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Design and Fabrication of a Hollow-Core Photonic Crystal Fiber Sensor for Different Edible Oils

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Abstract

In this work, a sensor for cooking oils was designed and fabricated for the first time using hollow-core photonic crystal fiber (HC-PCF). This sensor was studied practically, and the results showed a difference in sensitivity depending on the type of oil. The results showed that the wavelength shift occurred with very small changes in the refractive index of the edible oil. The confinement loss was computed. Seven oils with various refractive indices were utilized. Based on our results, the relative sensitivity to various kinds of Canola oil, Sunflower oil, Olive oil, Walnut oil, Sesame oil, Corn oil, and Wheat oil are 79.9321%, 80.1588%, 77.4523%, 77.4889%, and 77.5650%, 77.6652%, 80.5902% respectively. Moreover, the proposed sensor also has low confinement losses of 6.473×10^{-9}dB/m, 1.158×10^{-9}dB/m, 1.2×10^{-9}dB/m, 1.20×10^{-9}dB/m, 1.199×10^{-9} dB/m, 1.2×10^{-9}dB/m, and 6.347×10^{-9}dB/m respectively. This sensor can be used to measure the quality of oils and distinguish their types, and they can be a practical element in oil detection systems, which will bring about a change in the future in oil detection methods.

Keywords: Hollow-Core Photonic Crystal Fiber, Editable Oils, Photonic Crystal Fiber Biosensors, Confinement Loss.

تصميم وتصنيع حساس من الألياف الكريستالية الضوئية المجوفة لتمييز الزيوت الصالحة للأكل المختلفة

بتول هاشم قنبر,احمد كمال احمد

الخلاصة:

في هذا العمل، تم تصميم وتصنيع مستشعر لزيوت الطهي لأول مرة باستخدام ألياف الكريستال الضوئي المجوفة (HC-PCF).تم دراسة هذا المستشعر عمليًا، وأظهرت النتائج وجود اختلاف في الحساسية اعتمادًا على نوع الزيت. كما أظهرت النتائج أن الإزاحة في الطول الموجي تحدث نتيجة تغييرات صغيرة جدًا في معامل الانكسار للزيوت الصالحة للأكل. تم حساب خسائر الحصر. وقد تم استخدام سبعة أنواع من الزيوت ذات معاملات انكسار مختلفة. بناءً على نتائجنا، فإن الحساسية النسبية لأنواع مختلفة من الزيوت كانت كالتالي: زيت الكانولا ٧٩,٩٣٢، زيت دوار الشمس ٨٠,١٥٨%، زيت الزيتون ٧٧,٤٥٢%، زيت الجوز ٧٧,٤٨٨%، زيت السمسم ٧٧,٥٦٥%، زيت الذرة ٧٧,٦٦٥%، وزيت القمح ٨٠,٥٩%.علاوة على ذلك، أظهر المستشعر المقترح خسائر حصر منخفضة لكل من هذه الزيوت، وكانت على التوالي: ٦,٤٧٣×١٠$^{-٩}$ ، ١,١٥٨×١٠$^{-٩}$ ، ١,٢×١٠$^{-٩}$ ، ١,٢×١٠$^{-٩}$dB/m ، ١,١٩٩×١٠$^{-٩}$ ، ١,٢×١٠$^{-٩}$ ، و ٦,٣٤٧×١٠$^{-٩}$. يمكن استخدام هذا المستشعر لقياس جودة الزيوت والتمييز بينها، مما يجعله عنصرًا عمليًا في أنظمة الكشف عن الزيوت، وقد يحدث تغييرًا مستقبليًا في طرق الكشف عن الزيوت.

1 -Introduction

Edible oils are crucial in the kitchen since they enhance flavor and aid in cooking and frying. However, picking the healthiest oil is difficult owing to the numerous options accessible and their similar appearance. The greatest oils for health are those that include unsaturated fats and have a high smoke point. Oils such as olive oil and sunflower oil contain antioxidants and vitamins like vitamin E and omega-6, which help with memory[1]. Canola oil contains less saturated fat and is suitable for high-heat cooking. Sesame oil includes monounsaturated fats, which

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boost immunity[2]. Edible oils include vitamin K, which is necessary for blood clotting and bone health [3].On the other hand, excessive omega-6 in some oils may harm health[4]. With the presence of fake or chemically enhanced oils in the market, identifying pure and healthy oils is essential to reduce health risks, especially for people with heart conditions.

