

RESEARCH ARTICLE



A Novel Square-Core Photonic Crystal Fiber Sensor with Enhanced Sensitivity for Trace-Level Detection of Agricultural Pesticides

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Abstract: This study proposes and numerically evaluates a terahertz (THz) photonic crystal fiber (PCF) sensor with a hexagonal cladding structure and a square-shaped core for ultra-sensitive pesticide detection. The numerical results demonstrate exceptionally high relative sensitivities for ten commonly used pesticide chemicals, namely methyl parathion, dimethoate, methomyl, empenhrin, terallethrin, cyphenothrin, prallethrin, fenvalerate, cypermethrin, and allethrin. Among them, cypermethrin exhibits the lowest confinement loss of 7.84×10^{-14} dB/m with the relative sensitivity of 99.93177% at the optimum frequency of 1.7 THz, indicating excellent sensing performance. It is proven that the proposed square-core configuration significantly enhances the light-analyte interaction, leading to improved sensing performance for the detection of different pesticide analytes based on their individual optical responses. The proposed PCF structure shows strong potential for high-precision pesticide detection by distinguishing different analytes based on their refractive index-dependent optical responses and promising applications in industrial terahertz waveguide technologies, as well as in real-time agricultural monitoring and food production systems, to detect pesticide residues, ensuring improved crop safety, food quality, and environmental protection.

Keywords: PCF sensor, pesticide chemical detection, finite element method (FEM), sensitivity

1. Introduction

The development of advanced sensing platforms with improved accuracy, sensitivity, and immediate response is required due to the continually rising demand for quick and dependable sensing technologies in every aspect of life. In this context, compared to other standard types of sensing, optical sensing approaches have emerged as an effective method for detecting chemical, biological, and physical parameters due to their inherent advantages in high sensitivity, rapid response, and immunity to electromagnetic interference. These techniques rely on the interaction between light and matter, where variations in optical properties such as intensity, phase, wavelength, or polarization are used to infer changes in the surrounding environment. Compared to conventional electrical sensing methods, optical sensors offer non-invasive operation, remote sensing capability, and enhanced precision in harsh or complex environments and in particular photonic crystal fiber (PCF)-based sensors provide exceptional control over optical properties such as confinement loss, birefringence, and relative sensitivity [1–3]. Due to their flexible structural configuration, PCFs can be efficiently engineered via versatile design

strategies, allowing precise tuning of their guiding and sensing properties [4]. Consequently, PCFs are widely used in different kinds of sensing applications, including chemical detection, alcohol sensing, identification of harmful food additives, pesticide monitoring, and environmental analysis [5–7]. In this paper, a hexagonal lattice PCF (H-PCF) sensor is designed to detect and monitor the specific agricultural pesticide chemicals namely, methyl parathion ($C_8H_{10}NO_5PS$), dimethoate ($C_5H_{12}NO_3PS_2$), methomyl ($C_5H_{10}N_2O_2S$), empenhrin ($C_{18}H_{26}O_2$), terallethrin ($C_{17}H_{24}O_3$), cyphenothrin ($C_{24}H_{25}NO_3$), prallethrin ($C_{19}H_{24}O_3$), fenvalerate ($C_{25}H_{22}ClNO_3$), cypermethrin ($C_{22}H_{19}Cl_2NO_3$), and allethrin ($C_{19}H_{26}O_3$) [8].

In the field of agriculture and industry, these chemicals play an important role in protecting crops and improving agricultural productivity [9, 10]. The selected pesticides belong to three major classes of insecticides: organophosphates, carbamates, and pyrethroids [11, 12]. Methyl parathion and dimethoate are organophosphate insecticides widely used in agriculture. Methyl parathion is commonly applied to protect cotton crops from pests [13, 14], but it is highly toxic and can easily penetrate the skin, which makes accidental exposure very dangerous for humans and animals. It can also accumulate in soil for a certain period, increasing the risk of long-term environmental contamination.

