International Journal of Safety and Security Engineering
Vol. 14, No. 2, April, 2024, pp. 459-466
Journal homepage: http://iieta.org/journals/ijsse

Sulfuric Acid Highly Sensitive Detection at Different Concentrations Using Photonic Crystal Fiber Sensor

Raed Sattar Jebur*, Raad Hamdan Thaher

Department of Electrical Engineering, University Mustansiriyah, Baghdad 10047, Iraq

Corresponding Author Email: eeph008@uomustansiriyah.edu.iq

https://doi.org/10.18280/ijsse.140213

Received: 11 September 2023
Revised: 15 April 2024
Accepted: 22 April 2024
Available online: 26 April 2024

Keywords:
chemical sensor, confinement loss, nonlinearity, photonic crystal fiber, sensitivity, sulfuric acid

ABSTRACT

This paper presents a new PCF sensor developed explicitly for accurately detecting sulfuric acid. A complete vector finite element technique (FEM) in COMSOL Multiphysics was used to evaluate the optical parameters of the sensor, including its refractive index, power fraction, relative sensitivity, confinement loss, and effective area. The sensor demonstrated excellent sensitivity and minimal confinement loss during testing with different concentrations of aqueous sulfuric acid ranging from 0% to 40%. The PCF sensor demonstrated outstanding performance at a wavelength of 1.5 μm, with the incident light's polarization in the x-direction, which enhances evanescent field interaction by confining nearly all optical power within an enlarged air core, boosting sensitivity to analytes compared to the y-polarized mode. The test's sensitivity was high when exposed to different concentrations of sulfuric acid, ranging from 0% to 40%. The sensitivities recorded were 99.55%, 99.72%, 99.82%, 99.90%, and 99.97% for acid concentrations of 0%, 10%, 20%, 30%, and 40% respectively. In addition, the sensor's losses due to confinement were measured and recorded. The recorded values for the different concentrations were 3.04×10^{-11} dB/m, 4.65×10^{-11} dB/m, 6.99×10^{-11} dB/m, 8.52×10^{-11} dB/m, and 9.65×10^{-11} dB/m. The PCF sensor exhibits exceptional sensitivity and dependability in detecting sulfuric acid over various concentrations, rendering it a valuable tool for environmental monitoring, industrial safety, and health preservation.

1. INTRODUCTION

Sulfuric acid possesses numerous significant applications within the industrial sector. It is extensively utilized in several industrial contexts. The primary utilization of this compound lies in its role in manufacturing fertilizers. However, it also serves as a secondary component in creating various chemicals, such as hydrochloric acid, nitric acid, sulfate salts, synthetic detergents, and medicines. Any product using sulfuric acid must possess the utmost level of quality. Consequently, the detection of sulfuric acid necessitates a significant level of precision. Advancements in optical fiber technology have led to notable progressions in communication [1, 2], and chemical sensing [3, 4]. The fiber optic sensor for detecting sulfuric acid can enhance industrial safety, health, and environmental monitoring. The sensor can detect the amount of sulfuric acid in the soil, water, and air for environmental monitoring. This is crucial in industrial areas because sulfuric acid emissions can harm both humans and the environment. Sulfuric acid concentrations can be tracked by carefully positioning the sensor, and any deviations can be reported immediately. Effective pollution control and early warning systems can be developed using this data. In real-time, the sensor can detect sulfuric acid leaks or spills in chemical or manufacturing plants, improving industrial safety. Integrating the sensor into safety systems allows rapid alerts and appropriate responses to mitigate threats. This proactive strategy protects workers, prevents accidents, and reduces environmental impact. In healthcare, the sensor can detect sulfuric acid in samples or bodily fluids to help diagnose and monitor certain illnesses. Photonic crystal fiber (PCF) is an advanced optical fiber with distinctive characteristics such as zero dispersion light propagation, indicating that different wavelengths do not experience timing distortions as signals pass through the fiber. This allows high-fidelity transmission free of dispersion effects that degrade conventional fiber-optic performance [5, 6], negligible confinement loss [7, 8], and significant nonlinearity [9, 10]. There has been a notable surge in scholarly attention toward liquid and chemical sensing using optical fiber, with photonic crystal fiber (PCF) emerging as the most contemporary iteration of conventional optical fiber. Researchers have dedicated considerable time and effort to enhance the capacity of chemical sensing through the utilization of Photonic Crystal Fiber (PCF) [9, 10]. The dimensions and placement of air holes in both the core and cladding regions, along with the chemical concentration, can be adjusted to modify the sensing capabilities of a chemical sensor based on Photonic Crystal Fiber (PCF) [11, 12]. In the domain of chemical and liquid sensing, the attributes of sensitivity and confinement loss are widely recognized as the primary defining qualities. Currently, extensive research is being conducted with the objective of simultaneously enhancing sensitivity and reducing confinement loss [13]. Keeping confinement loss as low as possible is essential for raising the detection limit and making it easier for the analyte and directed modes in the PCF core to interact. PCF sensors can measure lower amounts of the analyte and pick up on more minor changes in the refractive index because they have lower confinement losses. This makes it possible for PCF sensor devices to detect and make more changes. Numerous researchers have investigated the development and optimization of photonic crystal fiber (PCF) sensors for chemical sensing applications, particularly for detecting sulfuric acid. A seminal study by Islam et al. [14] introduced a PCF sensor with a three-layer structure comprising nine circular core holes and 36 external air holes. This sensor exhibited functional capabilities in the infrared region, spanning from 1.0 μm to 1.7 μm, and demonstrated a notable relative sensitivity of 55.56% at a wavelength of 1.33 μm, accompanied by favorable optical characteristics such as the V-Parameter, spot size, beam divergence, and nonlinearity. Podder et al. [15] proposed an intricate PCF sensor design, incorporating three concentric cladding rings and a sophisticated configuration of circular apertures at its core. The experimental specimens utilized in this study involved varying concentrations of sulfuric acid. The sophisticated core PCF sensor was employed to evaluate optical parameters such as birefringence, power fraction, relative sensitivity, confinement loss, and effective area. The chemical sensor exhibited a remarkable relative sensitivity of 62.1% and a confinement loss of 10^{-15} dB/m at its optimal frequency and concentration. Caroline et al. [16] developed a PCF sensor specifically tailored for sulfuric acid detection. The relative sensitivity of this sensor was measured to be 68.5%, while the predicted confinement loss was determined to be 10^{-3} dB/m. The fiber's design featured a sophisticated core consisting of 16 circular and one rectangular hollow cavity intended to infuse sulfuric acid. Furthermore, the fiber incorporated three rings enclosing the air holes. The birefringence values and effective area were also subjected to rigorous testing. In a subsequent study, a different research group introduced a PCF sensor comprising three circular core holes and three layers of external air holes [17]. The researchers meticulously evaluated various parameters of the sensor, including relative sensitivity, confinement loss, chromatic dispersion, effective area, and nonlinear coefficient, to assess its performance. The hexagonal lattice sensor exhibited a confinement loss of approximately 10^{-10} dB/m and a relative sensitivity of 74.5% while operating at a frequency of 1.3 μm. Eid et al. [18] proposed using a hexagonal lattice PCF sensor equipped with five cladding rings and a core hole in a hexagonal configuration for chemical sensing purposes. The sensor demonstrated exceptional performance, with a relative sensitivity of 97.89% and a confinement loss of around 10-10 dB/m. Additional optical parameters, such as numerical aperture and nonlinearity, were also evaluated to determine the system's efficacy. Maidi et al. [19] employed a PCF sensor to detect sulfuric acid. The sensor exhibited a relative sensitivity of 98.6% and a confinement loss of approximately 10^{-12} dB/m. A central hole in the cladding was designed to be filled with sulfuric acid, surrounded by two cladding rings with circular and hexagonal air holes. In the aforementioned scholarly articles [14-17], researchers have proposed intricate structures that pose challenges in their construction. As mentioned earlier, the designs exhibit a substantial number of central perforations, more layers of air perforations in the outside layer, and holes, not a circular shape, perhaps resulting in errors during fabrication. The design should prioritize simplicity to facilitate ease of construction. The proposed configuration in this research investigation comprises five cladding layers and a solitary central aperture as a hollow circle. To conduct measurements, varying quantities of sulfuric acid samples will be introduced into the core hole using a pumping mechanism. Researchers have endeavored to refine the design of chemical sensors employing photonic crystal fibers (PCFs) to achieve remarkable improvements in critical parameters such as sensitivity, confinement loss, effective area, and nonlinearity. The performance evaluation of the proposed PCF sensor has undergone a comprehensive and meticulous examination across a broad operational wavelength spectrum, ranging from 0.8 μm to 1.8 μm. At the optimal wavelength, it was determined that the relative sensitivity of the sensor surpassed the exceptional threshold of 99%, while the confinement loss was estimated to be in the order of 10^{-11} dB/m, indicating an exceptional level of optical confinement and minimal signal attenuation. In this study, we fill the research gap in the design of photonic crystal fiber sensors by achieving ultrasensitive detection capabilities with a low-confinement loss and attainable fiber structure.