Since its inception in 1996, Photonic Crystal Fiber (PCF) has made substantial advances in photonic sensing and communication. Its unique optical qualities, such as indefinite single-mode operation, bigger core area, high transparency, design flexibility, and low loss, have allowed for the creation of cutting-edge telecommunications technology. PCFs are essential for both active and passive optical devices [8-9]. Furthermore, because of their high sensitivity and small size, PCF-based sensors are commonly employed in real-world applications such as chemical detection, biological analysis, and cancer diagnostics. Hollow-core PCFs (HC-PCFs) are very useful in sensing gasses, oil, blood, and alcohol [5,6,7,10,11].

Ahmad K. Ahmad and Zeina Khalifa [12] presented two types of HC-PCF for use as a blood biosensor in 2020, employing (HC19-1550 and HC-1550) overfilled with different bio-liquids like pentanol, liver blood, colon blood, and epidermis blood, using COMSOL Multiphysics. Their findings show that as the refractive index (RI) increases, so does the effective mode index. At the same time, the minimum value of confinement loss decreases and shifts to shorter wavelengths for the two types of PCF, allowing the PCF amplitude sensitivity to be computed.

Md. Ahasan Habib et.al. in 2021 [18], proposed a HC-PCF with a hexagonal structure was used as an alcohol sensor. The sensor showed a relative sensitivity of about 87%, and a confinement loss of 10^{-10}dB/m.

Mahmoud M. A. Eid et.al. in 2021 [19], To identify the various components of human blood, they used the COMSOL Multiphysics to design a HC-PCF sensor.

This research produced a frequency spectrum between 1.5 and 3 THz, with decreased absorption and confinement loss and higher relative sensitivity and numerical aperture.

In 2021 Ahasan Habib et al, [5]. Cancer cell detectors are numerically investigated; cancer cells have different refractive indices. This sensor achieved in the terahertz regime, at 2.5THz, shows a significant 98% relative sensitivity with a low loss of about <0.025 dB/cm and a high numerical aperture and spot size.

In 2023 A.H.M. Iftekharul Ferdous et.al. [13]. Development and analysis of a novel sensor for detecting edible oils using terahertz frequency range. The study aims to design an HC-PCF sensor operating in the THz range to detect edible oils. The sensor design involves a hybrid structure with a square hollow core. The suggested sensor reveals a high relative sensitivity of 98.45% to different edible oils at an optimum frequency of 1.8 THz. The sensor achieves shallow effective material loss (0.004632 cm^{-1}) and confinement loss (1.07×10^{-15} dB/m).

A review of various research collections revealed that most of the studies are numerical or computational. They compute relative sensitivity and confinement losses for various elements, such as liquids, gases, biomaterials, or edible oil measurements, using COMSOL or other software. Due to the limited experimental research in this area, conducting experiments using the HC-PCF as a sensor for seven distinct edible oils is recommended. Our findings demonstrate the value of employing HC-PCF to identify and differentiate between various kinds of oil and their qualities. This work is the first attempt to design and fabricate an HC-PCF sensor for edible oils. This suggested sensor will be a competitive tool for applications involving the detection of edible oil. Further studies could explore the trade-offs between different oils and optimize the HC-PCF design for targeted applications.

2 -Hollow-Core PCF Fibers (HC-PCF)

In this research, HC-PCF (HC-800B), as shown in Figure (1), was used as a sensor for edible oil; the clad diameter was 132.4μm, and the diameter of the core was 47.94μm as clear in the SEM photos in Figure (1). The fiber hole was full of oils; seven types of edible oils with different refractive indices, measured using a portable refractometer, were used (canola, sunflower, olive, walnut, sesame, corn, and wheat). Table (1) presents the measured refractive index using a refractometer (BOE (32400) digital ABBE Refractometer, 220V with aluminum carrying case), along with reference data from various sources. The measured refractive indices are observed to fall within the range reported in different references.

