26 with a FWHM of about 0.39 nm.

Figure of merit (FOM) denotes the ability of the sensor to detect any change of the refractive index. It is estimated by the ratio between the sensitivity and the full width at half maximum of the defect mode (Ding et al. 2017)

$$FOM = \frac{S}{\text{FWHM}} = \frac{\Delta \lambda}{\Delta n \times \text{FWHM}}$$  \hspace{1cm} (18)

The FOM value of the proposed detector is about 8977.98 RIU$^{-1}$.

Detection limit (DL) can be defined as the smallest change in the refractive index that can be precisely determined in refractometric sensing. The Detection limit is calculated as (White and Fan 2008)

$$DL = \left( \frac{\text{FWHM}}{\Delta \lambda} \right)^{\frac{3}{2}} \left( \frac{2 \Delta n}{3} \right)$$  \hspace{1cm} (19)

For the current sensor, the detection limit is equal to $1.77 \times 10^{-5}$ RIU. The value of DL is very low, which means that the proposed detector is effective to sense any very small change in the refractive index of an analyte.

Table 18 shows that the sensitivity of the proposed detector is higher than that of recently reported by other structures. In 2021, Arafa et al. investigated the sensitivity of a 1D-PC with a defect layer for detecting mycobacterium tuberculosis bacteria and they realized a sensitivity of 1390 nm/RIU. In the same year, Panda A. and Pukhrambam P. D studied the sensitivity of a 1D-defective PC for sensing waterborne bacteria and they achieved a sensitivity of 387.5 nm/RIU. The proposed detector in our work attained a sensitivity value much greater as compared other papers.

![Fig. 10](image_url) Defect mode position versus the refractive index of different water samples at $\theta_0 = 85^\circ$, $n_1 = 3.36$, $n_2 = 1.2887$, $d_1 = 200$ nm, $d_2 = 400$ nm, $d_3 = 13D$ and $N = 3$.
Comparing the sensitivity of our detector with sensitivities of the most recent biosensing designs

| Techniques/structures                                      | Sensitivity (nm/RIU) | Year | References                        |
|-----------------------------------------------------------|----------------------|------|-----------------------------------|
| Porous silicon-based Bragg-grating resonator for biosensing | 387                  | 2018 | Sahu et al. (2018)                |
| A graphene metasurface based sensitive infrared biosensor  | 431                  | 2019 | Patel et al. (2019)               |
| Refractometric sensors based on 1D-ternary dispersive PC   | 600                  | 2019 | Sovizi and Aliannezhadi (2019)    |
| Biosensor based on 1D PCs                                  | 1025                 | 2020 | El-Ghany et al. (2020)            |
| 1D binary PCs based hemoglobin sensor                      | 167                  | 2020 | Abadla and Elsayed (2020)         |
| A ring mirror 1D-PC for detecting mycobacterium tuberculosis bacteria | 700                  | 2020 | Failed (2019)                     |
| Biosensor based on PBG materials as a tuberculosis detector| 1390                 | 2021 | Aly et al. (2021)                 |
| 1D PC for detection of waterborne bacteria                 | 387.5                | 2021 | Panda and Pukhrambam (2021)       |
| A waterborne bacteria detector based on a binary PC        | 3639.53              | 2021 | Current work                      |
4 Conclusion

In this study, we have investigated a novel design based on 1D defective PC for sensing waterborne bacteria. The optical properties have been analyzed using the well-known transfer matrix method. The detector is designed using two alternating layers of GaAs and TiN. The defect layer is taken as a water sample either pure or contaminated with bacteria. The effects of the incident angle, the defect layer thickness, the constituent layers thickness and the number of periods on the performance of the proposed detector have been explored. There is a minute difference between the index of pure water and that of waterborne bacteria (V. cholera, E. Coli and S. flexneri). The sensing mechanism of the proposed detector is based on this refractive index difference. This index change leads to a shift in the resonant peak position in the transmission spectrum. Many interesting findings are found. Increasing the angle of incidence, the defect layer thickness, GaAs layer thickness and TiN layer thickness enhances the sensitivity of the suggested detector. The proposed detector offers high sensitivity that can reach a value of 3639.53 nm/RIU for the optimized parameters. The capability of the offered detector to distinguish between the different types of waterborne bacteria has been proven. The proposed structure showed a high-quality factor (7521.26), high figure of merit (8977.98 RIU⁻¹) and low detection limit (1.77 × 10⁻⁵ RIU). The proposed detector has many advantages such as simple structure, tunable design and rapid and real-time detection. It can be applied to any kind of biosensing.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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