Available online at www.ijournalse.org

Emerging Science Journal

(ISSN: 2610-9182)

Vol. 8, No. 6, December, 2024

Fiber Optic Breakthrough: Terahertz Detection of Illegal Drugs

Khalid Sifulla Noor [1], Most. Momtahina Bani [1], Md. Safiul Islam [1], A.H.M. Iftekharul Ferdous [1], Md. Jakir Hossen [2*], Abdullah Al-Mamun [3], Nasir Uddin Badhon [1]

[1] *Department of Electrical and Electronic Engineering, Pabna University of Science and Technology, Pabna, 6600, Pabna, Bangladesh.*

[2] *Faculty Engineering and Technology, Multimedia University, Melaka 75450, Malaysia.*

[3] *School of Information and Communication, Griffith University, Brisbane, Australia.*

Abstract

The article presents an illegal drug detector that utilizes photonic crystal fiber (PCF). The fiber structure of the H-PCF comprises a dodecagonal core and circular air gaps in cladding areas. We have analyzed the designed terahertz (THz) frequency range utilizing the Finite Element Method (FEM) and the COMSOL Multiphysics application. The revised design has a high sensitivity in detecting amphetamine ($n = 1.518$) and cocaine ($n = 1.5022$) at a frequency of 3 THz, via detection rates of 99.43% and 99.20%, correspondingly. Furthermore, the suggested fiber, which operates at a frequency of 3 THz, has a relatively tiny confinement loss of 4.93×10^{-08} dB/m and 6.16×10^{-09} dB/m and a minimal effective material loss of construction of 0.0032 cm^{-1}. In conclusion, it may be stated that drug misuse not only leads to immediate repercussions but also has severe and enduring impacts on human health, potentially resulting in fatality. Hence, it is imperative to accurately and effectively detect illicit substances. H-PCF architecture we offered is well-suited to detect illegal drugs.

Keywords:

Illegal Drug Sensing;
Numerical Aperture (NA);
Confinement Loss (CL);
Relative Sensitivity (RS);
Photonic Crystal Fiber (PCF).

Article History:

Received:	07	July	2024
Revised:	29	October	2024
Accepted:	11	November	2024
Published:	01	December	2024

1- Introduction

THz sensing in PCF utilizes the unique properties of these fibers to effectively manipulate and regulate THz pulses. PCF, or photonic crystal fiber, possesses characteristics such as tiny loss, birefringence, and adaptable architecture. These qualities make those highly suitable for a wide range of sophisticated and versatile THz detection implementations. Utilizing to detect THz with PCF involves harnessing unique optical properties of these fibers to manipulate and control THz waves. PCF, a specific particular variety of optical fiber, possesses a regular microstructure that creates a photonic bandgap. PCF directs light by trapping it within a repeating pattern of tiny air holes that extend throughout the fiber's length. By addressing the constraints of traditional fiber optics—such as enabling low-loss light guidance in a hollow core—these fibers are demonstrating a wide range of significant technological and scientific uses across various fields [1]. Because of their advantageous properties, the SM-OPCF waveguide enables effective transmission of broadband terahertz signals [2].

Fuel tampering is a major concern that can cause ecological problems, engine damage, and decreased efficiency. Finding illegal ingredients or differences in the gasoline's characteristics are common methods for detecting contaminated fuel. Detecting gasoline adulteration through the use of PCF sensors is one promising technological advancement [3]. PCF enables extremely precise and specific finding and is used in chemical sensing to detect shifts

* **CONTACT**: jakir.hossen@mmu.edu.my

DOI: http://dx.doi.org/10.28991/ESJ-2024-08-06-019

in light propagation brought about via alterations in the RI or absorption characteristics of chemicals [4]. A RI sensor provides accurate information on the composition or volume of a material by measuring fluctuations in RI of the compound by studying the shift in light transmission through the detector [5]. Only one light mode may be supported by a single-mode PCF at once, giving it excellent sensitivity to environmental changes and exact control over how light propagates. This makes it perfect for optical sensing applications that need exact evaluation and recognition [6]. PCF uses its unparalleled reactivity to tiny fluctuations in optical characteristics to identify variations in light propagation or reflection induced by an increase of cancer cells [7]. The study of nonlinear optics focuses on the way substances react to strong light fields, which can produce supercontinuum production, self-focusing, and harmonic multiplication [8]. Using a PCF sensor, it is possible to identify the contamination of petrol using kerosene by examining variations in the fuel mixture's digestion properties or RI [9]. Fuel integrity may be precisely and effectively monitored and ensured via this approach, which makes use of the tiny photonic variations that the rectangular core PCF can identify [10].

THz electromagnetic radioactivity corresponds to a narrow range of radiation spectrum, oscillating from 0.1 to 10 THz. Its wavelength lies in the region between that of optical light and radio signals [11]. In both medical and biological sciences, THz gadgets facilitate non-surgical imaging and spectroscopy for illness detection and diagnosis, cell property monitoring, and biomolecular association analysis. It is useful for early illness diagnosis and cell segmentation due to its acute reactivity to liquid and fluids [12]. Substance misuse is a major issue worldwide. When it comes to drug testing, on the other hand, which is conducted in a standard manner, the situation is different. There are multiple tests available to determine if an individual has used drugs or not. For example, bodily fluids, including blood, saliva, and urine, are tested for drugs. Blood tests can be performed more accurately, albeit certain collections, like urine, might not be the best [13].

A PCF biosensor will be designed after the planned study has been completed, which will be a much more advanced, precise, and effective way of blood testing for illegal substances. Due to its wide variety of sensing capabilities, THz-based PCF has remained a very prominent topic of study for quite some time. Utilizing PCF's distinct periodical structures—which provide tailored distribution and confining of THz waves—THz beam splitters may precisely manipulate and regulate THz radiation [14]. At THz frequencies, leveraging PCF, the authors proposed another technique for the detection of substances by spectroscopy [15]. PCF gauges are capable of accurately identifying and quantifying benzene, water, as well as ethanol due to their adaptability to variations in the RI of the surrounding medium [16]. By monitoring changes in transmitted light or directed modes, the PCF's architecture enables precise detection of ethanol concentrations with an effective sensitivity of 64.14% [17]. By identifying fluctuations in the water's RI that affect the fiber's optical transmission qualities, PCF reach a maximum RS of 41%, allowing for accurate liquid (water) detection [18]. PCF's, or microstructure fibers, are fibers of glass having a regular architecture that have the ability to influence light transmission in new and creative ways. They provide increased features like tailored variation, high discontinuity, and customized wavelength filtering by controlling light via their micro-structured construction [19]. A SPR sensor tracks variations in the resonant wavelength of surface plasmon waves to identify variations in the RI close to a metal-coated surface [20]. The sensitivity of a PCF detector was demonstrated in the THz range; however, at 1 THz frequency, the corresponding values for amphetamine, cocaine, and ketamine are 81.42%, 79.8%, and 80.25% [21]. By monitoring changes in the wavelength or brightness of light emitted across the fiber when ethanol alters the RI of the environment with an RS of 85.7% at 1.6 THz, ethanol can be detected using a PCF detector [22].

A THz waveguide or sensor that makes use of cyanide's distinct THz-absorbing properties can be used to detect cyanide at 1.8 THz with an RS of 85.7% [23]. Drawing upon the existing data, it is plausible to devise a fiber that is conducive to fabrication, possesses exceptional intelligence, and employs THz sensors. Additional statistical methods employed to evaluate the effectiveness of sensors are CL and RS. The principal aim of the present inquiry is to create a PCF-based biosensor that is remarkably sensitive, environmentally sustainable, and cost-effective in order to detect cocaine and amphetamine with minimal fabrication complexity. Furthermore, an inquiry was undertaken to examine the propagation properties of the proposed framework, which included a variety of performance indicators such as effective area, high NA, EML, spot size, and CL. The proposed methodology will enable the exploration of an uncharted territory in the realm of drug detection. The alleged optical sensor possesses the capacity to pave the way for uncomplicated and efficacious cancer detection methodologies, serving as a substitute for illicit drug (e.g., cocaine, amphetamine) strategies. The capability to identify illicit substances offers benefits including portability, sensitivity, and selectivity. PCF optical fibers exhibit remarkable qualities and substantial design versatility, rendering them exceptionally well-suited for applications in sensing, including the detection of drugs like cocaine and amphetamine.