2. MODEL AND METHOD

The property of a material that determines the extent to which it retards the speed of light is referred to as its "refractive index," which exhibits variation in response to the concentration of the substance present. Chemical sensors can use this characteristic by detecting alterations in the refractive index of the sensed substance. The sample's refractive index is employed in a photonic crystal fiber (PCF) chemical sensor to modulate the optical characteristics of the PCF. Consequently, this alteration affects how much light can transmit through the fiber. The fiber's refractive index can be modified by either maintaining the analyte within the hollow core or allowing it to interact with the air pores in the cladding [20]. By judiciously selecting the design parameters of the photonic crystal fiber (PCF), such as the quantity and dimensions of the air holes in the cladding and the diameter of the hollow core, it is feasible to maximize the sensor's sensitivity towards variations in the refractive index. As mentioned above, the feature enhances the precision and dependability of the sensor.

The PCF sensor's surface area has five layers of air holes, each with a width of 2.8 μm. The diameter of the entire fiber is 48 μm, with a centrally located hole with a diameter of 8 μm as a core region in the substrate material consisting of silica glass. A boundary requirement, known as a "perfectly matched layer" (PML), is implemented with a thickness of 2.4 μm. The purpose of the PML (Perfectly Matched Layer) is to mitigate the detrimental effects of light propagation in optical fibers caused by shadows or other undesirable factors. Figure 1 depicts a cross-sectional view of the fiber together with its internal structure, illustrating the conceptualization process of the photonic crystal fiber (PCF) sensor model. Extrusion, drilling, sol-gel casting, and stack and draw are some of the advanced manufacturing processes studied in the literature [21-24]. Other techniques that have been considered include drilling and stack and draw. The proposed PCF's production is contingent upon fulfilling the design feasibility criterion.

The proposed photonic crystal fiber (PCF) sensor design was numerically characterized to evaluate its efficacy using the COMSOL Multiphysics software version 5.5 and a comprehensive vector finite element method (FEM) analysis framework. A refined mesh discretization scheme was implemented during the computational design process to enhance the fidelity and accuracy of the modeling outcomes. The envisioned sensing mechanism relies on introducing the target analyte, specifically sulfuric acid in this investigation, into the central air hole of the PCF, facilitating chemical identification through the analysis of the guided optical modes. The 2D Wave Optics Module integrated within the COMSOL Multiphysics software suite was employed to investigate the properties of electromagnetic waves propagating through the PCF structure, mainly focusing on frequency domain physics and modal characteristics. Figure 2 illustrates the sequential steps in the computational design and construction of the photonic crystal fiber sensor utilizing the numerical simulation platform.