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Dimethoate acts internally by being absorbed into plant tissues and controls aphids, mites, and other sap-sucking insects through both contact and ingestion [15], but it can move quickly through plant systems and may remain in plant tissues for a certain period before breaking down. Its breakdown products can sometimes remain active, which makes monitoring even more important after application. Methomyl, a carbamate insecticide, provides rapid control of a broad range of insects, including caterpillars and beetles, by disrupting nerve signal transmission [16]. In addition, several synthetic pyrethroids such as emperthrin, terallethrin, cyphenothrin, prallethrin, fenvalerate, cypermethrin, and allethrin are widely employed in public health and agriculture because of their rapid knockdown impact against flies, mosquitoes, and insects that harm crops [17, 18]. These pyrethroids operate on sodium channels in the insect nervous system, leading to paralysis and death [19]. While some pyrethroids are primarily applied to field crops for long-lasting protection, others are commonly used in mosquito coils, vaporizers, and sprays for household pest control [20]. Together, these chemicals contribute significantly to pest management strategies by reducing insect populations, protecting crop yield, and supporting healthier agricultural production systems [21]. Although pesticides are commonly used in agriculture to shield crops from weeds, insects, and plant diseases, overuse of them can leave toxic chemical residues in food, soil, and water [22, 23]. Detecting pesticide chemicals is therefore essential to monitor contamination levels and ensure that they remain within safe limits for human consumption and environmental safety. To address this issue, optical sensing techniques are widely used because they provide high sensitivity, rapid response, and accurate detection of very small concentrations of chemicals [24–28]. In particular, sensors based on PCF enable strong interaction between light and the analyte, making them highly effective for real-time pesticide detection in agriculture, food safety monitoring, and environmental protection.

At present, terahertz (THz) radiation is extensively employed in several significant fields, including medical diagnostics, biophotonics, bioinformatics, chemical sensing, and communication technologies [29, 30]. The THz frequency range extends from 0.1 to 10 THz, which is placed between the microwave and infrared regions of the electromagnetic spectrum. A standard THz sensing system generally comprises three essential components: a source, a detector, and a waveguide [31]. However, conventional THz waveguides face several technological problems due to high material loss in the THz region, which reduces signal transmission efficiency [32]. They also have poor light confinement and are difficult to fabricate and modify for advanced sensing applications. To overcome these limitations, PCF is considered a better choice because it offers flexible design, improved light confinement, and stronger interaction between light and the sensing material [33].

Consequently, numerous research areas have concentrated on optimizing PCF geometries through numerical simulation techniques to enhance these key sensing characteristics [34–38]. In particular, hollow-core photonic bandgap (PBG) configurations are well suited for sensing purposes [39]. Moreover, versatile background materials such as Topas, silica glass, and Zeonex are widely utilized in PCF fabrication, enabling high relative sensitivity, low confinement loss, and improved performance parameters, including effective mode index, birefringence, and total power fraction for chemical sensing applications [40–42].

In this study, the proposed H-PCF structure is developed specifically for pesticide chemical sensing applications, with the goal of attaining high relative sensitivity and minimal confinement loss [43, 44]. The proposed sensor's distinct square-shaped

core is combined within a hexagonal cladding structure, which greatly improves the interaction between the guided THz wave and the analyte. Additionally, the proposed design demonstrates exceptionally high relative sensitivity and ultra-low confinement loss for ten different pesticide analytes through their individual refractive index-dependent optical responses, with enhanced light–analyte interaction compared to conventional PCF designs [45]. The detection analysis confirms that the proposed structure is highly effective, enabling the identification of pesticide chemicals with exceptional sensitivity and accuracy, even at very low concentrations.

The proposed structure offers a number of advantages over previously published THz-PCF chemical sensors, such as improved light–analyte interaction due to its square-shaped core geometry, better relative sensitivity approaches, and ultra-low confinement loss. In addition, the sensor enables the detection of ten different pesticide analytes using a single design while maintaining a simple and fabrication-friendly configuration. These features make the proposed PCF a promising alternative to existing sensing platforms for agricultural and environmental monitoring applications.

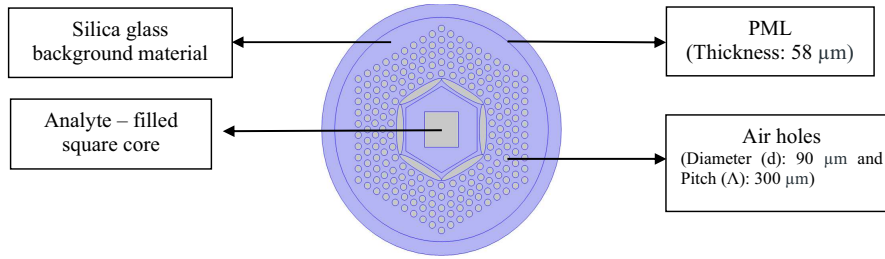
The remaining sections are arranged as follows: Section II describes the geometrical design of the proposed PCF sensor. The subsequent section presents the performance analysis along with the results and detailed discussion. The final section presents the conclusion of the study and the future scope is outlined.

