PAPERS IN PHYSICS, VOL. 17, ART. 170003 (2025)

www.papersinphysics.org

Received: 28 September 2024, Accepted: 21 August 2025
Edited by: O. Martínez, University of Buenos Aires, Argentina

DOI: https://doi.org/10.4279/PIP.170003

ISSN 1852-4249

Design and enhancing the performance of a hollow core-based photonic crystal fiber sensor for alcohols sensing in the THz spectrum

Jannatun Ferdous[1*], Md. Dulal Haque[1], Mahfujur Rahman[1], Md. Selim Hossain[1], Md. Abubakar Siddik[1]

In this work, we explore a wheel-shaped hollow-core photonic crystal fiber (HC-PCF)-based optical alcohol sensor that operates in the terahertz (THz) region. We employ the finite element method (FEM) along with COMSOL Multiphysics software to simulate the structure and perform a numerical analysis of the model. In this configuration, alcohol analytes are integrated into the fiber's core. The results from the FEM simulation indicate that the proposed optical HC-PCF sensor achieves high sensitivity levels of 97.61% for ethanol, 98.80% for butanol, and 98.53% for propanol, all at a frequency of 2.1 THz. The measured low confinement losses at 2.1 THz are 8.0696×10^{-8} dB/m, 7.1966×10^{-11} dB/m and 3.6334×10^{-10} dB/m. Furthermore, the effective areas are 7.5911×10^{-8} m^2, 7.8258×10^{-8} m^2, and 8.0847×10^{-8} m^2 for three types of alcohol. Additionally, we discuss the concepts of effective material loss, effective mode index, and total power fraction. Existing technologies can facilitate the fabrication of this proposed sensor. Moreover, we anticipate that the application of our fabricated sensor will extend to biomedicine, biosensing experiments, industrial applications, material research, healthcare, alcohol detection in drinks and liquids, and other THz communication technologies based on waveguides.

I Introduction

People use alcohol extensively around the world as a chemical and psychoactive drug. Moreover, humans have consumed it as a beverage for thousands of years, in forms such as whiskey or beer. Many sectors, including paints, medicines, and liquid petroleum gas stations, depend entirely or primarily on these chemicals. Alcohol primarily takes three forms in both personal and professional settings: methyl, ethyl, and isopropyl alcohol. The most basic type of alcohol is methyl alcohol, sometimes referred to as wood alcohol or methanol [1]. Because each type has unique traits and uses, it is vital to tell them apart for daily use. Even so, all alcohols are colorless liquids with the same scent, making them hard to tell apart [1, 2]. For our health, there is an urgent need for improved sensing technology that can handle these problems while also delivering reliable and effective alcohol detection and analysis capabilities. PCFs developed since 1996 have been increasingly attracting attention in sensing and communication applications because of their fantastic optical properties. These properties consist of increased birefringence, diminished scattering, effective material loss, heightened sensitivity, and a greater core power fraction when compared to conventional fibers [1, 3]. PCFs have opened new avenues to create photonic devices for sensing and communication. Such a glass fiber design allows for applying a broader range of optical properties, a greater effective core region, reduced loss, transparency, and infinite single-mode operation [1, 3]. However, because it is small and very sensitive in the THz band, the PCF-

* ferdous.ece@hstu.ac.bd

[1] Department of Electronics and Communication Engineering, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh.

based sensing device is still commonly used in real-life situations, such as detecting chemicals and toxic gases, imaging biological tissue, and finding cancer cells [1, 3, 4]. Recently, the terahertz region of the electromagnetic energy scale within the narrow frequency range of 0.1–10 THz, the low-frequency end of the radiation spectrum, has been the focus of considerable interest because of its potential applications. This radiation spectrum is popular because it falls between the infrared and microwave ranges, making it seemingly less harmful to people or the environment [3, 4]. The structure primarily categorizes PCFs into three types: solid-core, hollow-core, and porous-core. The first type is unsuitable for detecting chemicals or alcohol; a hollow-core photonic crystal fiber is the best choice because it provides the strongest local field strength of the radiation, allowing it to interact better with the substance being tested [3, 5]. Recently, terahertz, the low-frequency part of the radiation spectrum of the electromagnetic energy scale (narrow frequency range: (0.1–10 THz), has attracted much attention for potential applications for many years.