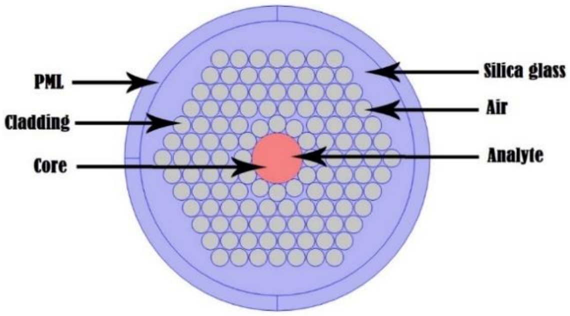

Figure 1. Proposed model's internal cross-section

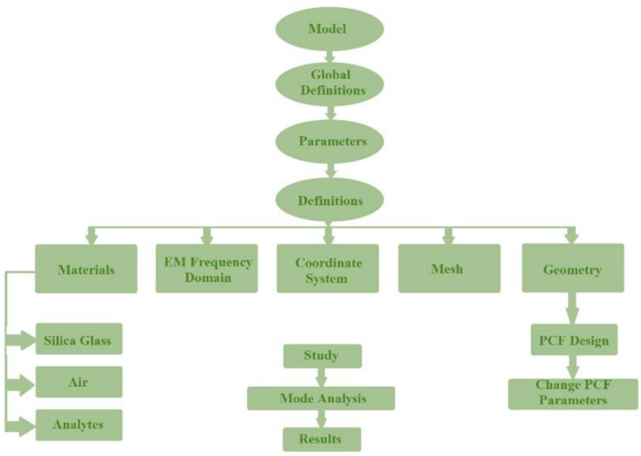

Figure 2. The design steps for the PCF structure using COMSOL Multiphysics

The computational modeling indicates the viability of the proposed PCF architecture for operational implementation within the wavelength window of 0.8 to 1.8 µm. Table 1 presents the impact of various concentrations and wavelengths of sulfuric acid on the refractive index and how this influences the sensitivity and accuracy of the photonic crystal fiber (PCF) sensor in detecting and quantifying the concentration of the desired analyte. Researchers can employ numerical characterizations to understand better the operational principles and fabrication processes underlying the suggested photonic crystal fiber (PCF) sensor. Enhancing the sensitivity, precision, and overall performance of the sensor makes it possible to develop a very effective chemical detecting mechanism.

Table 1. Variation of the refractive index of sulfuric acid at various concentrations concerning wavelength [15, 25, 26]

λ	Refractive Index				
	0%	10%	20%	30%	40%
0.8	1.329	1.3451	1.3576	1.3701	1.3821
0.9	1.328	1.344	1.3565	1.369	1.381
1	1.327	1.343	1.3555	1.368	1.38
1.1	1.326	1.342	1.3545	1.367	1.379
1.2	1.3245	1.3405	1.353	1.3655	1.3775
1.3	1.323	1.339	1.3515	1.364	1.376
1.4	1.321	1.337	1.3495	1.362	1.374
1.5	1.319	1.335	1.3475	1.36	1.372
1.6	1.317	1.333	1.3455	1.358	1.37
1.7	1.3145	1.3305	1.343	1.3555	1.3675
1.8	1.312	1.328	1.3405	1.353	1.365

The optical properties of the proposed photonic crystal fiber (PCF) design were assessed in order to evaluate its potential applications and effectiveness. Its optical features were looked at to determine what the design could be used for. These included power fraction, relative sensitivity, confinement loss, effective area, and nonlinearity. The features above provide valuable insights into the effectiveness and velocity at which the PCF sensor can detect and measure the concentration of the intended sample. By conducting thorough analysis and refinement of these characteristics, scholars can fabricate a photonic crystal fiber (PCF) sensor that demonstrates elevated sensitivity and precision, making it a desirable choice for real-world implementations in chemical detection.

Sulfuric acid is carefully injected into the core hole inside a substrate composed of silica-based material. The determination of the effective refractive indices, denoted as n_{eff}, may be achieved by the use of Sellmeier's equation. These refractive indices are often expressed as [17, 27]:

$$n_{eff}(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}} \tag{1}$$

The suggested photonic crystal fiber's optical characteristics were assessed to evaluate its potential applications and effectiveness. Different optical properties were looked at to determine what the design could be used for, such as nonlinearity, effective area, confinement loss, relative sensitivity, and power fraction.

The features above provide valuable insights into the effectiveness and velocity at which the PCF sensor can detect and measure the concentration of the intended sample. By conducting thorough analysis and refinement of these characteristics, scholars can fabricate a photonic crystal fiber (PCF) sensor that demonstrates elevated sensitivity and precision, making it a desirable choice for real-world implementations in chemical detection.

Sulfuric acid is carefully injected into the core hole inside a substrate composed of silica-based material. The determination of the effective refractive indices, denoted as n_{eff}, may be achieved by the use of Sellmeier's equation. These refractive indices are often expressed as [17, 27]:

$$S = \frac{n_r}{n_{eff}} \times f \tag{2}$$

The provided equation relates the refractive index of the detected material (n_r), the modal refractive index (n_{eff}), and the power fraction (f). The power fraction is determined by integrating the power within a chemical-filled patch and dividing it by the amount of power in the whole fiber. This quantity allows measuring energy passed via the PCF at a specific position. To derive this equation, Poynting's theorem is used [28-30].

$$f = \frac{(sample)\int Re(E_x H_y - E_y H_x)dxdy}{(total)\int Re(E_x H_y - E_y H_x)dxdy} \times 100 \quad (3)$$

Formulas for guided modes are based on electric and magnetic fields associated with the propagation direction, which are represented by, E_x, E_y , and H_x, H_y . The denominator of the equation integrates throughout the entire fiber region, whereas the numerator integrates over the fiber's core, where the analyte is located. This means the equation precisely calculates the analyte's power fraction within the fiber's core.