Table (1). Refractive index for edible oils

Oil	Refractive index [measured at room temp.]	Refractive index [14, 15]
wheat	1.4628	1.465 - 1.475
olive	1.4668	1.467 - 1.470
walnut	1.4705	1.469 - 1.476
corn	1.4719	1.470 - 1.474
canola	1.4728	1.465 - 1.467
sunflower	1.4739	1.469 - 1.475
sesame	1.4762	1.465 - 1.469

a

Confinement losses are the amounts of light that escape from the HC-PCF's core because of imperfect confinement. Low confinement losses are preferable for efficient light transmission. Air provides negligible guidance for light, resulting in relatively large confinement losses (3.5876×10^{-6}). Edible oils have much smaller confinement losses (1.1587×10^{-9} for sunflower and 6.3470×10^{-9} for wheat). This suggests that edible oils improve light confinement over air,

Relative sensitivity quantifies the HC-PCF's capacity to identify alterations in the surrounding medium. Sensing applications prefer higher sensitivity. The edible oils' relative sensitivities vary from 77.4523 (olive) to 80.5902 (wheat). The sensitivity of most oils is around the same as or slightly higher than that of air, with wheat oil exhibiting the highest sensitivity. As a result, it is possible that the oils improve the HC-PCF's ability to sense changes in refractive index.

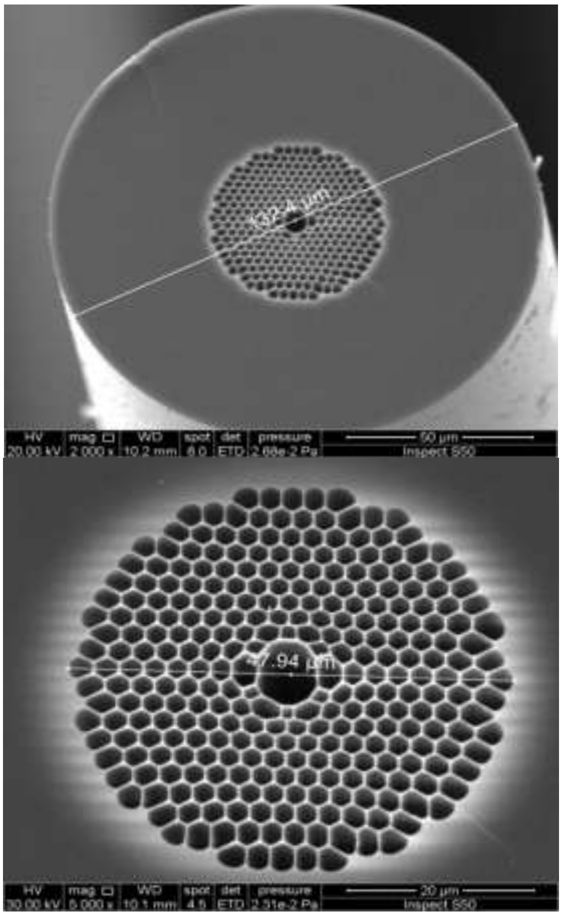


Figure (1): SEM (HRSEM FEI Inspect F50, USA), Picture for HC-800B a)in 2000×mag. b)5000×mag

3-Experimental Work

Following the refractive index measurements shown in Table 1, an experimental process was carried out with the HC-800B hollow-core photonic crystal fiber (HC-PCF) as the sensing element. The fiber's hollow core was filled with seven different edible oils through capillary action [16]: canola, sunflower, olive, walnut, sesame, corn, and wheat. The optical properties, such as wavelength shift and confinement loss, were investigated using a 650 nm Diode laser and an optical spectrometer. The experimental results revealed variations in wavelength shifts and confinement losses as a function of each oil's refractive index. These findings support the HC-PCF sensor's ability to differentiate edible oils based on their optical responses, indicating the sensor's usefulness in quality control and oil classification. In the HC-PCF-filled oils, the fiber length was approximately ٦cm. The fiber is fixed by clamping, alignment between the PCF and laser source, and the optical spectrometer OSA was done. Figure (2) shows the experiment setup. The laser used is the Diode laser, with a wavelength of 650nm and 10mW power.