Additionally, the PCF pumps specific light-wavelength decompositions, allowing the evaluated analytes to permeate the core. The waveguide possesses a refractive index that influences the behavior of light as it travels. This variation causes light of the same (laser) wavelength to take different amounts of time when traveling along various paths. Detection and interpretation of the incoming signal enable the quick and accurate determination of the properties of the analyzed analytes [1, 6]. Researchers are currently interested in the ongoing research on PCF-based chemical and alcohol analyte sensing. Several PCF-based sensors utilizing THz signal propagation have been proposed. For example, a hexagonal-shaped photonic crystal fiber has been suggested as an easy hollow core model, which Ahasan Habib and others found affects how sensitive the sensor is to different types of alcohol. The simulation results show that the sensor can achieve a high relative sensitivity (89%) in the optimal structure [1]. Sahawal Hossain and others created a grapefruit-shaped HC-PCF to measure how much kerosene is in dirty fuel; this sensor had a relative sensitivity of 97.27%, a confinement loss of less than 10^{-10} dB, and a total loss of less than 0.07 dB/cm [6]. This paper designed and tested a chemical PCF sensor. At 1.6 terahertz, ethanol, benzene, and water had relative sensitivities of 93.54%, 94.73%, and 92.50% [7]. Kawsar Ahmed et al. developed a hexagonal-structured intelligent photonic crystal fiber that is more sensitive to chemical changes. PCF was affected by ethanol, water, benzene, basic characteristics, confinement loss, and nonlinearity. The research explores the applications of PCF in communication technologies, biochemical sensing, and biosensing. It presents sensitivity levels of 53.22% for ethanol, 48.19% for water, and 55.56% for benzene detection at a frequency of 1.33 μm [8]. Accordingly, our HC-PCF sensor makes use of wheel-shaped and large circular air holes on the cladding. It has been demonstrated that the HC-PCF structure improves alcohol sensor sensitivity and reduces confinement loss. At 2.1 THz, the three alcohols (namely ethanol $n = 1.354$, butanol $n = 1.387$ and propanol $n = 1.399$), had higher relative sensitivities of 97.61%, 98.80%, and 98.53%, respectively. Additionally, for three similar alcohols at 2.1 THz, the effective areas are 7.5911×10^{-8} m², 7.8258×10^{-8} m², and 8.0847×10^{-8} m², respectively. The corresponding low confinement losses are 8.0696×10^{-8} dB/m, 7.1996×10^{-11} dB/m, and 3.6334×10^{-10} dB/m. Furthermore, the proposed photonic crystal fiber configuration demonstrates a very high relative sensitivity of 98.80% for butanol at 2.1 THz and exhibits significantly lower confinement loss compared to previously published work [1, 3, 6, 9].

II Sensor design and theoretical modeling

i Structure of the proposed sensor

To simplify manufacture, circular air holes were employed instead of elliptical holes for the core region. Our simple PCF optical alcohol sensor improves sensitivity and lowers material loss and production limits. We changed the strut dimensions and the simulation frequency to achieve the best design parameters for better sensor performance [10]. Fig. 1 shows the structured design process of the developed sensor model.

The center region of the proposed sensor, which has a circular shape in the center and essentially a wheel shape for the clad portions, is shown in Fig. 2, the structural view of the two-dimensional hollow-core PCF alcohol sensor. The proposed photonic crystal fiber design features a single circular air hole situated at the center. We systematically establish a dielectric medium for the fibers within a cladding region using wheel-shaped air holes. The measurement from one edge of the core to the opposite edge is referred to as the core diameter, denoted by D, and has a specific value. The

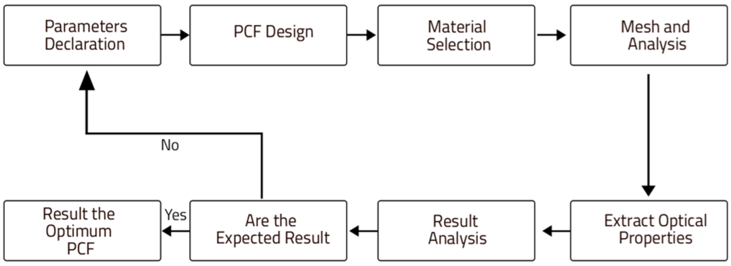

Figure 1: Block diagram showing the sequential design and analysis stages for the proposed sensor model.

cladding holes, designed in a wheel structure, have a radius of R, while the fiber radius is noted as R_1. In this design, $D = 340$ μm. The radius is given by $R = 2.2821D$ μm and $R_1 = 2.47D$ μm. The proposed sensor has demonstrated optimal performance under specific conditions. We identified these parameters through empirical investigation. Additionally, the symbol P, defined as 20 μm, represents the gap between the core and the adjacent cladding arm, as evidenced by the surrounding cladding holes and the relevant context. Adjacent cladding air holes were separated by 4-degree angle. Every design parameter is associated with a distinct factor that facilitates manufacturing. The outermost PML layer of the optical fiber is 10% of its total size [11].