The proposed photonic crystal fiber (PCF) design exhibits a distinctive characteristic that contributes to confinement loss, namely, the leakage of the guided optical mode from the core region into the surrounding cladding structure. This phenomenon arises due to the intrinsic geometric properties of the fiber architecture. To quantify the extent of confinement loss, evaluating the complex effective index's imaginary part, which can be derived by implementing the provided mathematical equation, is imperative [31-33].

$$L_c = 8.686 \times \frac{2\pi f}{c} Im(n_{eff})(\text{dB/cm}) \quad (4)$$

The mathematical formulation presented facilitates the evaluation of the confinement loss inherent to the photonic crystal fiber (PCF) by incorporating the operational frequency (f), the velocity of light in a vacuum (c), and the imaginary constituent of the complex effective refractive index, denoted as $\text{Im}(n_{eff})$.

The effective area is the specific region where light propagation is restricted to the central core region. The observed outcome is subject to variation when the sensor's wavelength is modified. The value of the effective area A_{eff} is given using the equation [28, 31, 34]:

$$A_{eff} = \frac{\left(\iint_{-\infty}^{\infty} |E|^2 dxdy\right)^2}{\iint_{-\infty}^{\infty} |E|^4 dxdy} \quad (5)$$

The mathematical formulation to derive the effective mode area of the fiber core region is predicated upon the utilization of the transverse electric field vector, denoted as E.

The degree of deviation from linearity in a fiber may be quantified using a non-linear numerical value. The fundamental concept underpinning this phenomenon is the correlation between the effective area of the fiber and the nonlinear refractive index. One method of determining the nonlinear refractive index of a fiber involves analyzing its response to variations in the intensity of incident light. Fibers with high nonlinear coefficients provide significant benefits in the transmission of high-bit-rate communications due to their effective confinement of high-intensity light [35].

In terms of nonlinear coefficients, the following definitions can be used [29, 32]:

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \quad (6)$$

Both the operating wavelength (λ) and the nonlinear refractive index (n_2) are variables that contribute to the calculation of the nonlinear coefficient (γ). The nonlinearity index of SiO_2 ($n_2 = 3.2 \times 10^{-20}\ m^2/W$) is used to calculate the nonlinearity value.

3. RESULTS AND DISCUSSION

The primary research objective was to evaluate the sensing efficacy of a photonic crystal fiber (PCF) architecture for detecting and quantifying varying sulfuric acid concentrations. The propagation characteristics of the guided optical mode within the PCF structure were numerically modeled utilizing the COMSOL Multiphysics simulation platform, facilitating the calculation and analysis of pertinent optical parameters to assess the sensor's performance metrics. Specifically, the modal profiles within the acid-infiltrated core region were investigated across different sulfuric acid concentration levels at an operating wavelength of 1.5 µm. As depicted in Figure 3, the simulated mode profiles elucidate the interaction dynamics of the guided light with the core region, exhibiting complete modal confinement within the core boundaries. This robust modal confinement is a critical prerequisite for achieving high sensitivity and selectivity in the envisioned sulfuric acid detection scheme employing the proposed PCF sensor architecture.

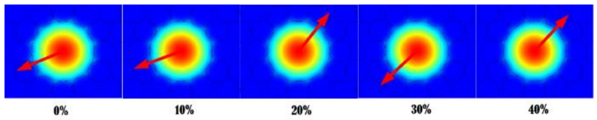

Figure 3. Mode profiles of acid-infiltrated hole in PCF core at 1.5 µm wavelength for various concentrations of sulfuric acid

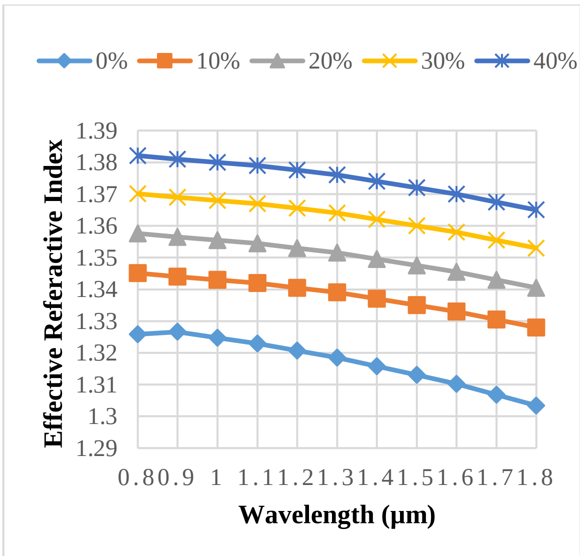

Figure 4. Effective refractive index variation with wavelength for proposed PCF at different concentrations

The simulation results pertaining to the effective refractive index characteristics of sulfuric acid, employed as the target analyte, are illustrated in Figure 4 across a concentration range spanning from 0% to 40% and an operational wavelength spectrum of 0.8 to 1.8 µm. The data shows an apparent decrease in the effective refractive index as the operating wavelength increases. This aligns with the principle that electromagnetic signals with shorter wavelengths tend to travel through materials with higher refractive indices, while signal weakening becomes more noticeable at longer wavelengths. Conversely, the effective refractive index of sulfuric acid exhibits a proportional increase with higher concentration levels, attributable to the inherently elevated refractive index of sulfuric acid at higher concentrations. This result is highly significant as it suggests that the proposed photonic crystal fiber (PCF) sensor can detect and measure changes in sulfuric acid concentration by precisely measuring differences in refractive index. Collectively, these findings provide valuable insights into the optical properties of sulfuric acid and their prospective practical applications in the realm of chemical sensing.

The power fraction, which was directly obtained from the COMSOL Multiphysics simulation, is represented in Figure 5 as a function of sulfuric acid concentration across a range of wavelengths from 0.8 µm to 1.8 µm. As illustrated in the figure, the power fraction escalates with longer wavelengths. This aligns with the expectation that increased wavelength would lead to greater light confinement through the sulfuric acid region. Additionally, an elevation in sulfuric acid concentration results in a rise in the power fraction as the overall refractive index in the core region increases. This rise in the power fraction points to an augmentation in light confinement through the core area.