2. Geometrical Configuration

In order to improve light confinement within the core and enhance the interaction between the guided mode and the analyte region, geometric alterations are usually included when building a PCF. Such structural tailoring should help in suppressing electromagnetic leakage, thereby reducing confinement loss [46]. Consequently, the overall propagation characteristics must be improved, making the design more suitable for high-performance sensing applications. With all of these goals in consideration, the developed PCF is made up of a precisely built hexagonal lattice structure with alterations in the core region aimed at attaining high sensitivity with minimum confinement loss in sensing applications. The cross-sectional view of the proposed H-PCF is illustrated in Figure 1. The cladding region is arranged in a hexagonal lattice pattern comprising five concentric layers of circular air holes with a diameter of 90 μm and a cladding pitch of 300 μm is maintained, while the central region contains a square-shaped core with a side length of 950 μm . To further enhance the sensing performance, additional ellipsoidal and hexagonal features are incorporated around the square core.

Note that the structural parameters were optimized through a systematic parametric analysis to achieve an optimal balance between sensing performance, optical confinement, numerical accuracy, and fabrication feasibility. The air-hole diameter was altered between 50 μm and 100 μm . Diameters less than 50 μm lowered the air-filling fraction, worsened the refractive index contrast between the analyte-filled core and cladding, and degraded mode confinement and light–analyte interaction. In contrast, diameters exceeding 100 μm resulted in excessively thin silica bridges, leading to mechanical instability and potential merging of adjacent air holes, thereby compromising the integrity of the photonic crystal lattice. Based on these constraints, an optimized air-hole diameter of 90 μm was selected. Similarly, the PML thickness was optimized through convergence analysis, and a thickness

Figure 1
The schematic cross-sectional view of the proposed hexagonal lattice PCF



of 58 μm was adopted to ensure complete absorption of outgoing electromagnetic waves while minimizing numerical reflections.

Figure 1 shows the schematic cross-sectional view of the proposed hexagonal lattice PCF, including the analyte-filled square core, surrounding air holes, silica glass background, and PML. The core region is selectively filled with ten different analyte pesticide chemicals namely, Methyl Parathion ($n = 1.56$), Dimethoate ($n = 1.475$), Methomyl ($n = 1.503$), Empenthrin ($n = 1.4836$), Terallethrin ($n = 1.500$), Cyphenothrin ($n = 1.5504$), Prallethrin ($n = 1.510$), Fenvalerate ($n = 1.5655$), Cypermethrin ($n = 1.5648$), and Allethrin ($n = 1.506$) [13, 16, 19].

Figure 2 shows the elliptical geometry with semi-major axis (a) of 675.2 μm and semi-minor axis (b) of 100 μm is used to define the ellipsoidal features inserted around the square core. A full elliptical sector of 360° is considered in the proposed structure. The positions of the ellipsoidal elements are arranged around the square core by varying their x- and y-coordinates according to the location of the surrounding hexagonal features.

The detailing of the core structure is explicitly depicted in Figure 3, and Figure 4 shows the triangular mesh of the proposed PCF. A fine triangular mesh was generated throughout the computational domain using the physics-controlled mesh option. The final mesh consisted of 80498 elements with 563671 degrees of freedom (DOF). The proposed PCF has an overall dimension of 2942 μm . The structural parameters of the proposed PCF were optimized through extensive parametric simulations using COMSOL Multiphysics. To find the best compromise between relative sensitivity and confinement loss, several air-hole diameters and PML thicknesses were methodically examined. Based on the optimization results, an air-hole diameter of 90 μm and a PML thickness of 58 μm were selected, as these values provided the highest relative sensitivity together with minimum confinement

loss and stable mode confinement. The background substrate material used for the H-PCF is silica glass.

Figure 3
The square-core structure of H-PCF fiber

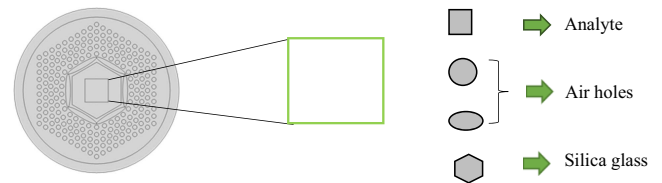


Figure 5 shows the optical confinement of the proposed PCF. By using cladding air holes and a PML boundary, the design effectively traps light in the core while minimizing confinement loss with the total internal reflection mechanism.