The PMLs are for absorbing signal light scattered away from the core towards the cladding, thereby preventing signal light from being reflected back towards the core. Table 1 provides the geometric dimensions and parameters of the proposed optical sensor.

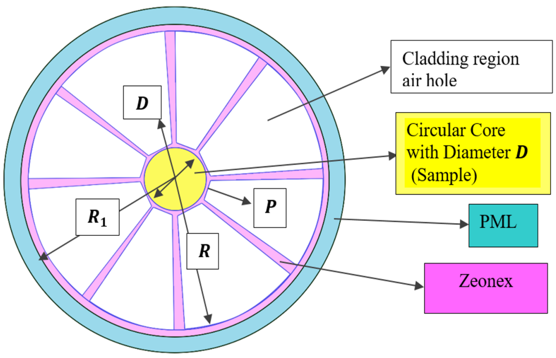

Figure 2: Structural view of the two-dimensional hollow-core PCF alcohol sensor.

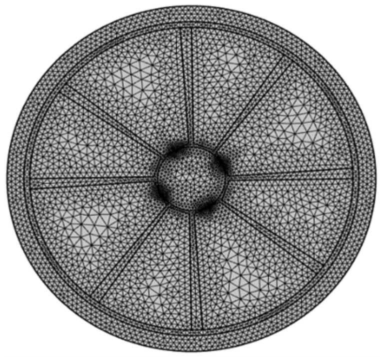

Figure 3: Depicts both the combined mesh output and the recommended sensor boundary.

We utilize Zeonex for the bulk material of the HC-PCF in the chemical detector due to its low material absorbance loss, reliable refractive indices at THz frequencies, and its smallest index of refraction variation ($n = 1.53$) from 0.1 to 3 terahertz [3, 5]. Meshing divides the area into finite-dimensional circular sections for computation. Fig. 3 illustrates the simulated phenomenon for consideration. Higher mesh density enhances light transmission to the sensor, improving numerical analysis and sensor accuracy. This simulation utilized physics-based meshing with smaller element sizes [11, 12].

Table 1: Accurate measurements and geometric parameters.

Parameters	Measurements
The core's diameter, (D)	340 μm
P	20 μm
Radius of cladding, R	2.2821×10^3 nm
Radius of the fiber, r	2.47×10^3 nm

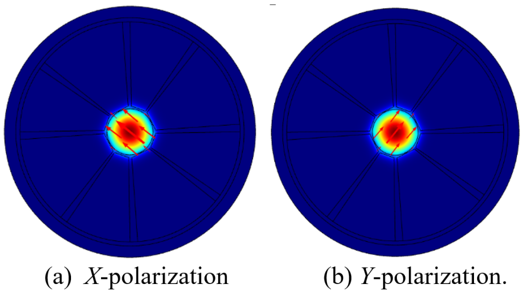

Figure 4: Light confinements of the proposed sensor-based PCF alcohol sensing system: (a) X-polarization and (b) Y-polarization.

Figs. 4(a) and 4(b) show the proposed sensor core's light confinement in the X-pole and Y-pole. Light modes at the X-pole and Y-pole for the PCF sensor at 2.1 THz vary when filled with ethanol, butanol, and propanol, as shown in Figs. 5(a) and 5(b). The HC-PCFs' X- and Y-polarized sensitivity should grow due to light confinement within the core. It has been found that different polarizations are scattered with various light intensities along the fiber, thereby resulting in sensitivity, leakage loss, and other issues for an optical filament that varies significantly. In this design, the light of both polarizations passes through the core area equally. Each illustration demonstrates how light is tightly contained within the core, necessary for a high level of sensitivity [13, 14].

ii Numerical Analysis

According to the Beer-Lambert rule, the intensity of the interaction between radiation and matter affects the sensitivity of an alcohol sensor. This principle applies specifically to the alcohol sensor. Eq. 1 illustrates how the proposed sensor uses this operational principle.

$$I(f) = I_0(f)e^{-r\alpha_m l_c} \tag{1}$$

Here, $I(f)$ represents the light intensity of alcohol analytes, and $I_0(f)$ represents the light intensity measured before alcohol analytes. The absorption factor (α_m), channel length (l_c), fibre frequency (f), and sensitivity factor (r) are also represented [9, 14].

III Simulation results and discussions

Perfectly matched layers (PML) and the finite element method (FEM) are used to examine the guiding properties of a hollow-core photonic crystal fiber sensor. All numerical results in the terahertz frequency range are calculated using the well-known software COMSOL Multiphysics version 5.5. We apply the finite element method to evaluate the proposed hollow-core photonic crystal fiber based on the sample we are testing [4, 15, 16].

