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# Design and Performance Analysis of Simple PCF Based Sensor with High Sensitivity for Sensing the Presence of Bacteria - *Pseudomonas aeruginosa*

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**Abstract**

*Pseudomonas aeruginosa* is a nosocomial infectious disease with high mortality rates due to its innate and acquired resistance to a wide variety of antibiotics. As a result, rapid identification of the pathogenic bacterium with high specificity and sensitivity is essential in protecting against disease. This paper presents a PCF-based biosensor with promising performance characteristics for detecting the existence of Pseudomonas bacteria. A simple structure of the proposed sensor most importantly the core regions may reduce the fabrication complexity. The proposed structure is numerically analyzed using the full finite element model and the optical parameters are investigated using Perfectly Matched Layer (PML). The designed PCFs have been put to the test for detecting the existence of *Pseudomonas aeruginosa* bacteria. The numerical investigation has done in a range of wavelengths from 0.9µm to 1.1µm and for the RI value of 1.33 to 1.37. Increasing the diameter of the air holes in the microstructure core and adjusting the thickness of the PML improve relative sensitivity considerably. The proposed sensor test is carried out on various PML radius values and hole's diameter variations in the core section. The proposed sensor provides maximum sensitivity is 44.06% and minimal confinement loss 0.008410 (dB/m) at a fixed wavelength 1µm.

**Keywords:** Photonic crystal fiber; Bacteria Sensor; Finite Element Method; Perfectly Matched Layer; Sensitivity; Confinement loss

## Introduction

*Pseudomonas aeruginosa* is a *Pseudomonadaceae* bacterium that is gram-negative, asporogenous, and mono flagellated (a member of the Gammaproteobacteria). It's a rod-shaped object that's about (1-5) µm long and (0.5-1.0) µm wide [1]. It has a pearlescent appearance and smells like grapes or tortillas. *Pseudomonas aeruginosa* is an important respirator that requires oxygen for optimum metabolism, though it can also breathe anaerobically using other electron acceptors. *Pseudomonas aeruginosa* thrives in temperatures ranging from 25°C to 37°C. *Pseudomonas aeruginosa* is a ubiquitous bacterium that can thrive in a wide range of environments, including distilled water [2]. Pseudomonads aeruginosa is primarily found in soil, seawater, and freshwater. They can also colonize plants and livestock, and they're common in homes and hospitals [3]. They have a large effect on biodiversity, agriculture, and trade due to their widespread distribution in both terrestrial and aquatic ecosystems. They are also responsible for food spoilage and degradation of petroleum products in the environment. *Pseudomonas aeruginosa* is one of the most common plant pathogens in agriculture [4]. It not only responsible for diseases in plants and animals but also in humans, causing serious infections in immunocompromised. Patients with cystic fibrosis, burn wounds, organ transplants, acute leukaemia, and intravenous drug abuse are all at risk for Pseudomonas infection [5]. It is a common cause of nosocomial infections in hospitals, particularly in intensive-care units (ICU). In most hospitals, it is responsible for 20% of all infections. Patients who have been in the hospital for a long time are often infected with this organism and are at a high risk of infection. The most serious infections include endophthalmitis, malignant external otitis, meningitis, endocarditis, septicaemia and pneumonia [6]. *P. aeruginosa* infections are not only normal, but they also have a high mortality and morbidity rate as compared to other bacterial pathogens. The nature of the patient's underlying condition determines the likelihood of recovery from pseudomonas infection. Furthermore, treatment of this infection is being rendered increasingly problematic due to the emergence and spread of resistance mutant among this pseudomonas group [5]. They are often immune to several antibiotics and have been dubbed "superbugs" due to their immense capacity to breed resistance. It suggests that due to low outer membrane permeability and adaptive mechanisms, this species is less susceptible to most antibiotics and is more likely to develop clinical resistance [7]. This resistance mechanism has complicated treatment options for *Pseudomonas aeruginosa* infections, which have become a severe and deadly problem in the United States, causing 51,000 healthcare infections per year [8]. Given the possible seriousness of these infections and the difficulty in determining the best treatment, detecting, and identifying *Pseudomonas aeruginosa* is a top priority.