3. Performance Evaluation

The finite element method (FEM) in COMSOL multiphysics was used to do the numerical analysis of the suggested PCF sensor. FEM is a powerful technique in which the cross-section of the photonic crystal fiber is divided into large number of small finite elements. Maxwell's equations are then solved over these elements to accurately determine the electromagnetic field distribution and modal properties of the fiber. This approach enables accurate modeling of the intricate air-hole geometry of the proposed PCF while maintaining high numerical precision. To ensure reliable simulation results, an eigenmode analysis was performed

Figure 2
Position and rotation of the six elliptical air holes surrounding the core in the proposed PCF structure

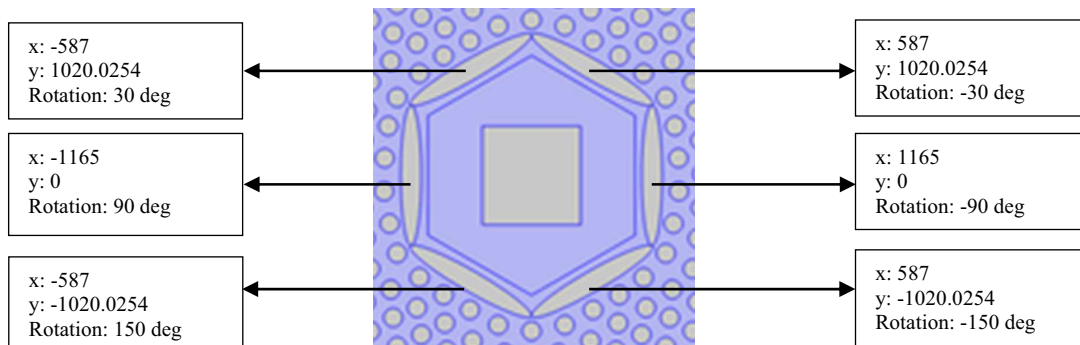


Figure 4
Triangular mesh of the proposed PCF

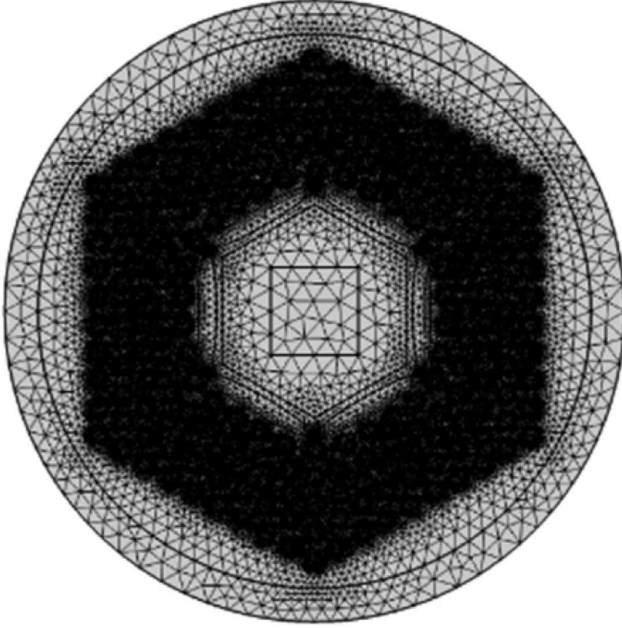
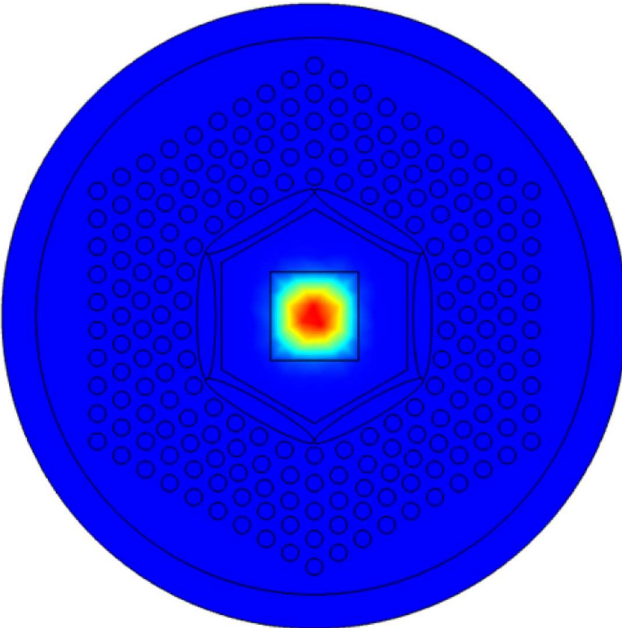


Figure 5
Optical confinement of the PCF



to compute the complex effective refractive index and guided mode profiles. The simulated modal field distributions were subsequently used to evaluate the performance such as confinement loss, analyte power fraction, and relative sensitivity of the proposed sensor. The performance metrics were calculated using the derived modal solutions at frequencies ranging from 0.5 to 1.7 THz. Additionally, details regarding the mesh generation, eigenmode analysis, and the perfectly matched layer (PML) have been provided to improve the clarity and reproducibility of the simulation methodology. The expressions used to determine the

suggested PCF sensor's sensing performance are taken from the formulation described in [47, 48].