Our primary motive was to develop a unique dodecagonal core PCF sensor with a hybrid cladding structure, incorporating both circles and rectangles. The main purpose of this design is to detect illegal drugs such as cocaine and amphetamine with high precision. We specifically selected a dodecagonal core to enhance the sensor's sensitivity, which is crucial for identifying these lethal compounds at low concentrations. This innovative approach aims to improve detection capabilities and contribute to more effective monitoring and control. The PCF sensor demonstrates outstanding relative sensitivities of 99.43% for amphetamine and 99.20% for cocaine at $f = 3$ THz. Such exceptional accuracy allows the sensor to detect illegal drugs even at very low concentrations, which is crucial for accurate and early detection. This capability greatly enhances drug detection, making it possible to identify and address drug-related issues more effectively. By providing more reliable and precise monitoring, the sensor contributes to stronger enforcement efforts and better public safety. Its advanced detection technology plays a vital role in improving drug control measures and safeguarding communities. Environmental elements that might impact light propagation and fiber stability in real-world settings include temperature variations, humidity, and vibration. As a result, the H-PCF may experience performance issues. When compared to fluctuating real-world contexts, laboratory settings typically offer controlled circumstances that limit these impacts, resulting in more consistent and reliable data. The creation of the fiber, which requires sophisticated materials and careful processing, as well as the setup for integration with detecting systems, are included in the anticipated expenses for producing and implementing suggested H-PCF sensors. Infrastructure for calibration, upkeep, and operation is included in deployment expenses. The device is scalable for widespread drug detection application, with possible cost reductions through mass production and breakthroughs in fabrication techniques. However, initial prices may be considerable due to the complexity and precision required.

The PCF sensor for detecting illegal drugs like cocaine and amphetamine starts with introducing the drug solution into the sensor system. The solution interacts with a PCF that is coated with a functionalized layer selective for the target drugs. As light is transmitted through the PCF, the presence of the drugs causes shifts in the optical properties, which are then detected. The changes in the optical signal are processed to quantify and identify the drugs, with the results displayed or recorded for further analysis. Here's a simplified block diagram for the PCF sensor structure designed for detecting illegal drugs such as cocaine and amphetamine shown in Figure 1.

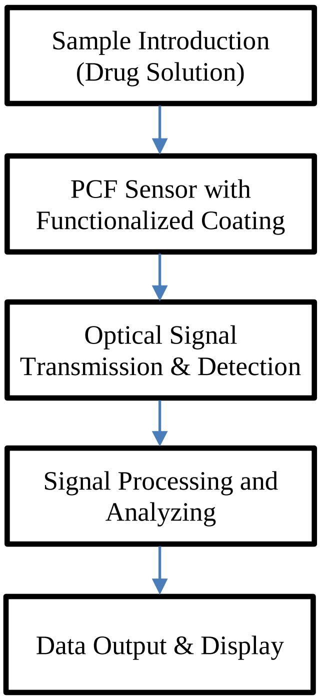


Figure 1. Present the structure of the proposed PCF sensor

2- Research Methodology

The initial phase in designing the H-PCF in COMSOL Multiphysics 5.6 is to define the geometry of the fiber, which includes the core and periodic cladding structure. Next, establish the physics of electromagnetic wave transmission and describe the optical characteristics of materials. After discretizing the fiber model with a mesh, simulate light behavior by solving Maxwell's equations. Evaluate the mode confinement and propagation properties by analyzing the obtained data. In order to satisfy particular performance criteria, use this knowledge to fine-tune the design parameters, such as core size and cladding layout. To identify amphetamines and cocaine in the THz spectrum, this study introduces a hybrid dodecagonal-shaped core PCF detector. Structures made of hybrid photonic crystal fibers allow for improved nonlinear effects, tunable dispersion control, and mode analyses for a wide range of optical uses. The design of this detector incorporates cladding around round and rectangular air holes and a big dodecagon core that is filled with medications. Because of its straightforward design, the dodecagon core is worth considering. In addition to being practically easy to make, dodecagon cores have excellent efficacy. Figure 2(a) shows the longitudinal configuration of the framework. Figure 2(b) shows that pitch (P), the distance within a pair of adjacent air vents, is 120 µm; *Aff* =D/P. With an *Aff* of 0.96 at the structure, light confinement is improved and fabrication is simplified. To customize optical characteristics and sensing capabilities, it is essential to understand the air filling fraction in PCF sensors. This knowledge paves the way for specialized applications in fields like telecommunications, biology, and environmental monitoring. As the affinity grows, so does the sensitivity. The air holes will overlap, nevertheless, when the *Aff is* greater than 0.96. Because of this, an affinity of 0.96 is ideal. For the sensor's backdrop, zeonex was utilized. The many advantages of Zeonex include its ability to withstand high temperatures, its remarkable resilience to chemicals, and its consistent refractive index of 1.53 with only 0.2 cm^{-1} of material loss. Photonic crystal fibers often make use of zeonex, a borosilicate glass, because of its many photonic uses, including their tiny optical losses, excellent resistance to heat, and interoperability, including a broad variety of frequencies. A perfectly matched layer is abbreviated as PML. More accurate simulations are achieved by using circular PML, which successfully decreases false contemplations and guarantees with area specifications that represent the real fiber geometry. A dimensionless parameter that represents the ability of an optical material to bend light is its RI. RI quantifies change in the velocity of light as it passes through different substances in comparison to its velocity in empty space. That describes the material's optical density and how light travels within itself.

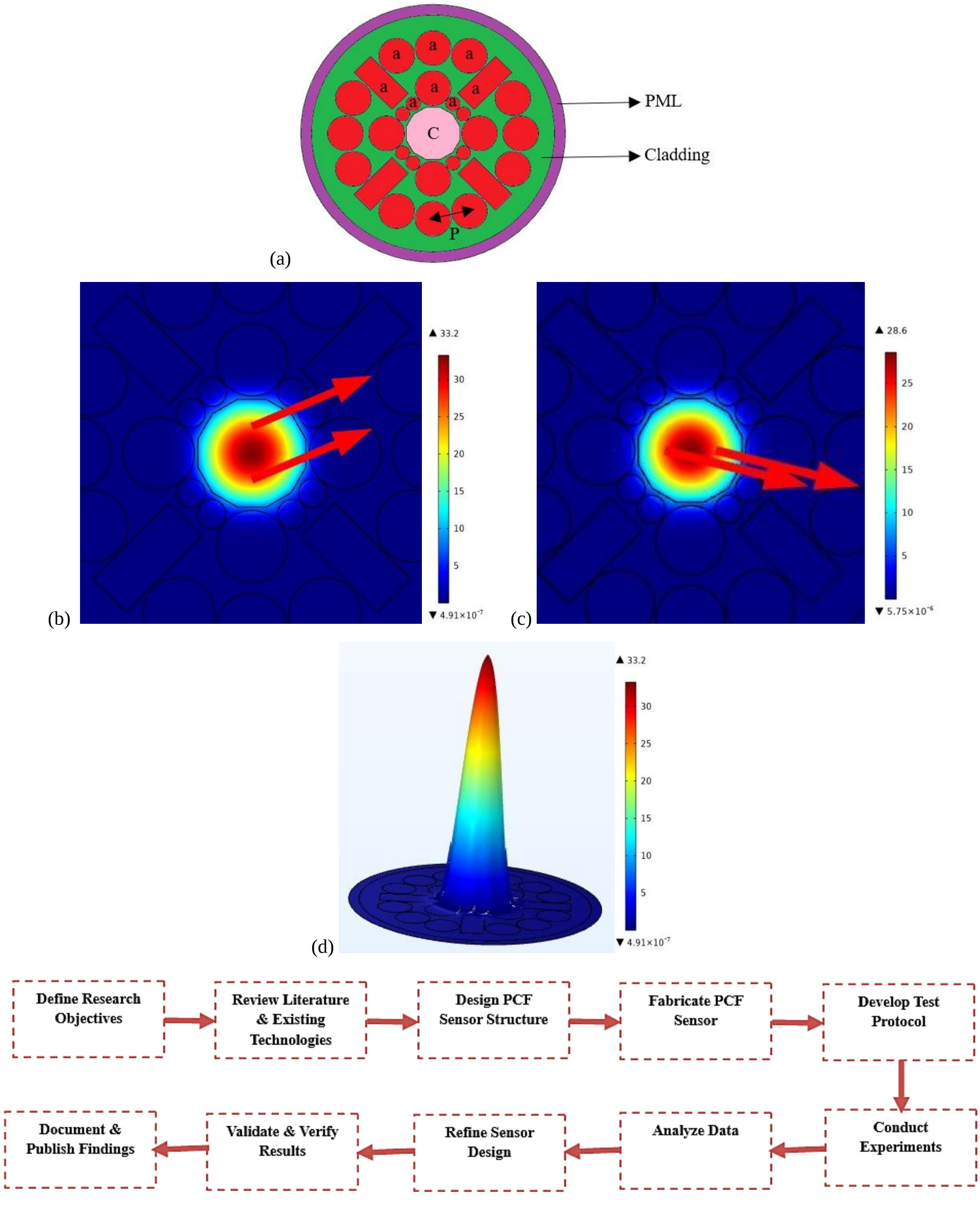


Figure 2. a) Depicts the suggested PCF in sectional dimension; b) Transmission of power for Cocaine at 3 THz; c) Transmission of power for amphetamine at 3 THz; d) Indicate the density distribution where f = 3 THz and *Aff* = 0.96; e) Indicate the flowchart for the research methodology.