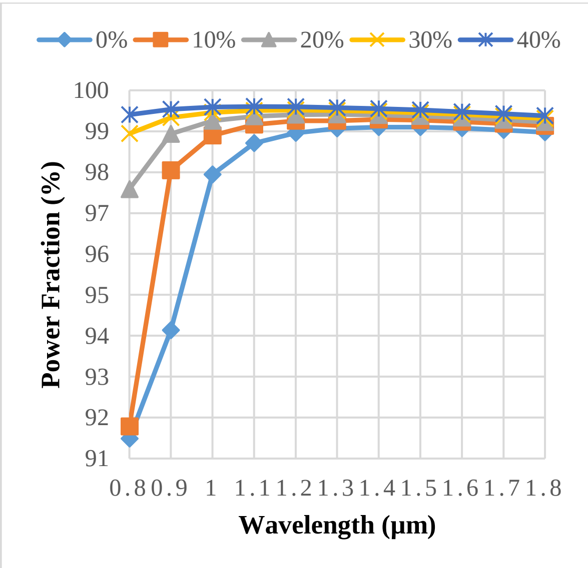

Figure 5. Power fraction variation with wavelength for proposed PCF at different concentrations

Figure 6 illustrates the sensitivity curve concerning different parameters derived from Eq. (2), such as the power fraction, the refractive index of sulfuric acid at various concentrations, and the effective refractive index. The graph shows a positive correlation between sensitivity and wavelength, with longer wavelengths resulting in increased light confinement in the sulfuric acid region. Additionally, sensitivity increases with higher sulfuric acid concentrations thanks to the higher overall refractive index in the core area, which leads to greater light confinement. Notably, sensitivity increases from 0.8 µm to 1.3 µm and remains almost constant for any changes in wavelength. The sensor design being evaluated demonstrates exceptional sensitivity, with sensitivity rates of 99.55%, 99.72%, 99.82%, 99.90%, and 99.97% for sulfuric solution concentrations of 0%, 10%, 20%, 30%, and 40%, respectively. These measurements were taken in the x-polarization direction at a wavelength of 1.5 µm.

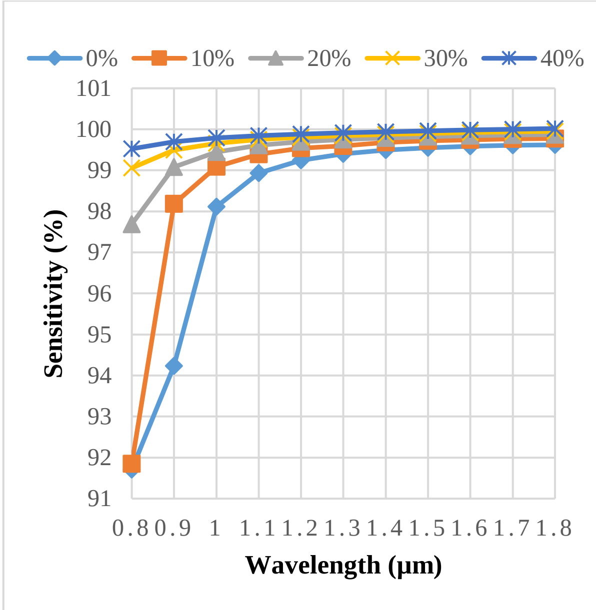

Figure 6. Sensitivity variation with wavelength for proposed PCF at different concentrations

Figure 7 showcases the confinement loss of sulfuric acid at different concentrations across an operating wavelength range of 0.8 to 1.8 µm. With an increase in the operating wavelength, the confinement loss exhibits a more pronounced escalation due to the enhanced leakage of the guided optical mode from the core region into the surrounding cladding structure. Nevertheless, the core's ingenious design, coupled with the air holes in the cladding, restrains the outflow of light signal, resulting in minimal confinement loss. The best confinement loss outcomes are achieved when the wavelength is 1.5 µm. The values that represent concentrations of 0%, 10%, 20%, 30%, and 40% sulfuric acid at this particular wavelength are 3.04×10^{-11} dB/m, 4.65×10^{-11} dB/m, 6.99×10^{-11} dB/m, 8.52×10^{-11} dB/m, and 9.65×10^{-11} dB/m, respectively.

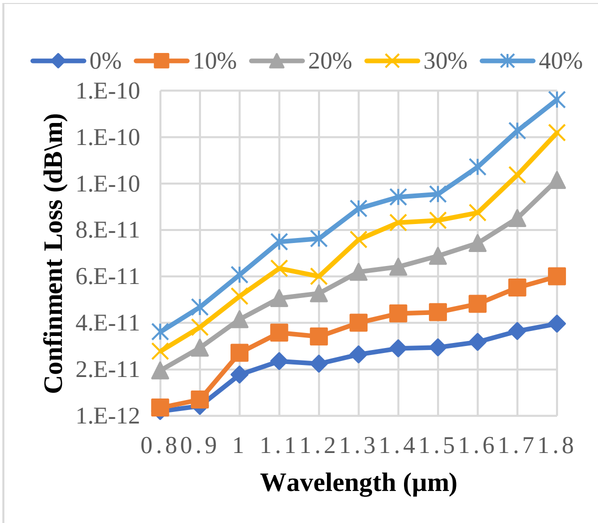

Figure 7. Variation of confinement loss versus wavelength of proposed PCF with different concentrations

Figure 8 demonstrates the variation in the effective area of the proposed photonic crystal fiber (PCF) as a function of wavelength. The effective area measures the magnitude of the transverse electric fields, which increase as the operating wavelength increases. The figure exhibits a moderate rise in effective area as wavelength increases. The maximum effective area is obtained for the highest concentration of sulfuric acid, which is a logical outcome. This is because inserting a large amount of sulfuric acid through the fiber core increases the core index, resulting in a greater sensing area. At a wavelength of 1.5 µm, an effective area of approximately 37 μm^2 is achieved for all sulfuric acid concentrations. The sensing performance of the photonic crystal fiber is contingent upon its effective mode area, with a larger effective area generally facilitating enhanced sensitivity in the sensor's response.