Confinement loss, sometimes referred to as leakage loss, is one of a PCF's main guiding characteristics. It describes the amount of optical power that leaks from the fiber core into the surrounding cladding region during light propagation. Hence, the confinement (leakage) loss, represented as (L_c), can be calculated using the following expression,

$$L_c = 8.686 \times K_0 \times \text{Im}(n_{\text{eff}}) \text{ (dB/m)} \quad (1)$$

$K_0 = \frac{f}{c}$, where f denotes the frequency and c denotes the speed of light. The term $\text{Im}(n_{\text{eff}})$ corresponds to the imaginary part of the effective refractive index, which accounts for the attenuation of the guided mode.

Birefringence measures the change in the propagation velocity of light depending on its polarization orientation as it travels through a material, and it is expressed as,

$$B = |n_{\text{eff}}^x - n_{\text{eff}}^y| \quad (2)$$

where n_{eff}^x is the effective mode index of x polarization and n_{eff}^y is the effective mode index of y polarization.

The key parameter in evaluating sensor performance is its relative sensitivity. This parameter indicates the proportion of the guided THz power that effectively interacts with the analyte material. Therefore, the relative sensitivity is expressed as,

$$S = \frac{n_r}{n_{\text{eff}}} \times P \text{ (\%)} \quad (3)$$

where n_r is the refractive index of the analyte filled in the core. n_{eff} is the effective refractive index of the guided mode and P is the power fraction.

The power fraction in the PCF represents the portion of electromagnetic energy that is confined within the analyte region, reflecting the degree of light-analyte interaction. The power fraction (η) is defined as:

$$\eta = \frac{\int_i S_z dA}{\int_{\text{all}} S_z dA} \quad (4)$$

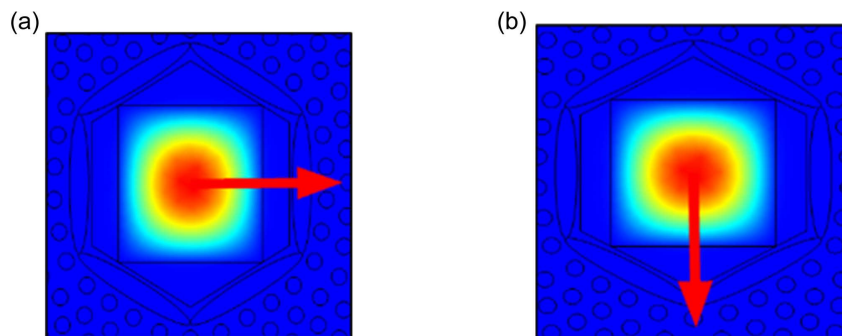
Here, the region in the numerator integral represents the specific area such as the core, cladding, or air holes, depending on the parameter being evaluated. In contrast, the denominator integral is taken over the entire cross-sectional area of the fiber structure.

4. Results and Discussions

COMSOL multiphysics was used to perform all numerical simulations in the terahertz frequency range of 0.5 to 1.7 THz. Figure 6 depicts the electric field distribution at 1 THz, emphasizing the modal behavior of the proposed fiber structure. The figure compares the two polarization states namely the x and y-polarized mode, to understand how the electromagnetic field propagates within the fiber. From the field profile, it is clear that the proposed design effectively confines the electromagnetic energy within the central square core.

This tight confinement improves the interaction between the guided THz wave and the analyte, resulting in improved overall

Figure 6
(a) Mode of x polarization and (b) Mode of y polarization



sensing performance for the device. Because the x- and y-polarized modes exhibit slightly different field distribution patterns, they show variations in sensitivity and confinement loss characteristics. These variations show the stability and effectiveness of the suggested H-PCF sensor design and offer more information about the modal characteristics of the structure. Moreover, the comparative evaluation of these polarization-dependent responses enables a deeper understanding of anisotropic behavior within the waveguide. Such analysis is essential for optimizing the structural parameters to achieve improved sensing accuracy and robust device performance under varying operational conditions.