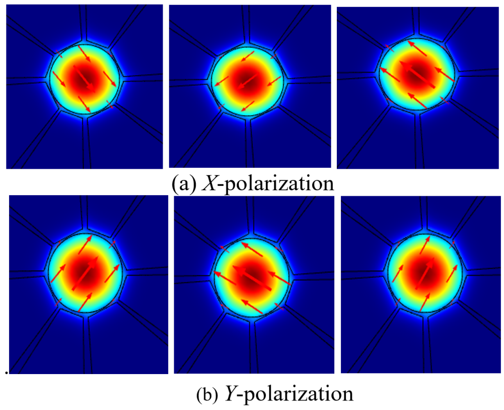

Figure 5: Proposed HC-PCF-based alcohol detection sensor light mode: (a) X-polarization, and (b) Y-polarization.

At room temperature, Table 2 shows the refractive index of different alcohol samples. In Fig. 6, this sensing device includes THz light, a light source, an illumination component, a spectrum analyzer, and a display unit. We position a sample channel appropriately to facilitate the inlet and outlet of liquid alcohol before activating the light source. It is crucial to utilize a low-bandwidth laser source for optimal accuracy during testing. We introduce the sample into the capillary and illuminate it with the light source [7]. Light travels through the sensor supported by single-mode fiber (SMF). After pass-

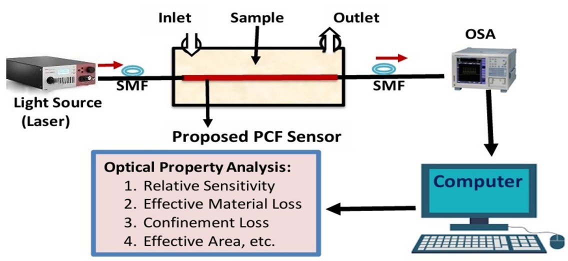

Figure 6: Illustration of the operational procedure for the proposed HC-PCF model.

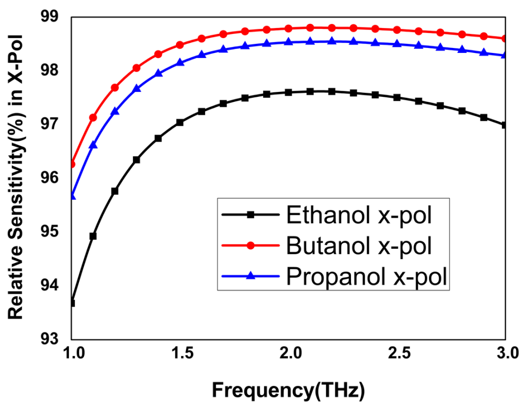

Figure 7: Relative sensitivity versus usable frequency (X-pole) for various alcohol samples.

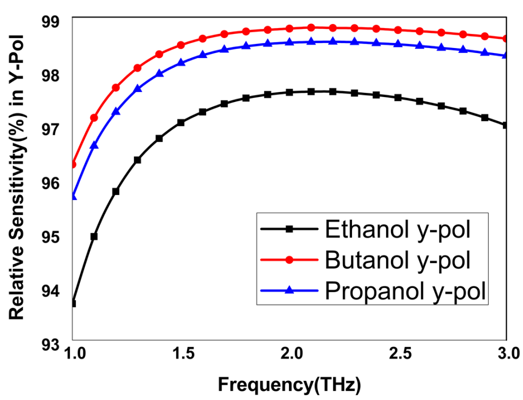

Figure 8: Relative sensitivity versus usable frequency (Y-pole) for various alcohol samples.

ing through the sensor, the single-mode fiber transmits the laser light to an optical spectrum analyzer (OSA). To determine the optical properties of the injected alcohols, the computer assesses the data from the optical spectrum analyzer, including their relative sensitivity, effective material loss, confinement loss, and other factors. The computer then displays this data in both graphical and numerical formats. Simulated data was entered into Origin Pro software, which generated relative sensitivity curves and other outputs for multiple frequencies within the terahertz spectrum [10].