For the research methodology Establish goals for detecting cocaine and amphetamine. Investigate current methods and technologies related to PCF sensors and drug detection. Plan the PCF design, select materials, and define the functionalization approach. Manufacture the PCF and apply the functionalized coating. Create protocols for testing the sensor with drug solutions and determining sensitivity. Perform experiments to test the sensor's response to known concentrations of drugs. Evaluate experimental results against standards and assess sensor performance. Make necessary improvements based on experimental findings to enhance sensitivity and accuracy. Ensure the reliability and reproducibility of the results through additional experiments. Record the research outcomes and publish the findings for dissemination. Here's a flowchart for the research methodology of developing the suggested PCF sensor for detecting cocaine and amphetamine, as exhibited in Figure 2(e).

3- Results and Analyses

A potent numerical method for studying and modelling the behaviour of systems and structures of the PCF sensor is the Finite Element Method (FEM). FEM enables extensive modeling of the intricate microstructure and light propagation properties of PCF sensors. FEM provides a precise prediction of the interaction between light and the periodic arrangement of air holes in the PCF by discretizing the fiber into smaller parts. By examining elements like modal propagation and coupling effects, this method aids in optimizing sensor performance, such as sensitivity and accuracy. The versatility of FEM also helps in the creation of PCFs with customized optical characteristics for certain sensing uses. A physical model is discretized into small, finite elements using the Finite Element Method (FEM) in COMSOL Multiphysics. The governing equations for each component are set up and solved, and these are then combined to create a global solution for the entire model. The software offers capabilities for mesh production, boundary condition definition, and material property definition. Its integrated graphical interface allows users to visualize and analyze complicated interactions, making the simulation of various physical phenomena more efficient. The suggested structure was simulated using the computational program COMSOL Multiphysics 5.6. The mesh represents the complete structure of the building, with 156 vertex elements, 1748 boundary elements, and a total of 21376 components, as well as a minimal component standard of 0.4971. To comprehend the sensing properties, such as CL, RS, NA, EML, and *Aff*, one must meticulously evaluate the subsequent components. The lattice depicted in Figure 3 is considered to accurately represent the general layout of the object. Cocaine has a RI of 1.5022, while amphetamine has a RI of 1.518. The difference between the two is substantial.

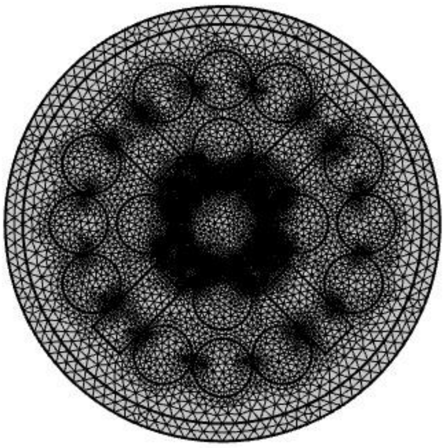


Figure 1. Recommended PCF mesh presentation

Subsequent simulations are performed with different function periods ranging from 2 to 3.8 THz. Making sure system components are functional throughout the expanded range is necessary when expanding a THz detection range to additional frequencies. Higher frequencies provide better resolution but less penetration, while lower frequencies increase penetration but decrease resolution. This necessitates recalibrating and could raise the cost and complexity of the system. Maintaining performance and maximizing detecting capabilities require striking a balance between these parameters. RS is the main measure utilized to evaluate the accuracy of sensors based on optical fiber. In contrast to other components, the sensitivity of a photonic crystal fiber (PCF) is affected by multiple elements such as fiber composition, light intensity, and ambient circumstances. Owing to its vast surface area and compact core, PCF is significantly more susceptible to damage compared to traditional optical fibers. This software technique facilitates a comprehensive comprehension of sensor attributes, including sensitivity (RS), EML, CL, NA, spot size, and effective area. Prior to calculating the RS response, it is vital to determine characteristics associated with the PCF utilized the way it was perceived. The proposed PCF exhibited remarkable sensing capabilities, as seen by its relative sensitivity responses.

The internal light-directing properties of a PCF are ascertained via the dielectric constant of its core, as mentioned before. Any alteration in the refractive index will directly impact the amount of radiation penetrating the center. For a PCF sensor, relative sensitivity quantifies how the sensor's response alters in relation to a change in the measurand. It is commonly described as the ratio of the amount being measured to the change in the output signal of the sensor. RS refers to a degree associated with variation resulting from variations in RI. A high RS value suggests that the sensor is of excellent quality. The relationship between light absorption and the concentration of an absorbing material, as well as the fiber's length, is explained by the Beer-Lambert Law for PCF sensors. The amount of substance present and the length of time light goes through the photonic crystal fiber determine how much light is there and how intense it is. Through the detection of variations in light intensity or wavelength, PCF sensors can use this relationship to determine the concentration of particular analytes. In essence, the rule facilitates the conversion of variations in the optical signal into quantitative measurements of the concentration of the substance, rendering PCF sensors useful for sensitive and accurate detection in a range of applications. Apply the following formula to calculate the RS of each detector [24].

$$r = \frac{n_r}{n_{eff}} \times p\% \tag{1}$$

However, with the exception of the p value, which may be estimated using the following method, and the n_{eff} value, which indicates the lens's refraction index guided mode [24], RI for cocaine has become $n_r = 1.5022$, whereas for amphetamine, it is $n_r = 1.518$.

$$p = \frac{\int_{sample} R_e(E_x H_y - E_y H_x)dxdy}{\int_{total} R_e(E_x H_y - E_y H_x)dxdy} \tag{2}$$

The diagonal magnetic gradients H_x and H_y represent fundamental assisted choice in this context, whereas E_x and E_y represent transverse electrical fields. Polarized patterns that are distinct between Both x as well as y axes have been marked by letters correspondingly. The sensitivity contour when accounting for frequency variations is shown in Figure 4(a). On the suggested PCF-based drug detection sensor, an analysis of the numerical THz regime (2-3.8 THz) was carried out. This sensor's sensitivity was 99.20% for cocaine and 99.43% for amphetamine at its peak pitch. Comparing the reported 99.43% amphetamine and 99.20% cocaine sensitivities to several existing THz detection systems, which typically have sensitivities in the 80–95% range, shows how high the sensitivity is. These high sensitivities imply that the system of detection is quite accurate and successful for these compounds. Plotting shows that optical power attracts more light constriction or analyte at higher frequencies; this attraction peaks at 3 THz. The RS graph is shown with pitch modulation taken into account in Figure 4(b).

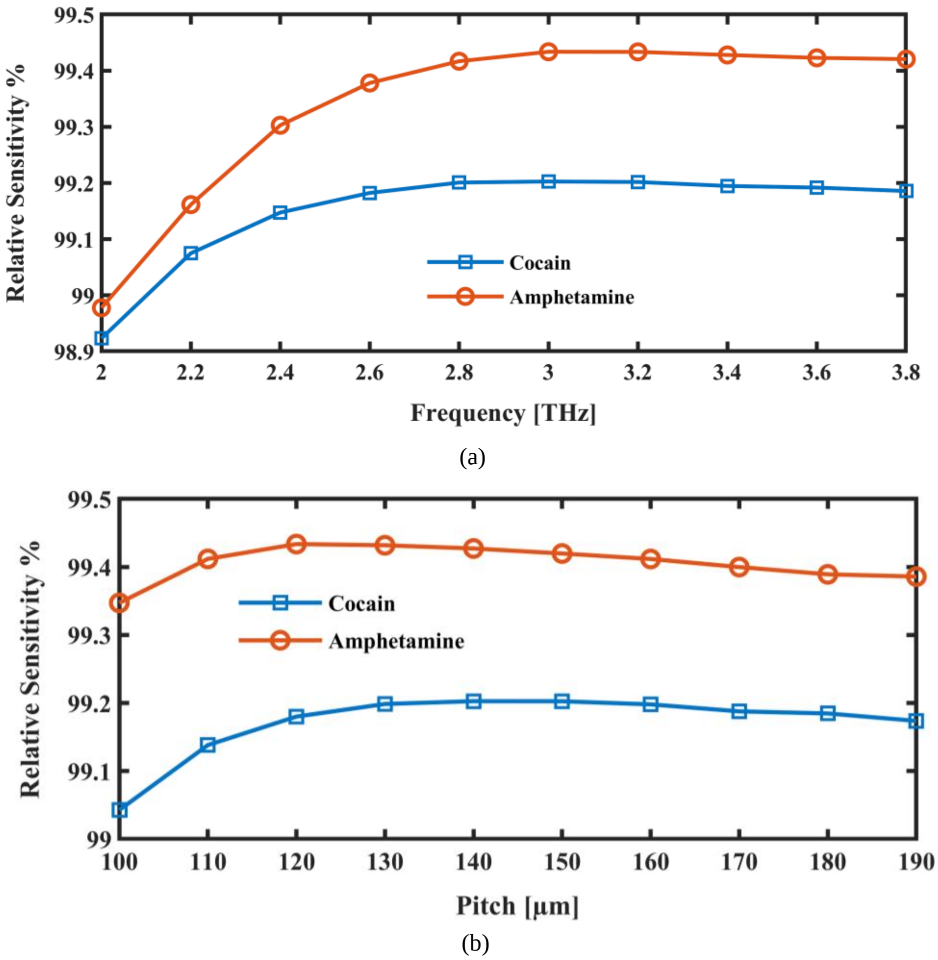


Figure 4. **The proposed sensing analyte's sensitivity with respect with (a) periodicity at fixed distance of 120 Pitching of µm and (b) 3 THz**

The percentage of air-filled (*Aff*) is a measure of the proportion of space occupied by atmosphere or voids within a substance. The subsequent formula is used to compute the worth of *Aff* [25].