Table 1 compares confinement loss and sensitivity of different insecticides from three pesticide groups, namely pyrethroid, organophosphates, and carbamates, based on their confinement loss and sensitivity performance. Among them, fenvalerate exhibits the highest sensitivity of 99.94%, indicating superior sensing performance. In contrast, cypermethrin has the lowest confinement loss of 7.84×10^{-14} dB/m, suggesting better light confinement characteristics. Organophosphate pesticides such as methyl parathion and dimethoate show comparatively higher confinement losses and slightly lower sensitivity than most pyrethroids, suggesting relatively weaker field confinement. Methomyl, the only carbamate listed, shows moderate confinement loss and slightly lower sensitivity compared to top-performing pyrethroids, placing it in an intermediate performance range. The pyrethroid group demonstrates consistently high

sensitivity (mostly above 99%) with relatively low confinement losses, indicating stable and reliable sensing behavior within this category.

In terms of operating frequency, target analytes, relative sensitivity, and confinement loss, Table 2 compares the suggested sensor with recently published THz photonic crystal fiber (PCF)-based chemical sensors. To the best of our knowledge, although a few optical fiber biosensors, SPR fiber sensors, and Photonic crystal sensors have been reported to detect pesticides, particularly for compounds such as methyl parathion and methomyl, no photonic crystal fiber (PCF)-based chemical sensor has been reported for the detection of agricultural pesticides. Existing THz-PCF sensors have primarily focused on conventional chemicals, food additives, and other hazardous compounds. In contrast, the proposed square-core hexagonal lattice PCF extends the application of THz-PCF sensing to ten agriculturally important pesticide chemicals, namely methyl parathion, dimethoate, methomyl, empenethrin, terallethrin, cyphenothrin, prallethrin, fenvalerate, cypermethrin, and allethrin. Furthermore, the proposed design achieves a maximum relative sensitivity of 99.94% with an ultra-low confinement loss of 7.84×10^{-14} dB/m over the 0.5–1.7 THz operating range, demonstrating its potential as a high-performance platform for pesticide detection.

Figure 7 depicts the fluctuation in confinement loss (dB/m) with frequency (THz) for ten distinct pesticide compounds in the core region of a PCF. The confinement loss values remain extremely low, generally between 10^{-12} and 10^{-14} dB/m across the

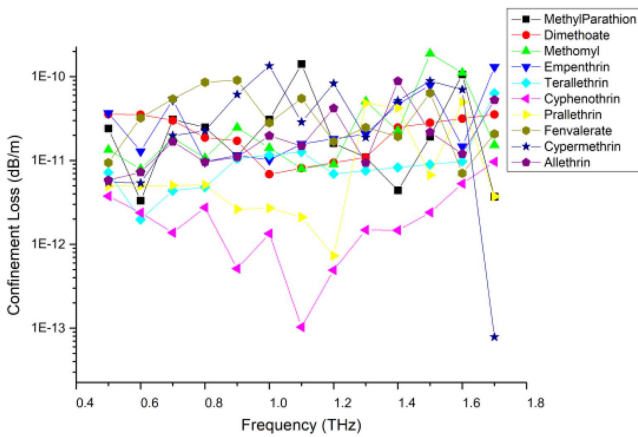
Table 1
Comparison table of high sensitivity and minimum confinement loss values for all ten pesticide chemicals

S. No.	Chemicals	Pesticides	Pesticide group	Confinement Loss (dB/m)	Highest Sensitivity (%)
1.	Methyl Parathion	Insecticide	Organophosphate	3.32×10^{-12}	99.91
2.	Dimethoate	Insecticide	Organophosphate	6.84×10^{-12}	97.30
3.	Methomyl	Insecticide	Carbamate	7.92×10^{-12}	99.20
4.	Empenthrin	Insecticide	Pyrethroid	9.63×10^{-12}	98.26
5.	Terallethrin	Insecticide	Pyrethroid	1.98×10^{-12}	99.10
6.	Cyphenothrin	Insecticide	Pyrethroid	1.03×10^{-13}	99.86
7.	Prallethrin	Insecticide	Pyrethroid	7.29×10^{-13}	99.37
8.	Fenvalerate	Insecticide	Pyrethroid	7.04×10^{-12}	99.94
9.	Cypermethrin	Insecticide	Pyrethroid	7.84×10^{-14}	99.93
10.	Allethrin	Insecticide	Pyrethroid	5.81×10^{-12}	99.28

Table 2
Comparative table summarizing the performance of the proposed sensor with previously reported PCF-based sensors for other chemicals