The core diameter ($D = 340\mu$m) measures the detector's relative sensitivity. In this work, we adopted a 2.1 THz frequency response. The basic sensing mechanism that indicates the presence and relative sensitivity of detected analytes is influenced by their concentration. We calculate the relative sensitivity using the corresponding formula [16]:

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

Here, the refractive index is denoted by n_r and n_{eff} symbolizes effective refractive index in the appropriate way. Total amount of light-matter interfaces, represented by E, may be determined applying the equation that follows [15, 17]:

$$\frac{\int_{sample} R_e(E_x H_y - E_y H_x) dxdy}{\int_{total} R_e(E_x H_y - E_y H_x) dxdy} \times 100\%. \tag{3}$$

In this context, the electric fields of elements x and y are denoted as E_x and E_y, whereas the magnetic fields are represented as H_x and H_y [18, 19]. The research work determines the relative sensitivity using Eq. 2. Figs. 7 and 8 show how different alcohol samples respond under the best design conditions, comparing their sensitivity at different usable frequencies (X-pol and Y-pol). Higher frequencies result in simpler relative sensitivity graphs, leading to a slow decline in frequency. The relative sensitivity of ethanol, butanol, and propanol goes up in the low-frequency range ($1.0 - 2.1$ THz) but goes down as the frequency increases ($2.2 - 3.0$ THz) [14, 20].

Additionally, butanol has a higher refractive index compared to the other two chemicals, which helps provide a strong response in the proposed sensor. Furthermore, the maximum relative sensitivity values for butanol are as follows: 98.802% for X polarization and 98.805% for Y polarization, in comparison to the best values reported in previous publications [1, 3–5]. As shown in Fig. 9, the EML sensor operates at an operation frequency of 2.1 THz. Thus, at an optimal core size, the EML range for various alcohol analytes is approximately 0.003987 cm^{-1}, 0.002848 cm^{-1}, and 0.003097 cm^{-1}, respectively. A lower EML will be as-

Table 2: The refractive index for various alcohol samples was measured at room temperature.

Analytes	**Refractive Index**
Ethanol	1.354
Butanol	1.399
Propanol	1.387

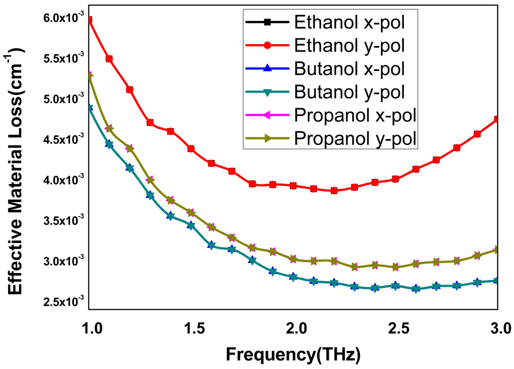

Figure 9: Effective material loss versus usable frequency for several alcohol samples.

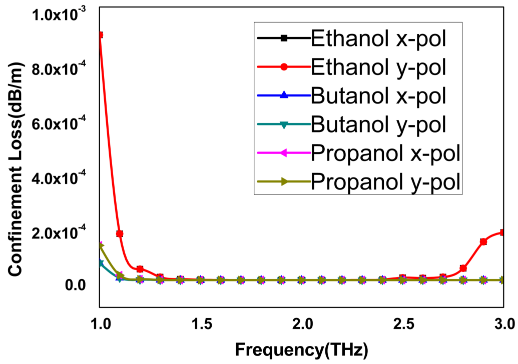

Figure 10: Confinement loss versus usable frequency for various alcohol samples.

sociated with an analyte that has a higher refractive index than one that has a lower refractive index. This is something that should be considered. During continuous operation, this feature makes it possible for lighter particles to flow through with greater ease. From Fig. 9, the sensor behaves the same regardless of operation frequency. The low-index cladding and the core's solid medium absorb less light at higher frequencies, improving light transmission. Higher frequencies have less loss, which is advantageous [1, 20].

Confinement loss denotes the quantity of light energy that escapes from the core of an optical fiber into the cladding or outside, instead of being guided along the fiber. It is usually measured in dB/m. For quick alcohol detection, the PCF with the least amount of loss of confinement (CL) also offers a greater relative sensitivity. This type of loss may be readily quantified using the following sentence [9, 18]:

$$L_c = 8.686 \times K_0 I_m[n_{eff}](dB/m). \tag{4}$$

In this case, $K_0 = 2\pi(f/c)$, where f is the operational signal frequency, c is the speed of light in free space, and I_m $[(n_eff)]$ is the imaginary part of the guided mode's effective refractive index, which indicates the amount of leakage or absorption loss. This parameter can be determined by simulation software [19]. Using Eq. 4, the CL is determined in the research work.

Fig. 10 illustrates the relationship between confinement losses and frequency for different alcohol samples. In the frequency range of 2 to 3 THz, a consistent trend is observed: confinement losses decrease as the frequency increases, particularly noted at 2.1 THz. According to the measurements, the confinement losses for ethanol are 8.06×10^{-8} dB/m, while for butanol they are $7.19 \times 10{-}11$ dB/m, and for propanol they are 3.63×10^{-10} dB/m [18]. Our observations confirm that all power transfer occurs within the photonic crystal fiber structure. The formula employed for calculating the power fraction (PF) is as follows:

$$PF = \frac{\int_{sample} S_z dA}{\int_{total} S_z dA}. \tag{5}$$

In this case, PF represents the power fraction, where the numerator indicates the power flowing in the sample region and the denominator reflects the total guided power within the waveguide or fiber mode. In this context, S_z refers to the z-component of the Poynting vector, and dA denotes the differential area element [9]. Furthermore, the research work determines the total power fraction using Eq. 5.