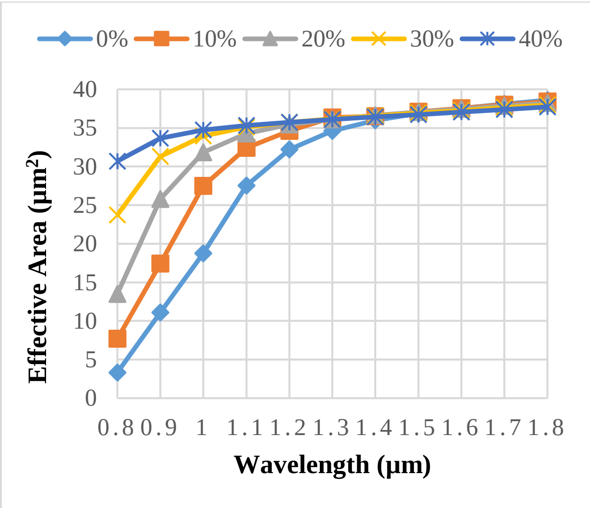

Figure 8. Variation of effective area versus wavelength of proposed PCF with different concentrations

A visual representation depicted in Figure 9 showcases how the measure of nonlinearity of liquid analytes varies with the operating wavelength. Different concentrations of sulfuric acid, ranging from 0% to 40%, appear to follow a similar pattern, with their nonlinear coefficients increasing as the wavelength becomes longer. However, there is an exciting twist in the correlation between the effective area and the nonlinear coefficient, as illustrated in Figures 8 and 9. In spite of this turn, all concentrations of sulfuric acid exhibit identical values at a wavelength of 1.5µm, showcasing their nonlinear coefficients of 4 $W^{-1} km^{-1}$. The implication is that the proposed PCF could be suitable for nonlinear applications, despite the possibility of a decrease in the effective area as the wavelength increases.

Table 2 presents a comparative evaluation of the proposed PCF chemical sensor against previously reported designs, highlighting the superior performance of the proposed architecture with regards to minimized confinement loss and maximized relative sensitivity. The comparative analysis underscores the advantages of the proposed sensor for enhanced chemical sensing capabilities. The tabulated data unveils that the proposed PCF sensor exhibits the maximum relative sensitivity among the compared counterparts while simultaneously demonstrating shallow confinement losses. This distinct combination of attributes distinguishes the proposed sensor and underscores its significant potential for practical chemical sensing applications.

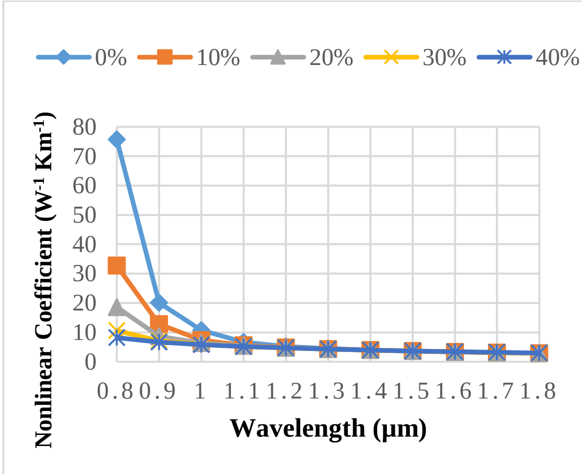

Figure 9. Variation of nonlinear coefficients versus wavelength of proposed PCF with different concentrations

Table 2. Comparative evaluation of the proposed PCF and previously reported PCF sensors

PCF	Sensitivity (%)	Confinement Loss (dB/m)
Reference [14]	55.56	-
Reference [15]	62.10	$\sim 10^{-15}$
Reference [16]	86.50	$\sim 10^{-3}$
Reference [17]	75.50	$\sim 10^{-10}$
Reference [18]	97.89	$\sim 10^{-10}$
Reference [19]	98.60	$\sim 10^{-12}$
Proposed PCF	99.97	$\sim 10^{-11}$

Translating photonic crystal fiber (PCF) chemical sensors from computational models to practical implementations necessitates consideration of their performance under realistic operating conditions. Environmental factors like temperature and pressure can significantly impact the optical properties of analytes and the resulting sensing response. Notably, specific analytes' refractive index depends on variations in temperature and pressure conditions. Careful consideration of these environmental influences ensures accurate and reliable chemical sensing performance. While the characterization and optimization are typically conducted under standard ambient conditions of 293.15 K and 1 atm, the sensor technology must be tailored to accommodate environmental fluctuations or be actively controlled and monitored for widespread utility. Simulating the PCF sensor's reaction under expected operating conditions and fine-tuning the photonic crystal's structure can reduce the negative impact of changes in the refractive index due to temperature and pressure fluctuations. This technique enables the creation of sensing architectures that are environmentally resilient and maintain consistent performance. The controlled laboratory settings employed in this study facilitate a fundamental understanding and elucidation of the operating principles of PCF chemical sensors, though further adaptations may be necessary for field deployment. However, to realize the practical implementation of this technology, the sensor designs must exhibit resilience to environmental fluctuations encountered in real-world conditions. This can be achieved by developing multiphysics models and integrating materials that exhibit minimal susceptibility to variations in temperature and pressure. Such an approach would enable the robustness and adaptability necessary to deploy these sensors in diverse operational scenarios successfully. Environmental monitoring applications can use the sensor to quantify sulfuric acid in aqueous solutions (soil and water studies), vapor phase concentrations, and ambient air quality. The sensor detects sulfuric acid leaks or spills in chemical syntheses and battery manufacturing plants before inhalation risks rise, improving industrial safety. The sensor's sensitivity makes it possible to measure the amount of sulfuric acid in bodily fluids precisely. This allows for diagnostic screening, treatment selection, and monitoring of treatment effectiveness for obstructive pulmonary diseases, where sulfuric acid is a sign of oxidative stress. With its remarkable speed, precision, and trace-level sensitivity, the sensor could revolutionize environmental tracking, occupational danger prevention, and clinical illness insight.