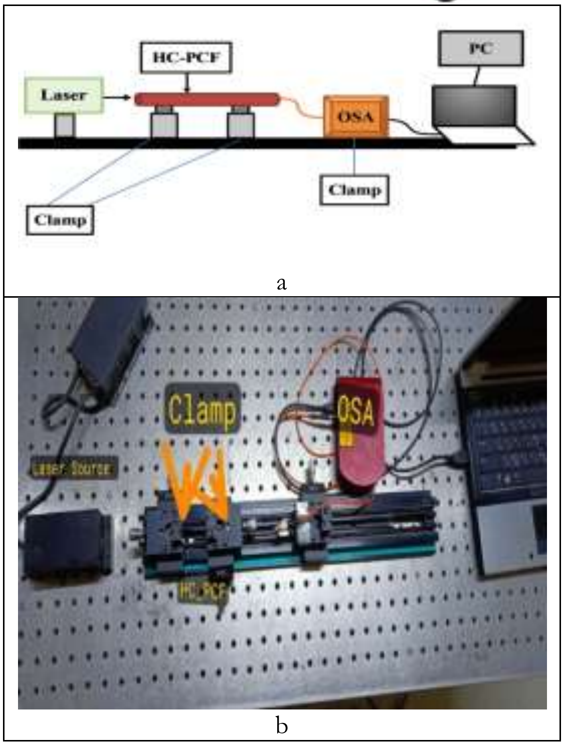


Figure (2): (a) Schematic drawing of the experiment setup (b) Image of the experimental setup

4 -Result and Discussion

Figure (3) shows the laser spectrum for HC-PCF without oil (only air) and with the seven different edible oils measurements by OSA. The relation between intensity and wavelength is shown in the spectrum in Figure (4). One can notice that the redshift is clear in this figure, and the intensity of the laser beam is constant. The measurement shows the shift in wavelength (red shift), starting from 659, 662.926, 661.314, 660.659, 661.373, 660.068, 660.219, 661.329 (nm) for air, wheat, olive, walnut, corn, canola, sunflower, and sesame edible oils respectively. The relation between the index of refraction and the wavelength shift is not linear but it is closer to a second-degree polynomial as shown in Figure (5). The relation between the refractive index and the confinement losses, wavelength shift, and the relative sensitivity of the sensor for all samples are shown in table 2. The measurements of the confinement loss, and the relative sensitivity of the sensor are calculated using equations 1 to 5.

One can determine the sensor's relative sensitivity using equation (1) [17]:

$$r = \frac{n_r}{n_{eff}} \times H \qquad (1)$$

where n_r refractive index and n_{eff} is the effective mode index. In Eq. (1), the effective refractive index is typically a complex number. The imaginary part is the attenuation of the coherent component of light during its propagation through the liquid samples (the editable oil in our case). Beer Lambert's law states that the coherent component of light's intensity (I) decays as [18]

$$I = I_o\, e^{-\mu_{ext} L} \qquad (2)$$

where I_o is the intensity of light before it enters the sample, L is the distance travelled by light through the sample medium, and μ_{ext} is the extinction coefficient and is given by equation (3) [18]:

$$\mu_{ext} = 2k_o \, Im(n_{eff}) \qquad (3)$$

H is the power fraction and is given by the following equation.

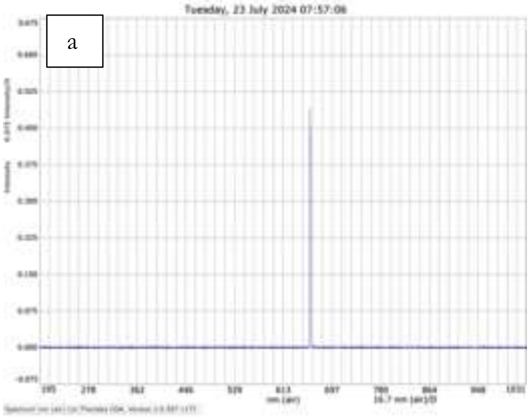
$$H=\frac{\int_{sample} Re(Ex\,Hy-Ey\,Hx)}{\int_{total} Re(Ex\,Hy-Ey\,Hx)} \times 100 \qquad (4)$$