As previously mentioned, the most common types of loss in PCF-based sensors are effective material loss and confinement loss. Fig. 11 shows the power fraction as a function of frequency for various alcohol samples under optimal design conditions. It indicates that the power fraction increases as the frequency rises within the 1 to 3 THz range [10]. We employed the following formula to estimate the effective area (EA):

$$A_{eff} = \frac{(\int I(r) r dr)^2}{\int I^2(r) r dr}. \tag{6}$$

Here, $I(r)$ is the intensity of the cross-sectional electric region, and A_{eff} is the effective area [21]. The research work determines the effective area using Eq. 6.

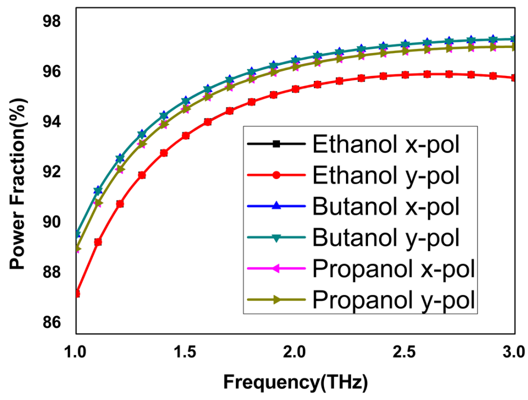

Figure 11: Power ratio with frequency for various alcohol samples.

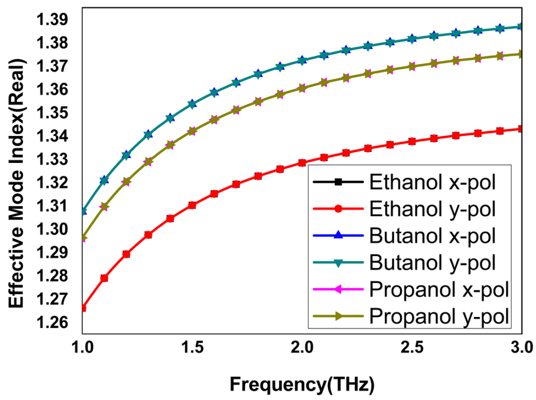

Figure 13: The effective mode index with frequency for various alcohol samples.

Fig. 12 illustrates the relationship between the new HC-PCF structure's effective area and frequency, as well as its appearance factors. The visual result showed that in the $1-3$ THz frequency range, the effective area decreased as the frequency increased. The larger effective area demonstrates increased sensitivity and decreased confinement loss for THz wave pulses. At a frequency of 2.1 THz, ethanol, butanol, and propanol have effective areas of 7.59×10^{-8} m^2, 7.82×10^{-8} m^2, and 8×10^{-8} m^2, respectively [20, 21]. Fig. 13 displays the effective mode index with frequency for various alcohol samples at optimal design conditions. It is visible that, when frequency increases, the effective mode index also increases. The effective mode index, η_{eff}, measures how a light wave propagates in the guided mode of an optical waveguide. The effective mode index is 1.26, and the frequency is 1 THz. When the frequency is raised to 3 THz for the butanol alcohol sample, the effective mode index reaches a peak value of 1.38 [1, 7]. PCF-based sensing analysis generates a comparison table 3. This table demonstrates that the recommended sensor is more sensitive than liquid, alcohol, and chemical sensors.

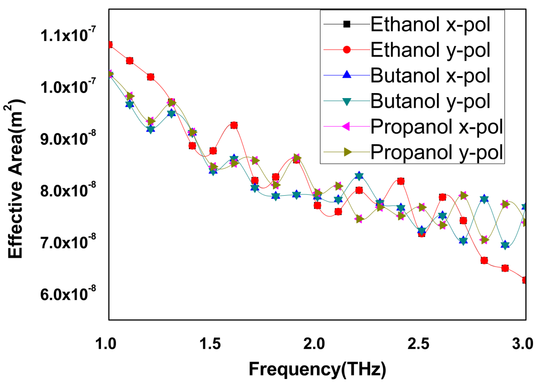

Figure 12: Effective area with frequency for various alcohol samples.