PCF is an optical fiber with a photonic crystal cladding that surrounds the cable's core. A photonic crystal is a low-loss periodic dielectric medium consisting of a regular pattern of microscopic air holes running the length of the fiber. Fiber optic cables have a constant refractive index difference in the core and a constant refractive index difference in the cladding. Light is concentrated


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in the core of PCF which provides a much stronger waveguide for photons than normal fiber optics. PCF is made of polymers rather than glass, resulting in a more durable fiber that is therefore easier and less expensive to produce. Photonic crystal fiber is also known as micro-structured or holey fiber. Photonic bandgap (PBG) structures with hollow cores may be more advantageous for sensing applications [9]. Light is directed in the hollow region of an optical fiber with a hollow core [10]. As a result, only a small amount of light can reach the solid fiber material (typically a glass). These fibers are known as photonic bandgap fibers. The PCF guides light by inserting and limiting air holes along the length of the fibers at regular intervals. The size of holes in the core and cladding can be adjusted to control light propagation. Because of its ability to detect light in hollow bodies, it has low blockage loss and enhanced light penetration, resulting in increased fiber sensitivity [11]. PCF-based sensors are also capable of detecting oil or fuel toxicity in addition to sensing applications [12].

Several studies on the performance of optical sensors based on PCF have been published. Photonic crystal fibers are used in spectroscopy, metrology, bioengineering, imaging, telecommunication, industrial machining, and military technology. PCF is used in a variety of applications, including gas detection [13], chemical detection [14], pressure detection [15], bio-medical and temperature sensing, and so on. The authors proposed a liquid (water) sensing sensor and designed the core section with holes of different diameters. The overall sensitivity of their sensor is about 49.13%, and it's become clear how the sensitivity increases as the diameter of the hole changes [16]. In [17], the authors suggested a basic circular lattice PCF made up of two air hole rings and a thin layer of gold on the outside of the PCF structure. The proposed structure should have the highest sensitivity possible, including amplitude sensitivity and sensor resolution. The author [18] proposed a gold-coated dual-core sensor with hexagonally arranged circular air holes based on the SPR-PCF sensor. The plasmonic material in this design is gold, a chemically inactive and stable element. The impact of changing gold layer thickness, pitch, and analyte layer thickness on confinement loss and amplitude sensitivity is described in this paper. The maximum sensitivity of the proposed structure is 10,700 nm/RIU for analyte RI changing from 1.39 to 1.40. The authors [19] modeled a structure to detect liquid analytes, but their proposed sensor can detect water, 10% glucose solution, and mucosa at the same time with corresponding sensitivity and birefringence using the same structure. Some authors [20] have proposed spiral type photonic crystal fiber (S-PCG) as a gas sensor. They proposed a porous PCF with a core region with a cluster of circular air holes and cladding with a spiral shape that also includes air holes. Between the wider wavelength ranges of 1 to 1.8m, the proposed S-PCF exhibited maximum relative sensitivity of about 55%.

Recently [21], authors designed vertical and horizontal PCF structures for sensing sulfur dioxide gas, and then formed the elliptical core to achieve high relative sensitivity and low confinement loss at the same time. They compared and contrasted the efficiency of H-PCF and VPCF, as well as how variations in PML thickness affect the sensitivity value of the proposed structure. The V-PCF sensor has the highest sensitivity of 59.344% while the HPCF sensor has a sensitivity of 58.34%.

Sensor systems for the detection of pathogenic bacteria have reawakened interest in recent years, especially in the fields of food safety, medical diagnosis, and biological warfare. This is due to an increase in the number of bacteria-related illnesses over the world. Authors [22] tested the sensor's performance by monitoring the adhesion of *Escherichia coli* K12 cells to the sensor surface. The sensor's output was evaluated by tracking the adhesion of *Escherichia coli* K12 cells to the sensor's surface. A bacterial solution was made by suspending and washing a single *Escherichia coli* K12 colony from an agar plate in a 10-mL phosphate-buffered saline solution (PBS) resulting in a concentration of $3\times10^7$ cells/mL They have calculated the peak angle sensitivity of 1.65 $\times10^{-6}$ (deg/cell)/mm$^2$. Obtained average single-cell sensitivities of $1.3\times10^{-6}$ and $1.65\times 10^{-6}$ (deg/cell)/mm$^2$ for TE and TM modes respectively.