4. CONCLUSIONS

This project included the development of a novel photonic crystal fiber (PCF) sensor capable of detecting varying concentrations of sulfuric acid. The PCF's enhanced design and testing environment demonstrated its sensitivity and low confinement loss, making it suitable for real-time monitoring hazardous chemical substances. This study contributes to developing enhanced optical sensors for use in industrial and environmental settings. Additionally, it can be used in conjunction with other significant substances. A sophisticated finite element method (FEM) modeling approach was used to investigate the design of a sensor, including a circular core positioned centrally, surrounded by five cladding layers containing circular-shaped apertures. The sensor recorded readings of 99.55%, 99.72%, 99.82%, 99.90%, and 99.97% when exposed to sulfuric acid concentrations of 0%, 10%, 20%, 30%, and 40%, respectively, at a wavelength of 1.5 µm. The proposed sensor was able to quantify the levels of sulfuric acid based on the observed decreases in confinement losses, which were quantified as 3.04×10^{-11} dB/m, 4.65×10^{-11} dB/m, 6.99×10^{-11} dB/m, 8.52×10^{-11} dB/m, and 9.65×10^{-11} dB/m. The efficacy of this sensor design is evident, suggesting its potential use in practical sensing scenarios.

REFERENCES

[1] Coelho, L.D., Gaete, O., Hanik, N. (2009). An algorithm for global optimization of optical communication systems. AEU-International Journal of Electronics and Communications, 63(7): 541-550. https://doi.org/10.1016/j.aeue.2009.02.009

[2] Furch, B., Sodnik, Z., Lutz, H. (2002). Optical communications in space–a challenge for Europe. AEU-International Journal of Electronics and Communications, 56(4): 223-231. https://doi.org/10.1078/1434-8411-54100102

[3] Jorgenson, R.C., Yee, S.S. (1993). A fiber-optic chemical sensor based on surface plasmon resonance. Sensors and Actuators B: Chemical, 12(3): 213-220. https://doi.org/10.1016/0925-4005(93)80021-3

[4] Xu, Z., Chen, X., Kim, H.N., Yoon, J. (2010). Sensors for the optical detection of cyanide ion. Sensors and Actuators B: Chemical, 39(1): 127-137. https://doi.org/10.1039/b907368j

[5] Kumar, P., Kumar, V., Roy, J.S. (2019). Design of quad core photonic crystal fibers with flattened zero dispersion. AEU-International Journal of Electronics and Communications, 98: 265-272. https://doi.org/10.1016/j.aeue.2018.11.014

[6] Hossain, M.B., Bulbul, A.A.M., Mukit, M.A., Podder, E. (2017). Analysis of optical properties for square, circular and hexagonal photonic crystal fiber. Optics and Photonics Journal, 7(11): 235-243. https://doi.org/10.4236/opj.2017.711021

[7] Kumar, C.S., Anbazhagan, R. (2017). Investigation on chalcogenide and silica based photonic crystal fibers with circular and octagonal core. AEU-International Journal of Electronics and Communications, 72: 40-45. https://doi.org/10.1016/j.aeue.2016.11.018

[8] Tameh, T.A., Isfahani, B.M., Granpayeh, N., Javan, A.M. (2011). Improving the performance of all-optical switching based on nonlinear photonic crystal microring resonators. AEU-International Journal of Electronics and Communications, 65(4): 281-287. https://doi.org/10.1016/j.aeue.2010.03.013

[9] Fini, J.M. (2004). Microstructure fibres for optical sensing in gases and liquids. Measurement Science and Technology, 15(6): 1120. https://doi.org/10.1088/0957-0233/15/6/011

[10] Wang, X., Wolfbeis, O.S. (2016). Fiber-optic chemical sensors and biosensors (2013-2015). Analytical Chemistry, 88(1): 203-227. https://doi.org/10.1021/acs.analchem.5b04298

[11] Yang, X., Lu, Y., Liu, B., Yao, J. (2017). Analysis of graphene-based photonic crystal fiber sensor using birefringence and surface plasmon resonance. Plasmonics, 12: 489-496. https://doi.org/10.1007/s11468-016-0289-z

[12] Otupiri, R., Akowuah, E.K., Haxha, S., Ademgil, H., AbdelMalek, F., Aggoun, A. (2014). A novel birefrigent photonic crystal fiber surface plasmon resonance biosensor. IEEE Photonics Journal, 6(4): 1-11. https://doi.org/10.1109/jphot.2014.2335716

[13] Mortensen, N.A. (2002). Effective area of photonic crystal fibers. Optics Express, 10(7): 341-348. https://doi.org/10.1364/oe.10.000341

[14] Islam, M.S., Paul, B.K., Ahmed, K., Asaduzzaman, S., Islam, M.I., Chowdhury, S., Sen, S., Bahar, A.N. (2018). Liquid-infiltrated photonic crystal fiber for sensing purpose: design and analysis. Alexandria Engineering Journal, 57(3): 1459-1466. https://doi.org/10.1016/j.aej.2017.03.015

[15] Podder, E., Hossain, M.B., Jibon, R.H., Bulbul, A.A.M., Mondal, H.S. (2019). Chemical sensing through photonic crystal fiber: sulfuric acid detection. Frontiers of Optoelectronics, 12: 372-381. https://doi.org/10.1007/s12200-019-0903-8

[16] Caroline, B.E., Umamaheswari, P., Jayasri, R., Kumar, D.S. (2020). Investigation on the detection of sulfuric acid using photonic crystal fiber sensor. In 2020 7th International Conference on Smart Structures and Systems (ICSSS), Chennai, India, pp. 1-5. https://doi.org/10.1109/icsss49621.2020.9202187