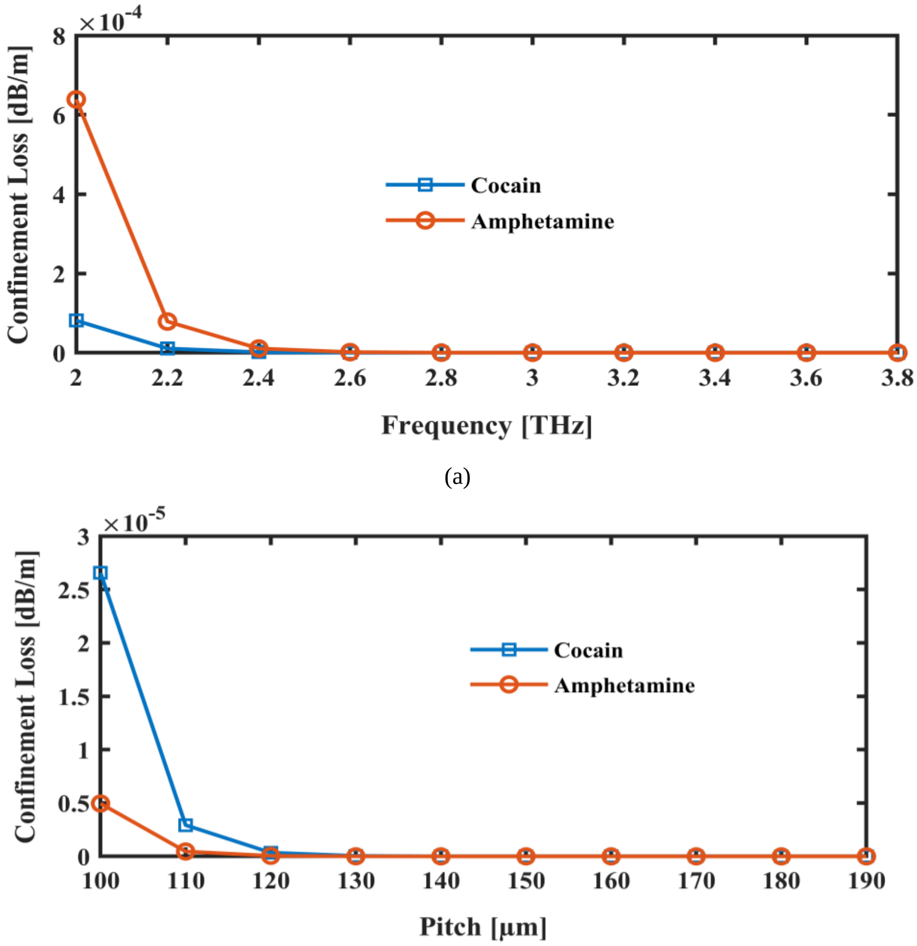
$$Aff = \frac{V_{air}}{V_{total}} \times 100 \quad (3)$$

We maintain the value of *Aff* at 0.96 in this section.

PCF detectors may encounter two forms of losses: confinement loss (CL) and effective material loss (EML). The term CL in a PCF describes the optical power lost during light propagation through the fiber as a result of inadequate confines throughout the core. It happens when light seeps into the sheathing around the core or via the PCF structure's air holes. CL is affected by the PCF's design, which includes the core and cladding's RI contrast, size, and placement of air holes. By lowering light transmission efficiency and affecting signal quality, high CL might deteriorate the PCF's performance. Furthermore, the presence of a rigid substance is the source of the EML, which leads to the absorption of photons by the center. The cumulative effect of expenditures that are reflected and absorbed by the fiber material is referred to as EML in PCF. PCF may experience costs related to substances due to factors such as impurities, defects, and inherent flaws in the fibers. The two types of losses are separated by Equations 4 and 5 [25, 26], respectively:

$$L_c = \frac{40\pi}{ln(10)\lambda} img\left(n_{eff}\right) \times \frac{10^6 dB}{m} \quad (4)$$

In this context, L_c represents confinement loss and Img(n_{eff}) denotes an imaginary value for ERI. Confinement loss may have a detrimental influence on functioning from a PCF detector. Amounts of light that can be transferred from the ends of the fibers to the detecting device or sensor diminish as the confinement loss increases. Whenever assessing the accuracy of the sensor, it is important to take CL into account as well. The loss might be ascribed to system leakage or to the erroneous placement or configuration of the air outputs. To reduce confinement loss, one can opt for materials that have minimal loss and construct with accuracy. A substantial reduction in the quantity of CL is illustrated in Figure 5(b), wherein the pitch is measured in micrometers. In Figure 5(a), correlation within the CL-THz bandwidth is depicted. A reduction in CL quantity is observed as pitch and frequency increase. The sensor fiber exhibits a coefficient of light loss (CL) of 6.16 × 10^{-09} dB/m for cocaine under ideal conditions, whereas it measures 4.93 ×10^{-08} dB/m for amphetamine.



(b)

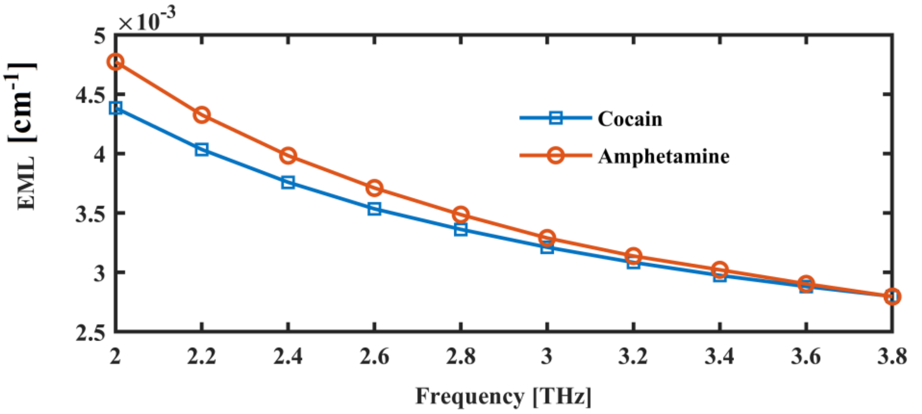
Figure 5. a) Sensing analytes confinement loss at 3 THz pitch modulation and (b) frequency at 120 µm placed pitch

These losses will be experienced by any photonic waveguide. In PCF, intrinsic material absorption and scattering losses within the fiber combine to attenuate light. This is referred to as EML. It represents the entire loss that light incurs while travelling through the structure of the fiber. Since EML affects the efficiency and signal quality of light transmission, it is essential for assessing a PCF's performance. Applications will perform better with lower EML. According to EML, Massive Digestion Damage is a crucial component of THz waveguide monitoring. Assimilation of light energy by the core component is depicted within EML. EML of this detector may have been computed using the following calculation [27].

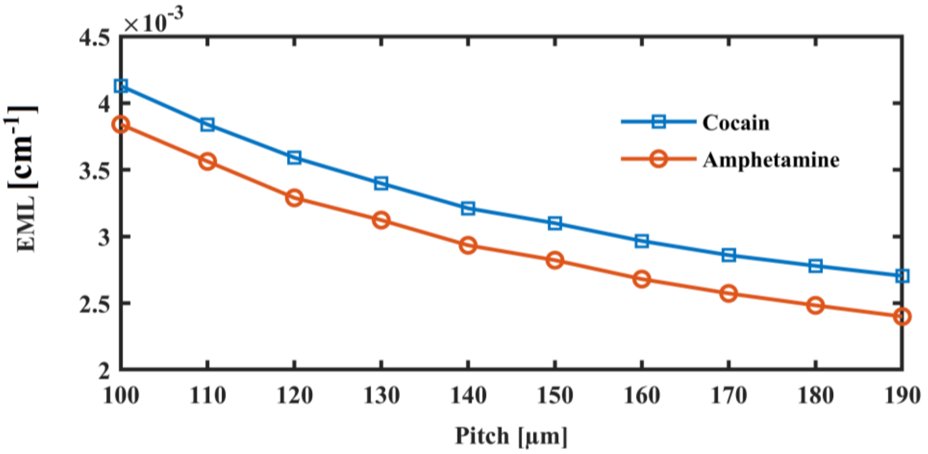
$$\alpha_{eff} = \frac{(\frac{\varepsilon_0}{\mu_0})^{\frac{1}{2}} \int_{A_{max}} n\alpha_{mat}|E|^2 dA}{2\int_{ALL} S_z dA} \tag{5}$$

where, E represents the modulated electric field, whereas α_{mat} signifies the loss coefficient of a strong context element. The loss coefficient is accountable for the element's power reduction.