For the detection of Pseudomonas bacteria, a highly sensitive SPR biosensor based on silver (Ag), barium titanate ($BaTiO_3$), graphene, and an affinity layer is proposed [23]. The proposed structure has been analyzed by using the angular modulation method in this paper. They investigated the reflectivity of a p-polarized incident light wave using the Fresnel multilayer reflection theory and the transfer ma-Trix process. They analyzed the impact of silver and barium titanate layer thickness on minimum reflectivity at a fixed wavelength of 633nm. The adsorption of Pseudomonas bacteria on the surface of the graphene layer with the guidance of the affinity layer is the detection mechanism. The sensing medium in their proposed SPR structure is water, which has a refractive index of 1.33. Maximum sensitivity, quality parameter and detection accuracy for this proposed structure are obtained as 220 degree/RIU, 101.38 RIU$^{-1}$ and 7.09 respectively for change in the refractive index of the sensing medium from n = 1.33 to 1.40. The authors [24] proposed a biosensor that detects changes in refractive index near the sensor surface using the attenuated total reflection process. When these findings are compared to those of a traditional gold layer surface plasmon resonance biosensor, it is clear that adding the graphene layer improves the overall performance of the proposed biosensor. In comparison to traditional SPR biosensors, their proposed SPR biosensor with graphene layer has low loss and maximum surface mode excitation. The dip in reflectance transitions towards a higher value of incident angle as the cover refractive index increases from nc = 1.33 to nc = 1.40. This is a bacterial symbol, and the angle shift is completely dependent on the concentration and mobility of bacteria. Proposed SPR biosensor with graphene layer provides Sensitivity (Degree/RIU) value is 33.98% when Conventional SPR biosensor without graphene layer shows 30.85%. A zinc oxide (ZnO), gold (Au), and graphene-based SPR biosensor for the identification of pseudomonas and pseudomonas-like bacteria suggested by the authors [25]. The performance of the proposed SPR biosensor is focused on the angular interrogation method and theoretical analysis of sensitivity, detection accuracy, quality parameter, and electric field intensity enhancement factor (EFIEF). They looked into the efficiency of a ZnO, gold and graphene-based hybrid SPR biosensor structure. BK-7 glass prism, ZnO, Au, graphene, and affinity layer are all part of their proposed four-layer planar structure. They've also examined at how a graphene layer affects the sensitivity of a proposed SPR biosensor for pseudomonas detection. It is also clear from their research that increasing the affinity layer refractive index reduces sensitivity, detection precision, and efficiency parameter over time. The proposed biosensor based on ZnO has better performance parameters than other traditional biosensors, and increasing the number of graphene layers reduces sensitivity, as described in this paper. The proposed biosensor has a greater sensitivity of 187.43 deg/RIU, the detection accuracy of 2.05deg$^{-1}$, quality parameter of 29.33 RIU-1 and enhanced EFIEF for the detection of pseudomonas-like bacteria when compared to other identified conventional SPR biosensors. Very recent time [26] a surface plasmon resonance (SPR) biosensor based on photonic crystal fiber (PCF) has been proposed to detect the presence of Pseudomonas bacteria with attractive performance characteristics. To overcome the limitations of the prism-based sensor, this paper uses a wavelength interrogation (WI) and amplitude interrogation (AI) approach. The proposed SPR sensor, which uses a single air hole ring to design the sensor. The pitch, or the distance between the centers of two contiguous air holes, is p = 1.5 m when all of the air holes inside the ring are spaced at 30. Two separate air holes are used in this ring, with the larger air holes having a diameter of D = 0.2×p m. The smaller air holes at 60, 120, 240, and 300 have a diameter of D1 = 0.75×D m, which helps to create a path that allows more light to pass through the metal interface, creating a more evanescent field. In this structure, water with a RI of 1.33 is used as a sensing medium. 20,000 nm/RIU and 1380 RIU$^{-1}$ are the highest wavelength and amplitude sensitivity, respectively. The sensor has an excellent spectral resolution, with a maximum value of $5.26\times10^{-6}$ RIU, allowing it to detect very minor changes in analyte refractive index (RI) in the range of 1.33 to 1.42. The author [36] presents a hollow core Photonic Crystal Fiber (HCPCF) to detect blood components. To detect each blood component, that component needs to place into the core hole and the amount of blood sample depends on the size of the core. Also, six rectangular holes (R1-R6) are considered surrounding the core where they put air to guide light within the analyte Their proposed HCPCF sensor provides high sensing performance and the relative sensitivity is achieved approximately 89.14% for water, 90.48% for plasma, 91.25% for white blood cells (WBCs), 92.41% for hemoglobin (HB), 93.50% for red blood cells (RBCs) at frequency 2 THz for the ideal design. This sensor also offers a very negligible amount of light confinement loss (CL) and a high effective area (EA). The CL is found around $1.3\times10^{-13}$ cm$^{-1}$, $9.1\times10^{-14}$ cm$^{-1}$, $7.52\times10^{-14}$ cm$^{-1}$, 4.98×10, cm$^{-1}$, $3.11\times10^{-14}$ cm$^{-1}$ and the EA is noticed almost $2.2\times10^{5}$ μm$^2$, $2.18\times10^{5}$ μm$^2$, $2.16\times10^{5}$ μm$^2$, $2.14\times10^{5}$ μm$^2$, $2.12\times10^{5}$ μm$^2$ for water, plasma, WBCs, HB, RBCs, respectively, at frequency 2 THz.