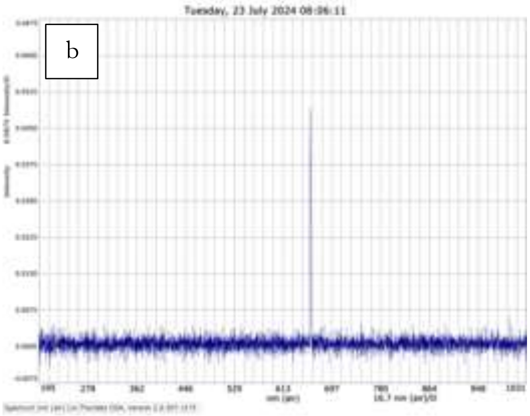
where **E** and **H** are the propagating signal's electric and magnetic fields, respectively, and the sample x and y designate the polarization in the x- and y-axis. Confinement loss (CL) is caused by the cladding air holes surrounding the core absorbing power. Therefore, confinement loss can be computed by equation (5) [17, 18, 19].

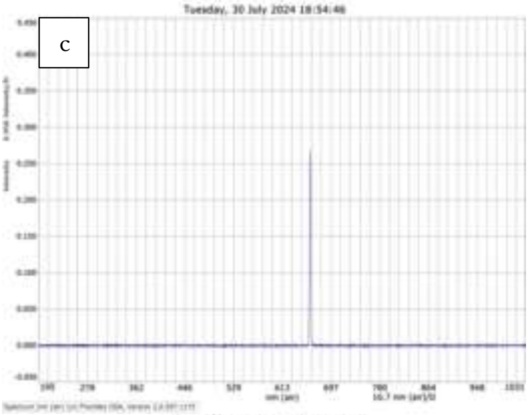
$$CL= 8.686\, K_o \, Im\,[n_{eff}] \;(dB/m) \qquad (5)$$

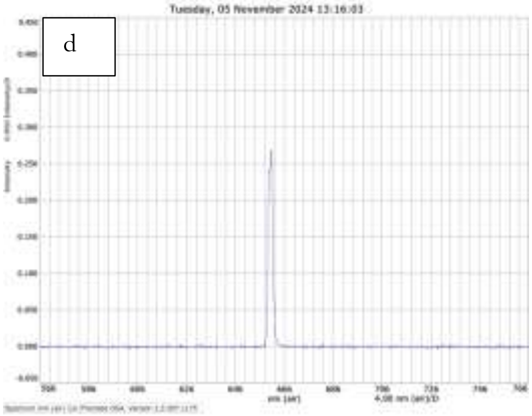
Im represents the imaginary component of the effective refractive index and $K_o = \frac{f}{c}$.
f represent the frequency, c is the speed of light in vacuum.

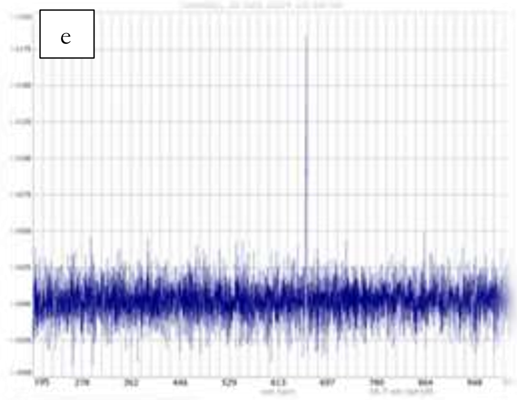
The relative sensitivity started from 79.1399 for air and 80.5902, 77.4523, 77.6653, 77.4889, 79.9321, 80.1589, 77.5651 for wheat, olive, walnut, corn, canola, sunflower, sesame edible oil samples respectively as sh. One can notice that the values of the relative sensitivity are between 77% and 81% which acceptable and it is comparable to published theoretical work [23]. Losses in all types of PCF-based sensors arise because of effective material loss (EML) resulting from solid material being present in the waveguide, as well as confinement loss (CL) caused by cladding air holes absorption power around the core. The losses decrease with increasing refractive index, as shown in Table (2).