Reference	PCF structure	Operating frequency	Application/Analyte	Relative sensitivity (%)	Confinement loss (dB/m)
[31]	Hexagonal PCF	1 THz	Ethanol, Benzene, and Water	81.46%, 82.26%, and 79.22%	5.85×10^{-08} dB/m, 6.07×10^{-08} dB/m, and 5.84×10^{-08} dB/m
[35]	Liquid infiltrated PCF	1 THz	Cocaine	87.02%	1×10^{-4} dB/m
[37]	Circular PCF	1 THz	Ethanol, Butanol, and Propanol	86.60%, 88.70%, and 84.71%	5.75×10^{-08} dB/m, 6.11×10^{-08} dB/m, and 5.70×10^{-08} dB/m
[44]	Hollow core PCF	2 THz	Saccharin, Sorbitol, and Butyl acetate	98.65%, 91.35%, and 92.66%	7.70×10^{-13} dB/m, 2.49×10^{-12} dB/m, and 1.95×10^{-12} dB/m
Proposed work	Square-Core hexagonal lattice PCF	0.5–1.7 THz	Ten agricultural pesticide chemicals	99.94%	7.84×10^{-14} dB/m

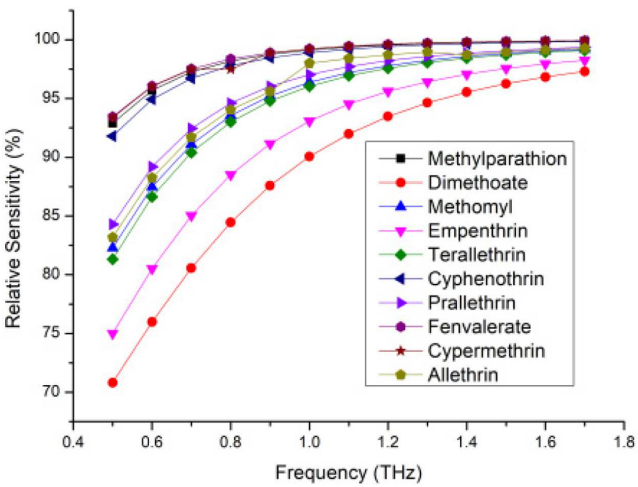
Figure 7
Frequency vs. confinement loss



frequency range of 0.5 to 1.7 THz, indicating efficient light confinement within the fiber core. Among the analytes, cypermethrin exhibits the minimal confinement loss of 7.84×10^{-14} dB/m. This shows the effectiveness of the proposed PCF sensor for pesticide chemical detection. Figure 8 shows the variation of relative sensitivity (%) with frequency (THz) for ten different pesticide chemicals in the core of the PCF. It is observed that the relative sensitivity gradually increases as the frequency rises from 0.5 THz to 1.7 THz for all analytes. At higher frequencies, the sensitivity reaches 99%, indicating a more intense interaction between the guided terahertz wave and the pesticide samples. Among the compounds examined, fenvalerate had the highest sensitivity of 99.94% at 1.7 THz. This demonstrates the superior sensing performance of the proposed PCF.

Figure 9 shows the variation of power fraction with frequency (THz) for different pesticide chemicals in the core

Figure 8
Frequency vs. relative sensitivity



of the PCF. It is observed that the power fraction increases steadily as the frequency rises from 0.5 THz to 1.7 THz for all analytes. At higher frequencies, the power fraction approaches almost one (or 100%), suggesting that the majority of the electromagnetic radiation is strongly bound within the analyte-filled core region. This behavior indicates a strong interaction between the pesticide compounds and the propagating THz signal. Notably, among the analytes, cypermethrin exhibits one of the highest power fraction values among the tested analytes, highlighting its stronger confinement characteristics within the core region. Figure 10 shows the variation of effective mode index with frequency (THz) for different pesticide chemicals in the core of the PCF. The effective mode index gradually climbs from 0.5 THz to 1.7 THz for all analytes. This increase indicates improved electromagnetic field confinement and stable wave propagation within