A dual-core liquid-filled photonic crystal fiber coupler (PCFC) with rectangular (RPCFC) and hexagonal (HPCFC) geometry are presented [37] from the 1200 to 1800 nm wavelength range in the proposed design. In the proposed design, four air-holes rings where each air-hole diameter, d=0.6 μm, and lattice pitch Λ = 2.3 μm is chosen at the 1.55 μm wavelength, RPCFC shows 0.000318, 0.000358, and 0.000379 m coupling lengths for the water, chloroform, and benzene-filled dual-core, respectively. Additionally, the confinement loss of $1.57\times10^{-7}$, $1.22\times10^{-7}$, and $1.05\times10^{-7}$ dB/km are achieved through RPCFC.

PCF-based chemical sensor model is suggested [38] where Zeonex is used as the fiber material and this sensor performance is analyzed in the terahertz regime. The reported sensor model provides enhanced sensitivity (94.4%) along with tiny confinement loss (1.71 × 10$^{-14}$ cm$^{-1}$) at a frequency of 1.8 THz. Besides, the fabrication of this model is also probable by exercising subsisting fabrication methods. The hollow-core PCF is chosen for its numerous advantages for instance hollow-core fiber offers lower effective material loss (EML) and the fabrication of this proposed PCF model is possible by using existing fabrication methods.

Prism coupled an SPR-based sensor that operates on the concept of angular interrogation. Prism coupled sensors have certain disadvantages, which are overcome by traditional OF-based sensors. But their sensitivity is not very high and they are also limited to their design parameters. Furthermore, remote sensing applications are not possible with the prism-based SPR sensing system. If an optical fiber is used instead of a prism, these limitations can be resolved. The optical fiber also has the benefit of allowing the SPR probe to be miniaturized, which is beneficial for samples. In this regard, PCF-based sensors have a wide range of design parameters, such as variable index profiles, air hole diameters, number of air holes, pitch, plasmonic material thickness, plasmonic material location, and so on. The wavelength interrogation (WI) and amplitude interrogation (AI) methods are used in the PCF based sensor. Although they are limited to fabrication complexity but show better performances. That's why PCF based sensors are nowadays being popular.

In this research, a PCF structure with a hexagonal arrangement and circular air holes designed. The proposed model has been demonstrated for sensing *Pseudomonas aeruginosa* bacteria with the goal of achieving higher sensitivity and minimal confinement loss at the same time. The light will be confined in the range of wavelength from 0.9 μm to 1.1 μm to detect the bacteria by the sensor. When light is well confined in the core area, the best result is obtained, and performance is measured. Variations in the diameter of the core region's hole as well as the variations in PML thickness and how they influence the overall output of the suggested sensor are discussed in detail here

## Proposed Structure

A PCF structure with a hexagonal arrangement of circular air holes in the cladding region has been suggested. The suggested PCF shape is hexagonal, rather than decagonal, square, or octagonal since the hexagon cell is decorative and can fill the entire region without gaps. The liquid in the core hole is allowed, according to research articles [27] since the refractive index allows incident light to pass directly through analytes.

Figure 1 shows a cross-sectional view of our proposed structure. The most important thing to note when designing a PCF-based sensor is to design the core section properly since light is confined there. Light confinement and design or fabrication complexity are often considered even before designing a new structure.

The cladding section is hexagonal in shape, and all holes have the same diameter (d1=0.4 um) in our proposed structure. Only four circular holes with the same diameter of d=0.23 um are designed in the core section, which is filled with the target material. A PCF based sensor may have a higher sensitivity value but if there is more light leakage and higher design complexity then the best outcome can never be obtained in terms of its performance. As a result, we proposed our design model to solve the problem (circular shape hole in the core

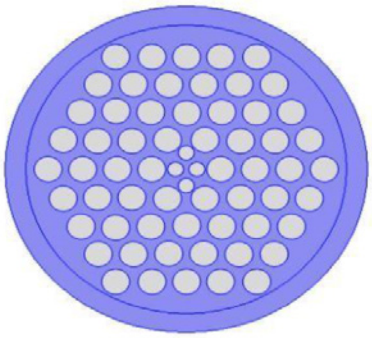

**Figure 1:** View of our proposed structure through the cross section.

region). The use of an elliptical shape hole in the core can improve sensitivity and but it can also increase fabrication complexity. The amount of light leakage in the circular hole can be reduced in our proposed model and reduced the design complexity also. Because in the case of designing a circular shape hole, its diameter is all that is needed to be declared.