[17] Maidi, A.M., Yakasai, I., Abas, E., Nauman, M.M., Apong, R.A., Kaijage, S., Begum, F. (2021). Design and simulation of photonic crystal fiber for liquid sensing. Photonics, 8(1): 16. https://doi.org/10.3390/photonics8010016

[18] Eid, M.M.A., Habib, M.A., Anower, M.S., Rashed, A.N.Z. (2021). Highly sensitive nonlinear photonic crystal fiber based sensor for chemical sensing applications. Microsystem Technologies, 27: 1007-1014.

https://doi.org/10.1007/s00542-020-05019-w

[19] Maidi, A.M., Kalam, M.A., Begum, F. (2022). Photonic crystal fiber sensor for detecting sulfuric acid in different concentrations. Photonics, 9(12): 958. https://doi.org/10.3390/photonics9120958

[20] Rahaman, M.E., Jibon, R.H., Mondal, H.S., Hossain, M.B., Bulbul, A.A.M., Saha, R. (2021). Design and optimization of a PCF-based chemical sensor in THz regime. Sensing and Bio-Sensing Research, 32: 100422. https://doi.org/10.1016/j.sbsr.2021.100422

[21] Kikuchi, K., Taira, K., Sugimoto, N. (2002). Highly-nonlinear bismuth oxide-based glass fibers for all-optical signal processing. In Optical Fiber Communication Conference and Exhibit, Anaheim, CA, USA, pp. ThY6-ThY6. https://doi.org/10.1109/ofc.2002.1036560

[22] Broeng, J., Mogilevstev, D., Barkou, S.E., Bjarklev, A. (1999). Photonic crystal fibers: A new class of optical waveguides. Optical Fiber Technology, 5(3): 305-330. https://doi.org/10.1006/ofte.1998.0279

[23] Petrovich, M.N., van Brakel, A., Poletti, F., Mukasa, K., Austin, E., Finazzi, V., Petropoulos, P., O'Driscoll, E., Watson, M., DelMonte, T., Monro, T.M., Dakin, J.P., Richardson, D.J. (2005). Microstructured fibres for sensing applications. In Photonic Crystals and Photonic Crystal Fibers for Sensing Applications, SPIE, Boston, MA, United States, pp. 78-92. https://doi.org/10.1117/12.631617

[24] El Hamzaoui, H., Ouerdane, Y., Bigot, L., Bouwmans, G., Capoen, B., Boukenter, A., Girard, S., Bouazaoui, M. (2012). Sol-gel derived ionic copper-doped microstructured optical fiber: A potential selective ultraviolet radiation dosimeter. Optics Express, 20(28): 29751-29760. https://doi.org/10.1364/oe.20.029751

[25] Hale, G.M., Querry, M.R. (1973). Optical constants of water in the 200-nm to 200-µm wavelength region. Applied Optics, 12(3): 555-563. https://doi.org/10.1364/ao.12.000555

[26] Krieger, U.K., Mössinger, J.C., Luo, B., Weers, U., Peter, T. (2000). Measurement of the refractive indices of H_2SO_4–HNO_3–H_2O solutions to stratospheric temperatures. Applied Optics, 39(21): 3691-3703. https://doi.org/10.1364/ao.39.003691

[27] Akowuah, E.K., Gorman, T., Ademgil, H., Haxha, S., Robinson, G.K., Oliver, J.V. (2012). Numerical analysis of a photonic crystal fiber for biosensing applications. IEEE Journal of Quantum Electronics, 48(11): 1403-1410. https://doi.org/10.1109/jqe.2012.2213803

[28] Yakasai, I.K., Abas, P.E., Ali, S., Begum, F. (2019). Modelling and simulation of a porous core photonic crystal fibre for terahertz wave propagation. Optical and Quantum Electronics, 51: 1-16. https://doi.org/10.1007/s11082-019-1832-x

[29] Hossain, M., Podder, E., Adhikary, A., Al-Mamun, A. (2018). Optimized hexagonal photonic crystal fibre sensor for glucose sensing. Advances in Research, 13(3): 1-7. https://doi.org/10.9734/air/2018/38972

[30] Yakasai, I., Abas, P.E., Kaijage, S.F., Caesarendra, W., Begum, F. (2019). Proposal for a quad-elliptical photonic crystal fiber for terahertz wave guidance and sensing chemical warfare liquids. Photonics, 6(3): 78. https://doi.org/10.3390/photonics6030078

[31] Begum, F., Namihira, Y., Kinjo, T., Kaijage, S. (2010). Supercontinuum generation in photonic crystal fibres at 1.06, 1.31, and 1.55 mm wavelengths. Electronics Letters, 46(22): 1-2. https://doi.org/10.1049/el.2010.2133

[32] Begum, F., Abas, P.E. (2019). Near infrared supercontinuum generation in silica based photonic crystal fiber. Progress in Electromagnetics Research C, 89: 149-159. https://doi.org/10.2528/pierc18100102

[33] Arif, M.F.H., Hossain, M.M., Islam, N., Khaled, S.M. ()2019). A nonlinear photonic crystal fiber for liquid sensing application with high birefringence and low confinement loss. Sensing and Bio-Sensing Research, 22: 100252. https://doi.org/10.1016/j.sbsr.2018.100252

[34] Kaijage, S.F., Ouyang, Z., Jin, X. (2013). Porous-core photonic crystal fiber for low loss terahertz wave guiding. IEEE Photonics Technology Letters, 25(15): 1454-1457. https://doi.org/10.1109/lpt.2013.2266412

[35] Benhaddad, M., Kerrour, F., Benabbes, O. (2018). Design and analysis of non-linear properties of photonic crystal fiber with various doping concentration. Journal of Physics: Conference Series, 987: 012010. https://doi.org/10.1088/1742-6596/987/1/012010