Figure 9
Frequency vs. power fraction

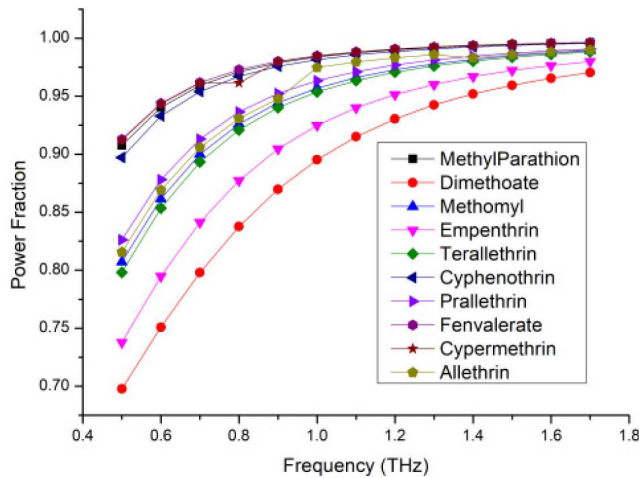
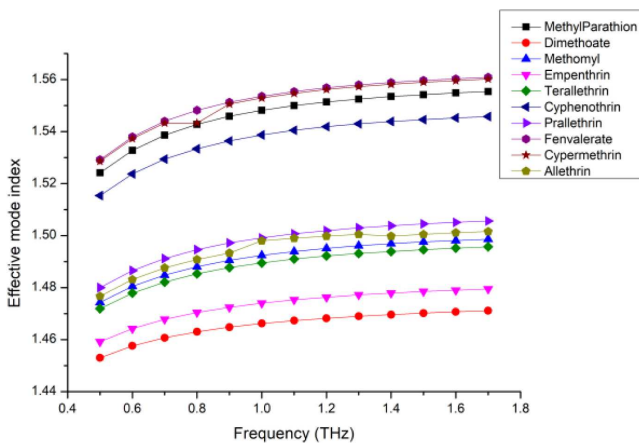


Figure 10
Frequency vs. effective mode index



the fiber core. The variation in the effective mode index among the analytes occurs due to their different refractive indices. Among them, cypermethrin and fenvalerate exhibit comparatively higher effective mode index values, indicating stronger light-analyte interaction and effective guiding performance of the proposed sensor. Furthermore, the smooth variation of the effective index with frequency indicates low modal dispersion within the considered operating range. This behavior is advantageous for maintaining signal integrity and achieving reliable sensing performance in practical applications.

5. Fabrication Considerations

The proposed PCF structure is numerically designed, and its geometry can be realized using existing fabrication techniques such as the extrusion method, stack-and-draw method, sol-gel casting, and advanced 3D-printing-assisted fabrication processes. The main fabrication challenge lies in maintaining the dimensional accuracy of the square-shaped core and the surrounding micro-structured regions during the drawing process. Confinement of the mode and sensing performance may be slightly influenced by changes in air-hole diameter, pitch, or core

shape. However, since the proposed design is based primarily on circular air holes and a simple square-core configuration, it is comparatively less complex than many recently reported PCF geometries. Therefore, the structure is expected to be practically feasible with current micro-structured fiber fabrication technologies.

6. Conclusion

The detailed design and analysis of a hexagonal PCF with a square-shaped core, specifically developed to detect pesticide chemicals in the THz frequency operating range is proposed in this piece of work. The structure is carefully modeled using the FEM with PML boundary conditions. To evaluate the sensing performance metrics, the proposed fiber is evaluated using the refractive index values of ten commonly used pesticide chemicals, namely methyl parathion, dimethoate, methomyl, emperthrin, terallethrin, cyphenothrin, prallethrin, fenvalerate, cypermethrin, and allethrin. The simulation results indicate that the designed H-PCF provides the maximum relative sensitivity, reaching nearly 99% at 1.7 THz operating range. Among the tested analytes, cypermethrin exhibits the minimal confinement loss of 7.84×10^{-14} dB/m, and fenvalerate shows the highest relative sensitivity, achieving 99.94% at 1.7 THz, highlighting the excellent sensing performance of the PCF sensor. At the same time, the fiber maintains extremely low confinement loss, which is essential for stable and efficient signal transmission.

Unlike conventional hexagonal lattice PCFs with simple circular or solid cores, the proposed design employs an engineered central sensing region consisting of a square analyte-filled core integrated with hexagonal and ellipsoidal features. These structural modifications introduced are the key inclusions that increases the overlap between the guided THz mode and the analyte while preserving strong optical confinement. Consequently, the suggested architecture achieves enhanced relative sensitivity and reduced confinement loss, validating its suitability for high-performance THz chemical sensing.

The present analysis is limited to individual pesticide analytes. Simultaneous identification of multiple analytes would require dedicated multi-channel or multi-core PCF architectures or advanced spectroscopic data analysis techniques which falls beyond the scope of the present study. Overall, the suggested fiber shows great potential as a reliable and efficient sensing platform for accurate pesticide detection and monitoring, which makes it ideal for cutting-edge agricultural and environmental safety applications.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

B. Swaathy: Methodology, Formal analysis, Data curation, Writing – original draft. **R. Niranjana:** Methodology, Validation, Formal analysis, Data curation, Writing – review & editing. **Ancem Joseph:** Conceptualization, Validation, Visualization, Supervision, Project administration, Funding acquisition. **P. Mohanraj:** Validation, Writing – review & editing.

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