We varied the diameter of the core section hole regularly to see how hole diameter affects the performance of the PCF based sensor, even though the diameter of the cladding holes remained constant. There is a salient effect on the performance especially on the sensitivity value due to the Changes in the diameter of the cladding sections hole from 0.4um (suggested) to 0.35um or 0.45um. In the case of light confinement in the core, the distance between cladding holes is essential. When we increased the pitch (hole to hole distance) value, light never confined perfectly in our designed structure. The proposed PCF is divided into a homogeneous triangular sub-space using the meshing technique, with the distance between cladding holes set to A=1.8um. By absorbing the waves inside a thin layer, a perfectly matched layer (PML) can be used to model free field conditions using a finite-sized grid. In this research, we looked into the optical properties of *Pseudomonas aeruginosa* bacteria. The refractive index of *Pseudomonas aeruginosa* is 1.3710 [28].

## Operating Principle

In this paper, the suggested structure is amalgamated with the Finite Element Method to evaluate guiding characteristics. In circular PML, the finite element method is used to solve Maxwell's equations. The software COMSOL Multiphysics 4.2 has been used to model the design. To test the proposed structure's performance, we used a wavelength range of 0.8m to 1.1m with 0.025 intervals A modal analysis is performed in the cross-section's x-y plane as the wave passes through the fiber's z direction. The field's formulation is found in the given equation, which has been obtained using Maxwell equations [29].

$$\Delta\times[S]^{-1}\times E - k_o^2 n^2 [S] E = 0 \quad (1)$$

Here, electric field vector $E$ and operating wavelength λ. is wave number, and $[S]$ and $[S]^{-1}$ are PML matrix and inverse PML Matrix respectively. In a cross-section view, the proposed PCFs can be split into three-sided subspaces. Mesh analysis can be used to classify PCF into subspaces. Here in this simulation:

Number of triangular components: 16032

Number of boundary elements: 1444

Number of vertex elements: 264

The leakage of light field energy from the core to the cladding causes confinement loss. The operating wavelength and the imaginary portion of the effective refractive index influence confinement loss. The structural parameters of PCF, such as pitch and ring numbers, cause confinement losses. Since confinement loss can reduce sensor performance, it's important to prevent it. The following equation [30] can be used to determine it.

$$\text{Confinement loss} = 8.686\ \text{ko lm}\ (n_{eff}) \times 106\ [\text{dB/m}] \quad (2)$$

where $Im\ (n_{eff})$ is the imaginary part of the effective index. The legibility of the technique relies on the precision of the imaginary part's value. Confinement loss is a type of loss caused by waveguide geometry in single-material fibers. With increasing wavelength value, the confinement loss changes. In our proposed structure, the confinement loss value is 0.008410 (dB/m) at fixed wavelength 1μm.

By matching the refractive index, PCF can detect any analyte. The sensitivity of any sensor, even PCF-based sensors, is the most important feature. It describes the sensing power of a sensor. Calculating the intensity of light that interacts directly with the analyte to be detected can be used to evaluate the sensor's relative sensitivity. The absorption coefficient makes determining the sum of light interaction much easier. The following formula can be used to calculate relative sensitivity, r: [31]: nr

$$r = n_r / n_{eff} \times f \quad (3)$$

where $n_{eff}$ represents an effective index and $n_r$ denotes the refractive index of sensing material.

The effective fiber core area is connected to the mode area [32].

$$f = \frac{\int_{Sample} \mathrm{Re}(E_x H_y - E_y H_x)}{\int_{total} \mathrm{Re}(E_x H_y - E_y H_x)} \times 100$$

The modes of electrical and magnetic fields are represented by $E_x$, $E_y$ and $H_x$, $H_y$ respectively.

## Results and Discussion

Our proposed structure has been designed for sensing *Pseudomonas aeruginosa* bacteria and its performance is evaluated using parameters such as sensitivity, confinement loss. The modal analysis has been carried out in the x-y axis of the cross-section, and the wave propagated in the z-direction. Figure 2 shows the proposed PCF structure's light confinement output and field distribution with a colour indication at a fixed wavelength of λ=1μm.

The operating wavelength as seen in Figure 3 dominates the refractive index and the effective mode index changes as the wavelength value increases.

A sensor's sensitivity determines how quickly it can sense something. If the operating wavelength is raised, the sensitivity curve varies. Figure 4 depicts the graphical relationship between sensitivity and wavelength. The peak sensitivity value is 44.06% at 1μm and then the curve gradually decreased as the wavelength value increased.