Next, a sensor production process is considered. This hybrid sensor's cross-section shows a circular core (Fig. 2). A single constant diameter (D) governs all core and cladding holes, simplifying the manufacturing process. Different fabrication methods have produced asymmetrically designed PCFs in the lab. We can easily fabricate our suggested PCF in a lab by comparing its structure. The sensor's optimal PCF fiber size of 1.679 mm suggests its potential for laboratory manufacturing. Photonic sensors' outstanding sensitivity and rapid reaction times allow them to detect physical, chemical, and biological changes. Its simple geometric structure allows production and practical use. Thus, this technology presents a novel method for detecting alcohol samples that surpasses previous research in terms of accuracy, cost-effectiveness, and sensing efficiency. Drilling, stacking, capillary stacking, the sol-gel technique, 3-D printing, and other modern technologies may quickly create circular air holes in the core and cladding. Over the last few decades, various PCFs with circular air holes have been carefully manufactured utilizing the extrusion process. As a result, our suggested optical alcohol sensors may be used in the extrusion process [14, 18].

Table 3: Comparing the identifying and performance parameters of PCF-based sensors.

Ref.	**Frequency (f)**	**Sensing Sample**	**Relative Sensitivity (%)**	**Effective Area (m^2)**	**Effective Material Loss (cm^{-1})**	**Confinement (dB/m)**
[9]	1.0 THz	ethanol	89.50	NA	NA	5.45×10^{-08}
		butanol	91.80	NA	NA	6.01×10^{-08}
		propanol	90.81			5.60×10^{-08}
[22]	2.0 THz	camel milk	81.16	NA	0.033013	8.675×10^{-18}
		cow milk	81.32		0.03284	1.435×10^{-18}
[23]	1.0 THz	ethanol	68.87	NA	NA	7.79×10^{-12}
[24]	1.0 THz	ethanol	81.46	NA	NA	5.85×10^{-08}
		benzene	82.26	NA	NA	6.07×10^{-08}
		water	79.22			5.84×10^{-08}
[25]	1.0 THz	ethanol	86.60	NA	NA	5.75×10^{-08}
		butanol	88.70	NA	NA	6.11×10^{-08}
		propanol	84.71			5.70×10^{-08}
This work	2.1 THz	ethanol	**97.61**	7.59×10^{-8}	**0.003987**	$\mathbf{8.06 \times 10^{-8}}$
		butanol	**98.80**	7.82×10^{-8}	**0.002848**	$\mathbf{7.19 \times 10^{-11}}$
		propanol	**98.53**	8.08×10^{-8}	**0.003097**	$\mathbf{3.63 \times 10^{-10}}$

IV Conclusion

Alcohol consumption has a detrimental effect on health and is often associated with an increased risk of serious accidents and alcohol-related crimes. To address this issue, we are developing new sensor systems to detect exhaled breath in real time. Our simulated experiment indicated that the concentrations of ethanol, butanol, and propanol are 97.61%, 98.80%, and 98.53%, respectively, at a frequency of 2.1 THz. In the terahertz region, the proposed hollow-core photonic crystal fiber demonstrates confinement losses of 8.06×10^{-8} dB/m for ethanol, 7.19×10^{-11} dB/m for butanol, and 3.63×10^{-10} dB/m for propanol. Additionally, the fiber demonstrates minimal effective material loss, measured at 0.003987 cm^{-1}, 0.002848 cm^{-1}, and 0.003097 cm^{-1} under ideal geometric conditions. Alcohol sensing using HC-PCF is crucial in ensuring safety, health, and regulatory compliance across various sectors, including chemical industrial processes, biomedical and industrial fields, food and beverage industries, medical technology, business, and biological research. The technology helps mitigate the risks associated with alcohol consumption and supports efforts to promote responsible drinking behavior and public safety.

[1] M. A. Habib, et al., *Efficient way for detection of alcohols using hollow core photonic crystal fiber sensor*, Optical Review **28**, 383–392 (2021).

[2] A. Elfasakhany, *Investigations on the effects of ethanol–methanol–gasoline blends in a spark-ignition engine: Performance and emissions analysis*, Eng. Sci. Technol. Int. J. **18**(4), 713–719 (2015).

[3] A. C. Shi, A. M. Maidi, N. Zou, and F. Begum, *High-Performance Microstructure Core Photonic Crystal Fibre-Based Biosensor for Alcohol Detection*, Progress In Electromagnetics Research M **114**, 27–36 (2022).

[4] M. Abdullah-Al-Shafi and S. Sen, *Design and analysis of a chemical sensing octagonal photonic crystal fiber (O-PCF) based optical sensor with high relative sensitivity for terahertz (THz) regime*, Sensing and Bio-Sensing Research **29**, 100372 (2020).