Figure 6(b) illustrates functional parameters at a range of THz frequencies and wavelengths. Figure 6(a) subsequently illustrates the impact of various architectural styles on EML. The graph depicts loss characteristics that diminish as the core increases. Although the lengthier core of Zeonex permits greater light transmission with fewer obstructions, it also reduces the material's power absorption capacity. Constant and substantial obstructions exist, as was previously demonstrated, regarding the passage of higher-frequency radiation through the core. As a result, we noted that the sensor fiber illustrated in Figure 6(a) demonstrates an exceedingly low extinction coefficient (EML) of 0.0032 cm^{-1} for both cocaine and amphetamine at a frequency of 3 THz. Moreover, as the frequency increases, the EML of the detector under consideration decreases. The sensor's RS and SNR may be significantly compromised due to the depletion of effective material. In light of the fact that minimizing EML is essential for improving the detector's precision and efficacy, it is critical to avoid significant EML. Experimental and theoretical methods are combined to validate the claimed low confinement and effective material loss values. Through direct measurement of attenuation and comparison with expected values, experimental validation is achieved through methods including optical transmission measurements and loss spectroscopy. Utilizing programs such as COMSOL to model and forecast loss characteristics, simulations are used to validate theories. These low loss values indicate greater performance when compared to similar sensors, demonstrating improved efficiency and sensitivity in signal retention and light propagation.



(a)



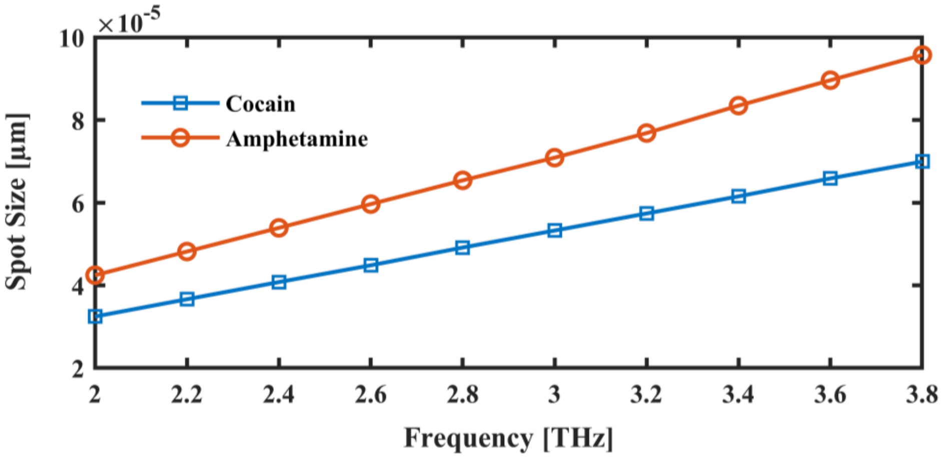
(b)

Figure 6. **The EML of selected detecting substance is shown when (a) the bandwidth with a precise 120 µm pitch and (b) f = 3 THz is the pitch at which**

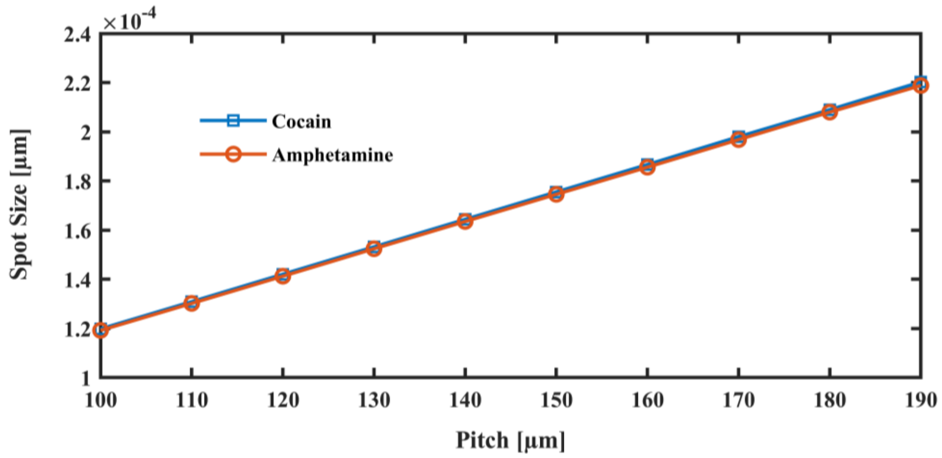
The dimension of the optical phenomenon that a photonic crystal fiber directs. This is what is meant by the term "spot size." Comprehending the extent of light absorption within the fiber core is an essential aspect of optical fiber communications and is regarded as an essential metric. The effective diameter where light is focused and steered is called the spot size in PCF. Smaller spot sizes enhance light contact with the fiber's structure, improving sensor sensitivity. This affects mode confinement. The way light enters and exits the fiber is likewise impacted, as is optical performance and coupling efficiency. Having a well-designed spot size is essential to maximize PCF performance. In order to achieve the most effective interaction with the sensing element, the sensitivity and efficacy of PCF detectors are directly influenced by the spot size. The measurement of the spot size in standard step-index optical fiber is denoted by the abbreviation MFD, which represents the extent of the guided mode. However, the notion of spot size in PCF may be more complex as a result of their intricate and frequently microstructured structure. In order to assess the recommended detector, it is imperative to meticulously contemplate the size of the location. It is suggested that the spot size be increased in order to strengthen the connection between the sample and the radiation during measurements. The calculation method is illustrated by Equation 6 [24].

$$W_{eff} = R \times (.65 \times 1.619 \times V^{-1.5} + 2.789 \times V^{-6}) \tag{6}$$

The central radius (R) and the hollow-acceptable frequency (V) of a component are, respectively, represented by these symbols. The spot size grows more in a straight line as the pitch increases due to a variable core compared to a constant core, as seen in Figure 7(a). During the operation of the PCF sensor, Figure 7(b) shows the fluctuation in spot size induced by differences. Whenever the frequency of operation is raised. The sensor achieved spot size of 1.64×10^{-04} µm and 1.41×10^{-04} µm for cocaine and amphetamine respectively.



(a)



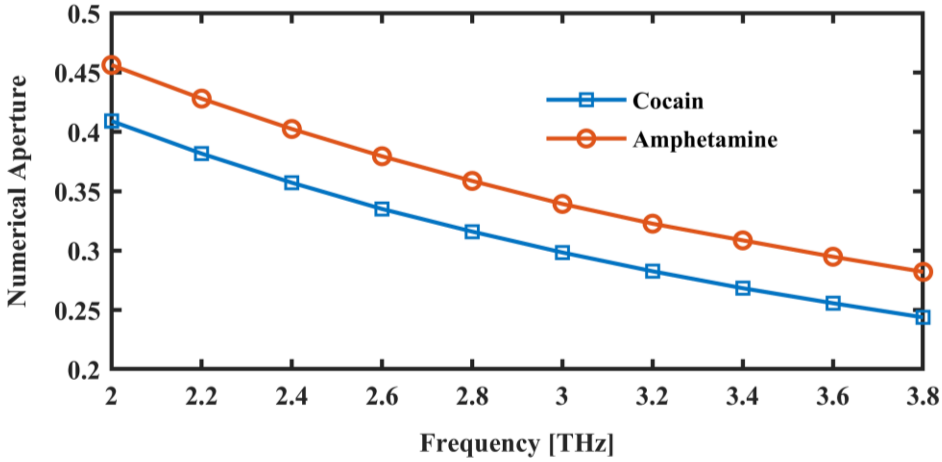
(b)

Figure 7. Demonstrates the change in spot size of the recommended detecting materials when exposed to two different signal frequencies: (a) 120 µm at a specific spacing and (b) 3 THz at a spacing