It's important to make sure the hole filling procedure is done

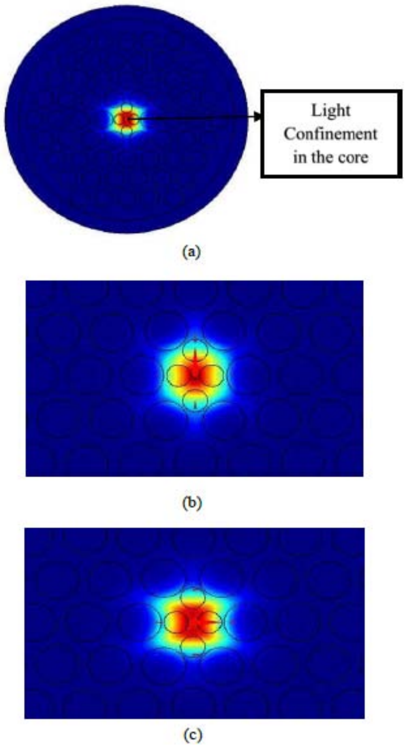


**Figure 2:** (a) Light confinement output in the core; (b) Distribution of field for x-polarization mode; (c) Distribution of field for y-polarization mode.

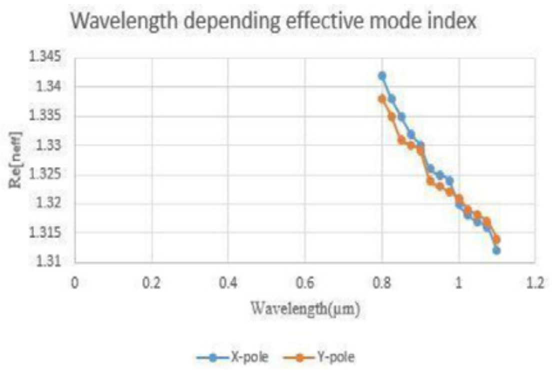


**Figure 3:** The x-pole and y-pole effective mode indexes differ with wavelength.

properly the first time. There are already many methods for selectively filling the target materials of the air gaps. It may be difficult to fill the void with analytes. A novel technique for selectively filling PCF holes with analytes is described in [32] (Figure 5).

Optical fibers are now commonly produced with great skill, but PCF fabrication remains a significant challenge. A variety of techniques may be used to create micro-structured fiber. Drilling [33], extrusion, stack and draw [34], sol-gel, and other techniques are used.

Though our primary goal is to evaluate and increase the sensitivity of our proposed framework, we took the factors confinement loss with sensitivity into account when analyzing the sensor's results.

It's worth noting that output parameters interact with one

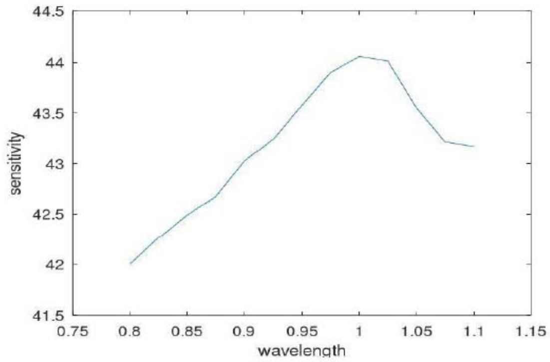


**Figure 4:** Sensitivity variations as a function of operating wavelength (µm).

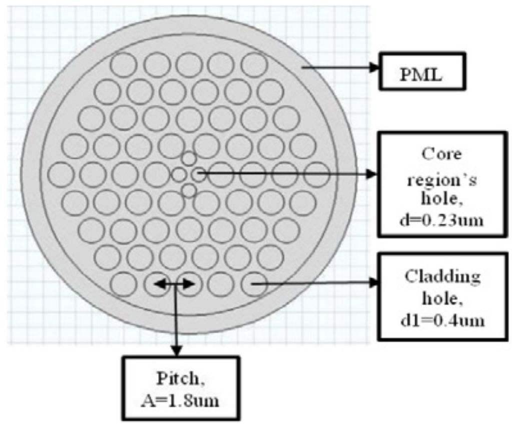


**Figure 5:** Proposed structure with proper Indication.

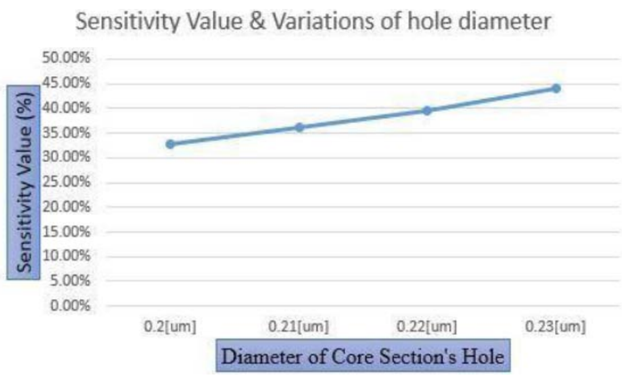


**Figure 6:** Sensitivity value changes with respect to the hole's Diameter.

another. There is a relationship between sensitivity and diameter, as well as confinement loss. We have calculated confinement loss and sensitivity for our proposed structure and observed how performance changes with respect to the wavelength. Similarly in Figure 4, a lower sensitivity value observed at lower wavelength and maximum sensitivity value found at 1µm is 44.06%. Then again sensitivity value decreasing with the rising value of wavelength. At a certain point of wavelength 1µm, sensitivity gives comparatively satisfactory value but confinement loss gives a lower value 0.008410 (dB/m).