[5] J. Ferdous et al., *Design and Performance Analysis of a Novel Hollow Core-Based Photonic Crystal Fiber for Edible Oil Sensing in the Terahertz (THz) Regime*, Health Science Journal **18**(S10), 002 (2022).

[6] S. Hossain et al., *Designing of Hollow Core Grapefruit Fiber Using Cyclo Olefin Polymer for*

the Detection of Fuel Adulteration in Terahertz Region, Polymers **15**(1), 151 (2023).

[7] J. Ferdous, M. D. Haque, M. A. Siddik, *Hollow Core-based Photonic Crystal Fiber Sensor: Design and Performance Development of Chemical Sensing in THz wave Propagation*, J. Electrical Systems **20**(4), 482–494 (2024).

[8] M. S. Islam et al., *Liquid-infiltrated photonic crystal fiber for sensing purpose: design and analysis*, Alexandria Engineering Journal **57**(3), 1459–1466 (2018).

[9] R. Hossen et al., *Design and performance analysis of alcohols sensing using photonic crystal fiber in terahertz spectrum*, Physics Open **17**, 100192 (2023).

[10] M. S. Hossain et al., *Design and numerical analysis of a novel photonic crystal fiber based chemicals sensor in the THz regime*, Physics Open **17**, 100168 (2023).

[11] M.M. Eid, M. A. Habib, M. S. Anower, and A. N. Z. Rashed, *Hollow core photonic crystal fiber (PCF)–Based optical sensor for blood component detection in terahertz spectrum*, Brazilian Journal of Physics **51**, 1017–1025 (2021).

[12] M. J. B. M. Leon and M. A. Kabir, *Design of a liquid sensing photonic crystal fiber with high sensitivity, bireferingence & low confinement loss*, Sensing and Bio-Sensing Research **28**, 100335 (2020).

[13] M. S. Hossain et al., *Design and performance analysis of PCF-based octagonal chemical sensor to detect benzene, ethanol, and water in terahertz spectrum*, Results in Optics **14**, 100599 (2024).

[14] J. Ferdous, Md. D. Haque, Md. A. Siddik, *Hexagonal core photonic crystal fiber optical sensor: the analysis of design and performance improvement for alcohols sensing in THz wave propagation*, EUREKA: Physics and Engineering **2**, 121–131 (2025).

[15] K. Panwar et al., *Design and analysis of decagonal photonic crystal fiber with elliptical air hole core for liquid sensing*, Indian Journal of Engineering and Materials Sciences **27**(2), 465–470 (2020).

[16] M. A. Habib et al., *Hollow core photonic crystal fiber for chemical identification in terahertz regime*, Optical Fiber Technology **52**, 101933 (2019).

[17] A. HM Almawgani et al., *Identification of four detrimental chemicals using square-core photonic crystal fiber in the regime of THz*, Journal of Applied Physics **133**, no. 24 (2023).

[18] M. S. Islam et al., *Sensing of toxic chemicals using polarized photonic crystal fiber in the terahertz regime*, Optics Communications **426**, 341–347 (2018).

[19] M. J. B. M. Leon, S. Abedin, and M. A. Kabir, *A photonic crystal fiber for liquid sensing application with high sensitivity, birefringence and low confinement loss*, Sensors International **2**, 100061 (2021).

[20] M. S. Reza and M. A. Habib, *Extremely sensitive chemical sensor for terahertz regime based on a hollow-core photonic crystal fibre*, Ukr. J. Phys. Opt. **21**(1), 8–14 (2020).

[21] S. Sen et al., *Zeonex based decagonal photonic crystal fiber (D-PCF) in the terahertz (THz) band for chemical sensing applications*, Sensing and Bio-Sensing Research **31**, 100393 (2021).

[22] M. A. Islam et al., *Wheel structured Zeonex-based photonic crystal fiber sensor in THz regime for sensing milk*, Applied Physics A **127**(5), 311 (2021).

[23] J. Sultana et al., *Terahertz detection of alcohol using a photonic crystal fiber sensor*, Applied Optics **57**(10), 2426–2433 (2018).

[24] S. Sen, M. Abdullah-Al-Shafi, and M. A. Kabir, *Hexagonal photonic crystal Fiber (H-PCF) based optical sensor with high relative sensitivity and low confinement loss for terahertz (THz) regime*, Sensing and Bio-Sensing Research **30**, 100377 (2020).

[25] M. S. Hossain et al., *Performance analysis of alcohols sensing with optical sensor procedure using circular photonic crystal fiber (C-PCF) in the terahertz regime*, Sensing and Bio-Sensing Research **35**, 100469 (2022).