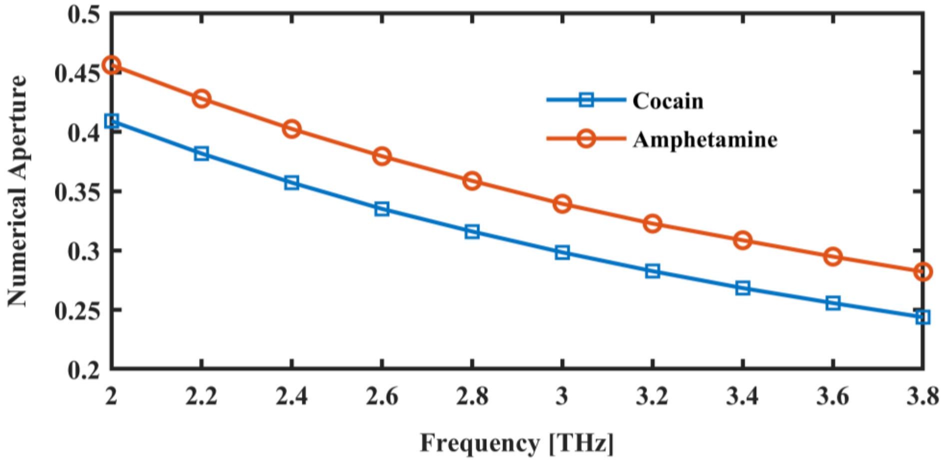
One way to measure a photonic crystal fiber's ability to focus light is by looking at its numerical aperture. The unique structural properties of PCF, as well as the refractive index of the surrounding surroundings and center portion, influence it. There has been a lot of talk about NA in relation to photonic crystal fiber and processes that control the structure of the fiber. An optical system's (such as a lens or fiber) numerical aperture (NA) indicates how well it can gather and transfer light. It influences the effectiveness of light collecting and coupling by reflecting the range of angles over which the system can gather light. In image and sensing applications, a higher NA enhances performance by enabling the capture of more light. It has a wider angle of view for light capture. The NA of a fiber is the highest level of light transmission that can be maintained through its core in a chosen direction. The index of refraction of its surrounding environments and central component is widely used to describe it in the past. An important statistic to consider while analyzing a chosen sensor is NA, which does not have a scale value between 0.32 and 0.5. It controls the maximal quantity of illumination that has been able to come in camera. After plugging the numbers into Equation 7 [25], we get the numerical aperture of the sensor.

$$NA = \frac{1}{\sqrt{1+\frac{\pi A_{eff} f^2}{c^2}}} \approx \frac{1}{\sqrt{1+\frac{\pi A_{eff}}{\lambda^2}}} \tag{7}$$

The variable λ denotes the wavelength under consideration, whereas A_{eff} signifies the effective area encompassing the cells under detection. The correlation between NA and pitch and frequency variations is illustrated in Figures 8(b) and 8(a). It is evident from the data presented in both instances that numerical aperture decreases just like pitch and bandwidth rise. The sensing analyte possesses a NA of 0.298 and 0.339 for cocaine and amphetamine.



(a)



(b)

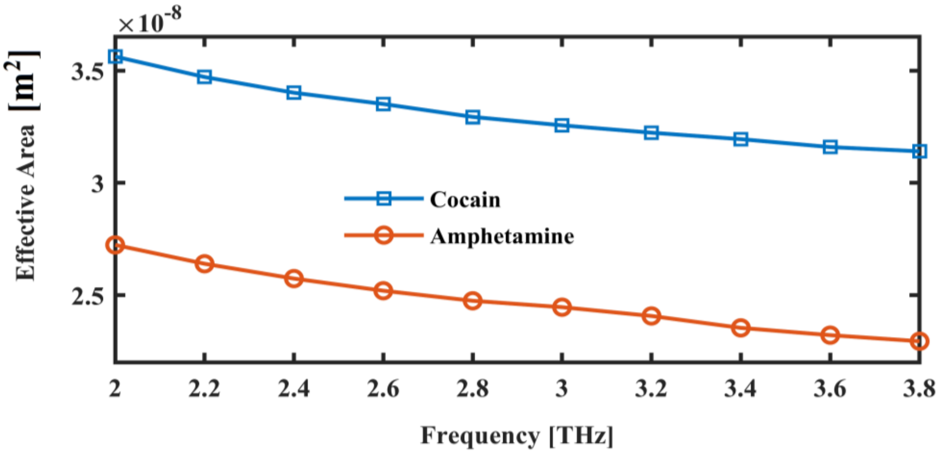
Figure 8. **Illustrates a comparison between the pitch depicted in graph (a) at f = 3 terahertz and the signal frequency (b) 120 micrometers pitch. The NA of the selected sensing agent is also presented**

An estimation of the longitudinal length of a fiber pattern served as an effective mode area. The cross-sectional area that the light is spread and steered over in optical fibers is referred to as the effective area (EA). It is essential for figuring out things like nonlinear effects and signal loss since it affects the fiber's light confinement. While attenuation and nonlinear interactions are reduced by bigger EAs, sensitivity and light concentration can be increased by smaller EAs. For communication and sensing applications, this parameter is essential for maximizing fiber performance. The effective area (A_{eff}) of a sensor comprises its complete signal-passing zone. The microstructure of PCFs enables them to absorb light via photonic band gap and total internal reflection methods. Particle confinement fibers (PCFs) offer numerous advantages over conventional fibers owing to their significantly reduced effective area. The formula provided below computes the effective area [27].

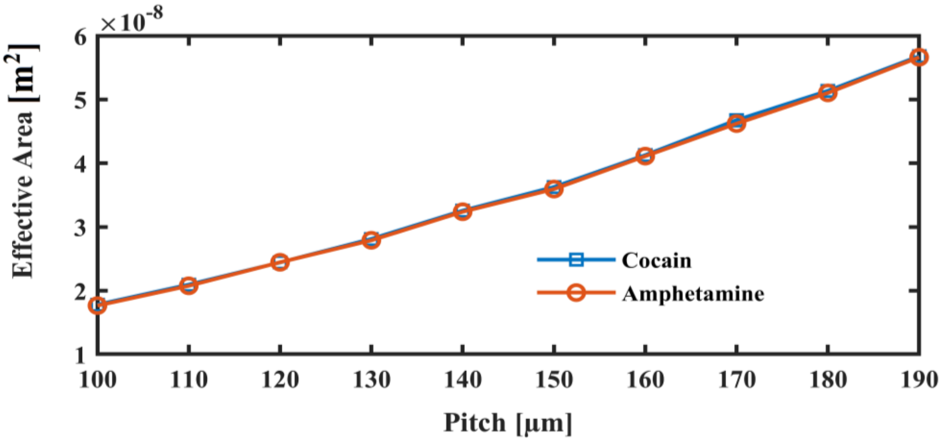
$$A_{eff} = \frac{\left[\int I(r)rdr\right]^2}{\left[\int I^2(r)rdr\right]^2} \quad (8)$$

Symbol $I(r)$ is equal to $|E|^2$. denotes scattering in order to sense cells field of electricity.

The practical region of the aforementioned PCF is demonstrated in Figure 9 for various pitch and frequency configurations. Effective area decreases as operating frequency and pitch increase, as depicted in the image. This indicates that the signal at the nucleus is stronger. At an optimal frequency of 3 THz, this sensor fiber exhibits an effective area of 2.44×10^{-08} m^2 and 3.25×10^{-08} m^2 detects amphetamine and cocaine as well.



(a)



(b)

Figure 9. Demonstrates the correlation between the effective area (*Aeff*) of the chosen monitoring material and (a) the frequency indication at a specific pitch of 120 µm, and (b) the pitch variation with a constant frequency of 3 THz

A list comparing the detection capabilities of specialized optics with those of traditional optics can potentially be obtained by inputting certain criteria. Table 1 provides a clear comparison between the outcomes of this proposed detector development and conventional detectors. Due to technological breakthroughs like the extrusion technique, three-dimensional printing equipment, and sol-gel interpretation, it is now feasible to efficiently manufacture the suggested analyte design utilizing current production techniques. A 3-D printer may create complex forms that are then removed using an extrusion process [29, 30]. While extrusion can be employed for constructing various types of structures, a number of crucial processes are involved in the sol-gel process for creating the proposed H-PCF. First, precursors like silica or other minerals are used to create a sol, which is a colloidal suspension of nanoparticles in a liquid. The solvent is then allowed to evaporate before this sol is spun or extruded into the form of fibers, forming a gel-like structure. To eliminate any leftover solvent and solidify the substance, heat treatments are applied to the gel. Because the gelation and drying processes were precisely controlled, the final H-PCF has a hollow core surrounded by a periodic microstructure.

This method offers scalability and fine control over fiber characteristics for a range of uses. The sol-gel formation process provides more aesthetic flexibility because of its capacity to change the size, placement, and structure of the atmosphere voids. Due to its specific orientation and exclusive utilization of diamond-shaped apertures, the manufacturing process for this sensor will be straightforward. One of the problems in the development of H-PCF is to achieve fine control over the microstructure in order to guarantee homogeneity and ideal confinement of light. Limiting flaws and variances that can affect performance is a requirement for fabrication procedures. To prevent structural damage during processing, it is also essential to control mechanical and thermal stresses. It is more complicated when you have to guarantee a constant quality of materials and scale up the fabrication process without sacrificing performance. According to the reference table supplied, our recommended sensor exhibits exceptional capability in detecting illegal drugs such as cocaine and amphetamine. It has a high level of sensitivity, as supported by the latest research investigations.