Our proposed sensor works better at lower wavelength application

**Table 1:** Variation of the proposed PCF's sensitivity for changes in the diameter of core region's hole at a fixed wavelength.

| Wavelength | Diameter of | Sensitivity |
|---|---|---|
| (μm) | hole's | Value |
| 1(μm) | 0.20[um] | 32.87% |
| 1(μm) | 0.21[um] | 36.10% |
| 1(μm) | 0.22[um] | 39.44% |
| 1(μm) | 0.23[um] | 44.06% |

**Table 2:** Variation of the proposed PCF's sensitivity for changes in the thickness of PML at a fixed wavelength.

| Wavelength (μm) | PML thickness value | Sensitivity value |
|---|---|---|
| 1 μm | 0.4[um] | 42.91% |
| 1 μm | 0.6[um] | 44.06% |
| 1 μm | 0.8[um] | 42.11% |

**Table 3:** Sensitivity value changes with respect to the Refractive index value.

| RI value | Wavelength (μm) | Sensitivity Value |
|---|---|---|
| 1.33 | 1(μm) | 41.58% |
| 1.35 | 1(μm) | 42.24% |
| 1.37 | 1(μm) | 44.06% |

and comparison as well as the performance analysis we have done at the value of wavelength 1μm because maximum sensitivity obtained at this wavelength

Several studies [35] have found that the diameter of core region holes, as well as the number of holes, has a major impact on PCF-based sensor performance.

## Effect of variations of the diameter of core section's hole

In our paper, we only used a circular shaped hole of the same in diameter to design the core section of the proposed structure which may reduce design complexity also. There is a correlation between efficiency and hole diameter, specifically sensitivity. We increased the hole diameter to see how the hole diameter of the core section affects the performance by keeping the same thickness of PML As mentioned early that the hole diameter of the core sections hole is 0.23 [um] here in our structure and to observe the effect of diameter variations we first reduced the diameter of the core region's hole at 0.20 [um]. Then gradually increased the diameter like 0.21[um], 0.22[um] Wavelength (μm) Diameter of hole's Sensitivity Value 1(μm) 0.20[um] 32.87 % and finally set at 0.23[um]. It is found that lower sensitivity obtained at a lower value of the hole's diameter. Maximum sensitivity obtained when the diameter value is 0.23[um] at fixed wavelength 1 (μm) (Table 1 and Figure 6).

Authors [21] recently observed how PML influences the overall performance of a proposed structure and how sensitivity changes as PML thickness increases. As the proposed structure's PML thickness is reduced, then a comparatively lower sensitivity value has come.

## Effect of change of PML in the proposed PCF based sensor

As the PML values change, we can see how the sensitivity of our proposed structure changes. The greater the PML radius value, the greater the sensitivity observed. In our proposed structure the diameter value of the outermost circle is 5.2[um] and the inner circle diameter value is 4.6[um] so PML thickness is 0.6[um]. At first, we reduced the PML thickness at 0.4[um], the sensitivity obtained is around 42.91%. The higher value of thickness provides a comparatively lower sensitivity value, suppose sensitivity value is 42.11 % when thickness value is 0.8 [um]. The highest sensitivity value we have been calculated is 44.06% at 0.6 [um] thickness of PML.

We gradually increased PML value to see the effect of PML variations on sensor performance. When we changed the PML thickness value from 0.4[um] to 0.8[um], we noticed a small difference in the sensitivity value as compared to the previous result. A better value of sensitivity has come when we increased the PML value at 0.6[um]. 44.06 % sensitivity obtained at wavelength 1μm and this is our proposed structure (Table 2).

Figure 7 shows how sensitivity varies as the PML thickness of the proposed structure changes and comparatively higher sensitivity values obtained at higher PML thickness values.

In fact, the sensing medium's RI is dependent on the Pseudomonas bacteria's culture concentration and motility, ranging from 1.33 to 1.40 for various culture concentrations and motility. Because of the presence of Pseudomonas bacteria, the refractive index of the sensing medium ranges from 1.33 to 1.40, and this difference is dependent on the culture concentration and motility of Pseudomonas bacteria [25]. The refractive index of water changes from 1.33 to 1.40 when pseudomonas adsorption occurs.

We have examined our proposed sensor's performance from the refractive index (RI) value 1.33 to 1.40 with an interval. The maximum sensitivity obtained by our structure is 44.06% when RI value is 1.37. At RI value of 1.33 and 1.35, the proposed structure provides comparatively lower sensitivity.

Unfortunately, light is not confined when the RI value is more than 1.37 in our structure which means 1.38, 1.39 or 1.40. As light is

**Table 4:** Comparison the Performance of our proposed PCF and previous.

| PCFs | Target Material | Sensor Type | Sensitivity Value | Confinement loss |
|---|---|---|---|---|
| Ref [22] | *Escherichia coli* K12 cells | Waveguide sensor | Peak angle value of $1.65 \times 10^{-6}$ (deg/cell)/mm$^2$ | Not calculated |
| Ref [23] | *Pseudomonas* bacteria | $BaTiO_3$ Graphene Affinity Layer-Based SPR biosensor | Maximum value of 220 degree/RIU | Not calculated |
| Ref [24] | *Pseudomonas* bacteria | Graphene layer based SPR biosensors | Maximum Value of 33.98 degree/RIU | Not calculated |
| Ref [25] | *Pseudomonas* bacteria | Zinc oxide, gold and graphene-based SPR biosensor | Greater Sensitivity of 187.43 degree/RIU | Not calculated |
| Ref [26] | *Pseudomonas* bacteria | PCF based SPR biosensor | Wavelength Sensitivity 20,000 nm/RIU and amplitude sensitivity 1380 RIU−1 | 35(dB/cm) when RI 1.37 |
| Proposed PCF | *Pseudomonas aeruginosa* | Normal PCF based Sensor | Maximum value 44.06% | 0.008410 (dB/m) |

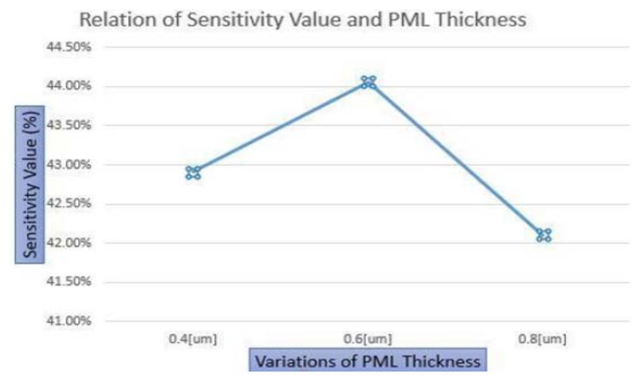


**Figure 7:** Sensitivity changes with respect to the value of PML thickness.

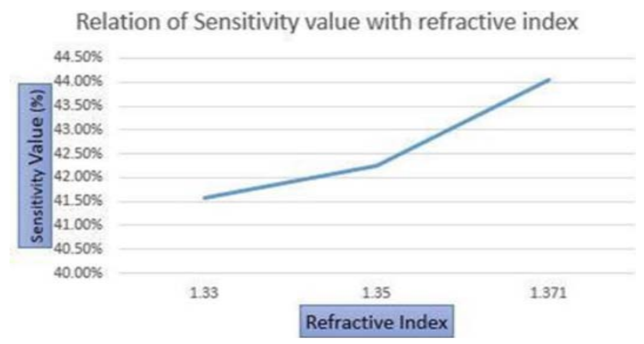


**Figure 8:** Presents how the sensitivity value changes for the changes of refractive index within the range from 1.33 to 1.37.

not confined properly in the core of our structure so that we never calculated the sensitivity value or overall performance at those Refractive index value (Table 3 and Figure 8).

We may be able to learn more about the sensor's capabilities by checking and sorting the previously proposed sensors for target material (Pseudomonas bacteria) and operating wavelength. By comparing our proposed model to the previously proposed sensors, we can get a better understanding of our sensor's functionality or acceptability (Table 4).

## Conclusion

In this paper, a simple structure of PCF based sensor we have proposed for the detection of *Pseudomonas aeruginosa* bacteria. Key parameter sensitivity and the confinement loss are numerically evaluated by utilizing the FEM for sensing medium RI of 1.33 to 1.40 within the wavelength range from (0.9-1.1) μm. The maximum sensitivity obtained is 44.06% when n=1.37 and λ=1μm according to the resulting performance of our proposed sensor. The hole's diameter variation and variation of PML thickness have a great impact on the overall performance of the sensor which properly discussed here and how sensitivity value changes from RI value of 1.33 to 1.37 are disclosed. The proposed structure is expected to be more easier to fabricate because of it's simple structure especially the core region. PCF with these properties could be used in applications including poisonous and toxic chemical sensors or biosensors.

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