Table 1. The suggested device configuration is compared to earlier iterations across various aspects

Reference	The foundation of PCF	Sensitivity (%)	Frequency (THz)	EML (cm^{-1})	CL (dB/m)	NA
PCF [28]	A structure in the shape of a V, a structure in the shape of an H, and extra circular air holes in both.	23.8%	Wavelength, 1 μm	-	-	-
PCF [29]	Fiber optic core and cladding with a microstructure.	42.27%	Wavelength, 1.33 μm	-	4.78345×10^{-6}	-
PCF [24]	Octagonal core with circular air holes.	95.5%	2.2	0.00920	5.10×10^{-13}	0.317
PCF [30]	The cladding region contains four evenly distributed circular airholes.	78.68%	2.2	-	5.1406×10^{-26}	-
PCF [23]	Rectangular air holes	85.6% (water), 85.7% (ethanol), and 85.9% (benzene)	1 – 3 THz	-	4.5×10−9 cm^{-1}, 1.7×10−9 cm^{-1}, 1.02×10−9 cm^{-1}	0.372
PCF [31]	Rectangular core and air holes.	92.2% (Bio-Sensor)	1.5–3.0 THz	0.0117	6.52×10^{-14}	0.194
PCF [32]	Rectangular core and air holes.	94.4% (Chemical)	1.8 THz	0.00859	1.71×10^{-14}	-
This PCF	Dodecagonal-shaped core and circular-shaped air holes	Cocaine	99.20%	3 THz	0.0032 cm^{-1}	6.16×10^{-09} dB/m
		Amphetamine	99.43%	3 THz	0.0032 cm^{-1}	4.93×10^{-08} dB/m

4- Performance Comparison

To compare the efficacy of different PCF sensors in different applications, it is necessary to assess a number of important variables. These variables include Spot Size, RS, CL, EML, NA, and EA. Different PCF sensor designs have different benefits depending on the material and structural characteristics that affect the way the sensor interacts with the measurand. An understanding of each sensor's ability to identify and quantify particular characteristics, including temperature, pressure, biological, or chemical concentrations, can be gained by evaluating these performance criteria. Knowing these distinctions makes it easier to choose the best PCF sensor for a particular application. A model of a PCF sensor was proposed for liquid sensing with an RS of 23.8% at an operating wavelength of 1 μm [28]. Another PCF gas sensor proposed to sense methane and hydrogen fluoride having RS of 42.27% at a wavelength of 1.33 μm and CL of 4.78345×10^{-6} dB/m [29]. Recently a PCF sensor was suggested to identify the fuel admixture with max RS of 95.5% at f = 2.2 THz and EML of 0.0092 cm^{-1} as well as NA of 0.317 [24]. A biosensor was suggested to detect cervical cancer at f = 2.2 THz with RS of 78.68% and CL of 5.14×10^{-26} dB/m [30]. A chemical sensor was proposed to detect chemicals (ethanol, benzene, water) with max RS of 85.9% and NA of 0.372 at f = 1-3 THz [23]. Another biosensor was suggested for the identification of breast cancer with an RS of 92.2%, an EML of 0.0117 cm^{-1}, and an NA of 0.194 [31]. A PCF sensor was proposed for bane chemical with a max RS of 94.4% and CL of 1.71×10^{-14} dB/m [32]. Our suggested sensor was proposed to identify illegal drugs (cocaine, amphetamine). It obtains max RS of 99.20% and 99.43% for cocaine and amphetamine, respectively. It achieved CL and EML of 6.16×10^{-09} dB/m, 0.0032 cm^{-1} and 4.93×10^{-08} dB/m, 0.0032 cm^{-1} for cocaine and amphetamine, respectively. It also achieved NAs of 0.298 and 0.339, respectively.

5- Numerical Modeling

For any PCF sensor to be designed and optimized, numerical modeling is necessary. In order to forecast the PCF's performance prior to physical construction, it entails modeling its optical behavior. Detailed instructions for numerical modeling of the proposed PCF sensor, which is intended to identify illicit substances such as amphetamine and cocaine, are provided below:

- ***Define Objectives and Requirements*:** To comprehend the PCF sensor's sensitivity to variations in the RI brought on by medication interactions, simulate the device. Establish characteristics like the operating environment, target detection limits, and wavelength range (e.g., visible or THz).
- ***Choose a Numerical Method:*** FEM is common for solving complex optical problems involving variable RI and geometries.
- ***Design the PCF Structure:*** Specify the core and cladding structure, air hole arrangements, and periodicity. Input the RI of the materials used, including the core, cladding, and any functionalized coatings.
- ***Develop a Computational Model:*** Use CAD software or simulation tools to create the PCF geometry. Divide the geometry into discrete elements or cells for numerical analysis. Ensure fine mesh in regions with high field gradients.
- ***Implement Optical Properties:*** Input the refractive index profile of the PCF, including variations due to functional coatings. Set appropriate boundary conditions for the simulation, such as periodic boundaries for a repeating structure or perfectly matched layers to absorb outgoing waves.
- ***Run Simulations:*** Compute the propagation constants and field distributions for different modes. Simulate the propagation of light through the PCF, observing how light interacts with the functionalized layer.
- ***Analyze Optical Responses:*** Calculate how the PCF transmits and reflects light across different wavelengths. Analyze how changes in the refractive index (due to drug interactions) affect the optical properties of the PCF.
- ***Optimization:*** Adjust geometrical and material parameters to optimize sensitivity and performance. Evaluate the sensor's response to small changes in refractive index and optimize the design to enhance detection capabilities.
- ***Validation:*** Validate numerical results against theoretical models or experimental data if available. Ensure that the PCF sensor can accurately detect the target substances with the desired specificity and sensitivity.
- ***Refinement and Documentation:*** Make necessary adjustments based on validation results to improve accuracy and performance. Prepare detailed documentation of the modeling process, results, and any design modifications.
- ***Preparation for Fabrication:*** Confirm the final design parameters and prepare for physical fabrication based on the optimized model. Ensure that all design aspects are verified and ready for practical implementation.

6- Conclusion

The initial phase in designing the H-PCF in COMSOL Multiphysics 5.6 is to define the geometry of the fiber, which includes the core and periodic cladding structure. COMSOL utilizes the FEM for the modeling of the PCF. The H-PCF comprises a dodecagonal core and hybrid air gaps in cladding areas. A number of crucial processes are involved in the sol-gel process for creating the proposed H-PCF. One of the problems in the development of H-PCF is to achieve fine control over the microstructure in order to guarantee homogeneity and ideal confinement of light. The primary application for this sensor is the detection of illicit narcotics like cocaine and amphetamines. At 3 THz, amphetamine and cocaine have relative sensitivities of 99.43% and 99.20%, respectively, and CL of 4.93×10^{-08} dB/m and additionally 6.16×10^{-09} dB/m, respectively. Additionally, EML is found to be 0.0032 cm <1. Such exceptional accuracy allows the sensor to detect illegal drugs even at very low concentrations, which is crucial for accurate and early detection. This capability greatly enhances drug detection, making it possible to identify and address drug-related issues more effectively. By providing more reliable and precise monitoring, the sensor contributes to stronger enforcement efforts and better public safety. Environmental elements that might impact light propagation and fiber stability in real-world settings include temperature variations, humidity, and vibration. As a result, the H-PCF may experience performance issues. The device is scalable for widespread drug detection application, with possible cost reductions through mass production and breakthroughs in fabrication techniques. However, initial prices may be considerable due to the complexity and precision required.

7- Declarations

7-1- Author Contributions

Conceptualization, K.S.N. and A.H.M.I.F.; methodology, K.S.N., M.M.B., and S.I.; software, K.S.N., M.M.B., and S.I.; validation, A.H.M.I.F., J.H., and A.A.; formal analysis, N.U.B.; investigation, N.U.B.; resources, A.H.M.I.F.; data curation, K.S.N.; writing—original draft preparation, K.S.N. and S.I.; writing—review and editing, A.A. and N.U.B.; visualization, J.H.; supervision, J.H.; project administration, A.H.M.I.F.; funding acquisition, J.H. and A.A. All authors have read and agreed to the published version of the manuscript.

7-2- Data Availability Statement

The data presented in this study are available in the article.

7-3- Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7-4- Institutional Review Board Statement

Not applicable.

7-5- Informed Consent Statement

Not applicable.

7-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

8- References

[1] Russell, P. (2003). Photonic crystal fibers. science, 299(5605), 358-362. doi:10.1126/science.1079280.

[2] Hossain, M. S., Sen, S., & Hossain, M. M. (2021). Performance analysis of octagonal photonic crystal fiber (O-PCF) for various communication applications. Physica Scripta, 96(5), 55506. doi:10.1088/1402-4896/abe323.

[3] Habib, M. A., Reyes-Vera, E., Villegas-Aristizabal, J., & Anower, M. S. (2020). Numerical modeling of a rectangular hollow-core waveguide for the detection of fuel adulteration in terahertz region. Fibers, 8(10), 63. doi:10.3390/fib8100063.

[4] Russell, P. S. J. (2006). Photonic-crystal fibers. Journal of Lightwave Technology, 24(12), 4729-4749.

[5] Wong, W. C., Zhou, W., Chan, C. C., Dong, X., & Leong, K. C. (2012). Cavity ringdown refractive index sensor using photonic crystal fiber interferometer. Sensors and Actuators, B: Chemical, 161(1), 108–113. doi:10.1016/j.snb.2011.09.056.

[6] Habib, M. A., & Anower, M. S. (2019). Design and numerical analysis of highly birefringent single mode fiber in THz regime. Optical Fiber Technology, 47, 197–203. doi:10.1016/j.yofte.2018.11.006.

[7] Habib, A., Rashed, A. N. Z., El-Hageen, H. M., & Alatwi, A. M. (2021). Extremely Sensitive Photonic Crystal Fiber–Based Cancer Cell Detector in the Terahertz Regime. Plasmonics, 16(4), 1297–1306. doi:10.1007/s11468-021-01409-6.

[8] Russell, P. S. J., Hölzer, P., Chang, W., Abdolvand, A., & Travers, J. C. (2014). Hollow-core photonic crystal fibres for gas-based nonlinear optics. Nature Photonics, 8(4), 278–286. doi:10.1038/nphoton.2013.312.

[9] Ferdous, A. H. M. I., Anower, M. S., & Habib, M. A. (2021). A hybrid structured PCF for fuel adulteration detection in terahertz regime. Sensing and Bio-Sensing Research, 33, 100438. doi:10.1016/j.sbsr.2021.100438.

[10] Habib, M. A., Reyes-Vera, E., Villegas-Aristizabal, J., & Anower, M. S. (2020). Numerical modeling of a rectangular hollow-core waveguide for the detection of fuel adulteration in terahertz region. Fibers, 8(10), 1–17. doi:10.3390/fib8100063.

[11] Yang, T., Ding, C., Ziolkowski, R. W., & Guo, Y. J. (2021). An Epsilon-Near-Zero (ENZ) Based, Ultra-Wide Bandwidth Terahertz Single-Polarization Single-Mode Photonic Crystal Fiber. Journal of Lightwave Technology, 39(1), 223–232. doi:10.1109/JLT.2020.3022719.

[12] Siegel, P. H. (2004). Terahertz technology in biology and medicine. IEEE Transactions on Microwave Theory and Techniques, 52(10), 2438–2447. doi:10.1109/TMTT.2004.835916.

[13] Lounkine, E., Keiser, M. J., Whitebread, S., Mikhailov, D., Hamon, J., Jenkins, J. L., Lavan, P., Weber, E., Doak, A. K., Côté, S., Shoichet, B. K., & Urban, L. (2012). Large-scale prediction and testing of drug activity on side-effect targets. Nature, 486(7403), 361–367. doi:10.1038/nature11159.

[14] Reyes-Vera, E., Usuga-Restrepo, J., Jimenez-Durango, C., Montoya-Cardona, J., & Gomez-Cardona, N. (2018). Design of Low-loss and Highly Birefringent Porous-Core Photonic Crystal Fiber and Its Application to Terahertz Polarization Beam Splitter. IEEE Photonics Journal, 10(4), 5900413. doi:10.1109/JPHOT.2018.2860251.

[15] Ho, L., Pepper, M., & Taday, P. (2008). Signatures and Fingerprints. Nature Photonics, 2(9), 541-543. doi:10.1038/nphoton.2008.174.

[16] Hossain, M. S., Sen, S., & Hossain, M. M. (2020). Design of a chemical sensing circular photonic crystal fiber with high relative sensitivity and low confinement loss for terahertz (THz) regime. Optik, 222, 165359. doi:10.1016/j.ijleo.2020.165359.

[17] Paul, B. K., Ahmed, K., Asaduzzaman, S., & Islam, M. S. (2017). Folded cladding porous shaped photonic crystal fiber with high sensitivity in optical sensing applications: Design and analysis. Sensing and Bio-Sensing Research, 12, 36–42. doi:10.1016/j.sbsr.2016.11.005.

[18] 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. doi:10.1016/j.sbsr.2018.100252.

[19] Bise, R. T., & Trevor, D. J. (2005). Sol-gel derived microstructured fiber: Fabrication and characterization. Conference on Optical Fiber Communication, Technical Digest Series, 3, 269–271. doi:10.1109/ofc.2005.192772.

[20] 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(2), 489–496. doi:10.1007/s11468-016-0289-z.

[21] Tahhan, S. R., & Aljobouri, H. K. (2023). Sensing of Illegal Drugs by Using Photonic Crystal Fiber in Terahertz Regime. Journal of Optical Communications, 44(s1), S505–S515. doi:10.1515/joc-2019-0291.

[22] Islam, M. S., Sultana, J., Dinovitser, A., Ahmed, K., Ng, B. W. H., & Abbott, D. (2018). Sensing of toxic chemicals using polarized photonic crystal fiber in the terahertz regime. Optics Communications, 426, 341–347. doi:10.1016/j.optcom.2018.05.030.

[23] Islam, M. S., Sultana, J., Ahmed, K., Islam, M. R., Dinovitser, A., Ng, B. W. H., & Abbott, D. (2018). A novel approach for spectroscopic chemical identification using photonic crystal fiber in the terahertz regime. IEEE Sensors Journal, 18(2), 575–582. doi:10.1109/JSEN.2017.2775642.

[24] Ferdous, A. H. M. I., Noor, K. S., Balamurugan, K., Ramkumar, G., Kumar, C. R., Mohan, S. B., Xavier, B. M., Hossain, M. S., Noor, S. Z. E., Sathi, B. N., Rashed, A. N. Z., & Hossain, A. (2023). Terahertz spectrum petrochemical sensing: a photonic crystal fiber refractive index hybrid structure approach. Journal of Optics (India). doi:10.1007/s12596-023-01553-8.

[25] Shobug, M. A., Noor, K. S., Sagaya Raj, A. G., Ramkumar, G., Padmanaban, P., Mallan, S., Ferdous, A. H. M. I., Bani, M. M., & Rashed, A. N. Z. (2024). Fuel quality assurance based on hybrid hexagonal circular hollow core PCF sensing through management of terahertz region operation. Journal of Optics (India), 1-16. doi:10.1007/s12596-024-01756-7.

[26] Iftekharul Ferdous, A. H. M., Noor, S. Z. E., Kalpana Devi, P., Kavitha, K. R., Anitha, G., Jayakumar, T., ... & Ahammad, S. H. (2024). Unlocking insights of oil derivatives with terahertz spectrum analysis: the hybrid refractive index rectangular core photonic crystal fiber perspective sensing. Journal of Optics, 53(4), 3655-3665. doi:10.1007/s12596-023-01520-3.

[27] Bani, M. M., Noor, K. S., Ferdous, A. I., & Anower, M. S. (2024). High- performance photonic crystal fibre biosensor for identifying Jurkat cells by refractive index analysis. IET Nanodielectrics. doi:10.1049/nde2.12086.

[28] Ademgil, H., & Haxha, S. (2015). PCF based sensor with high sensitivity, high birefringence and low confinement losses for liquid analyte sensing applications. Sensors (Switzerland), 15(12), 31833–31842. doi:10.3390/s151229891.

[29] Morshed, M., Imran Hassan, M., Roy, T. K., Uddin, M. S., & Abdur Razzak, S. M. (2015). Microstructure core photonic crystal fiber for gas sensing applications. Applied Optics, 54(29), 8637. doi:10.1364/ao.54.008637.

[30] Srivastava, D., Yadav, S., Mishra, A. C., Singh, S., Lohia, P., & Dwivedi, D. K. (2024). Numerical study of photonic crystal fiber-based optical biosensor for detection of cervical cancer. Journal of Optics (India), 53(2), 1155–1162. doi:10.1007/s12596-023-01254-2.

[31] Bulbul, A. A. M., Rahaman, H., Biswas, S., Hossain, M. B., & Nahid, A. Al. (2020). Design and numerical analysis of a PCF-based bio-sensor for breast cancer cell detection in the THz regime. Sensing and Bio-Sensing Research, 30, 100388. doi:10.1016/j.sbsr.2020.100388.

[32] Hossain, M. B., Podder, E., Bulbul, A. A. M., & Mondal, H. S. (2020). Bane chemicals detection through photonic crystal fiber in THz regime. Optical Fiber Technology, 54, 102102. doi:10.1016/j.yofte.2019.102102.