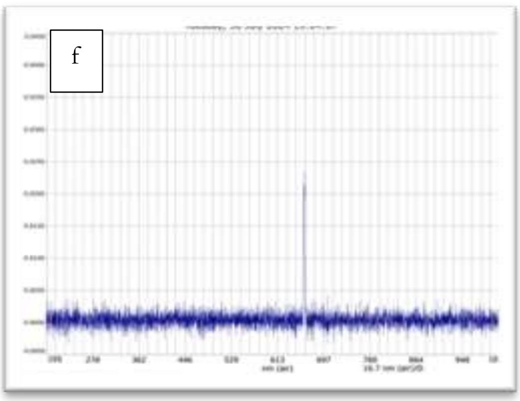












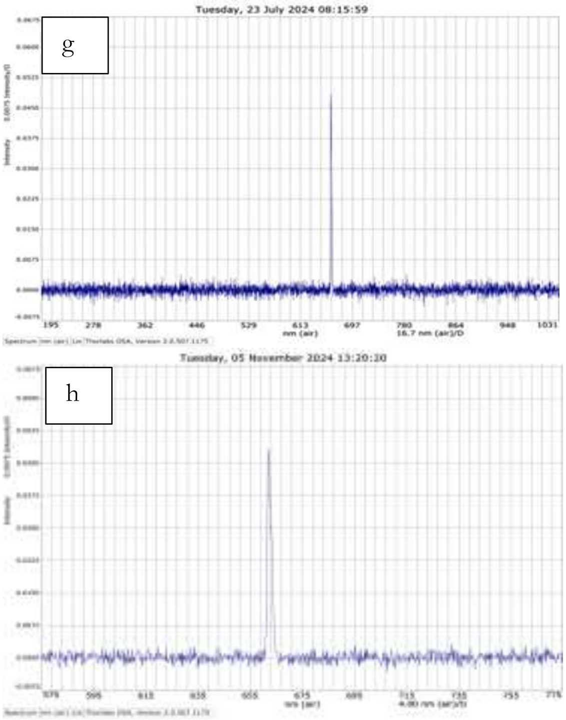


Figure (3): Shows the laser spectrum for different editable oils: (a) air-filled, (b) canola oil, (c) sunflower oil, (d) olive oil, (e) walnut oil, (f) sesame oil, (g) corn oil, and (h) wheat oil.

Figure (4) show the spectral response of different oils (canola, sunflower, olive, walnut, sesame, corn, and wheat) compared to air in the wavelength range of 659-662 nm using an HC-PCF (HC-800B) sensor. The graph shows featured intensity peaks around 659 nm with red shift wavelength with a detailed inset Focuses on the variations in intensity profiles for each oil, refers to differences in their optical absorption characteristics.

Figure (5) illustrates the relationship between the refractive index and the wavelength for different types of oils. This relationship explain the dispersion behavior of light as it passes through each oil type. Dispersion refers to how the wavelength shifted when passed through different refractive index. The relation is inverse for most oils, the shifted in wavelength increases when the refractive index decreased, which is consistent with normal dispersion behavior. This trend is visible for some oils like wheat and sesame, where their wavelength shift increases with refractive indices low. The graph illustrates the linear relationship between refractive index and wavelength for each oil.

Table 2 presents data on the performance of a Hollow-Core Photonic Crystal Fiber (HC-PCF) filled with various materials, including air and different edible oils such as wheat, olive, walnut, corn, canola, sunflower, and sesame. The evaluated parameters include refractive index, wavelength shift, confinement losses, and relative sensitivity. Among these, sesame oil exhibits the highest refractive index (1.47615), while air has the lowest. As shown in Table 1, the refractive indices vary slightly across the oils.

Table (2): The result of confinement losses and relative sensitivity, for all edible oil samples.

i	Refractive index	Wavelength Shift	Confinement losses (dB/m)	Relative sensitivity (%)
Air	1	659	3.587×10^{-6}	79.139
Wheat	1.4628	662.926	6.347×10^{-9}	80.59
Olive	1.4668	661.314	1.2×10^{-9}	77.4523
Walnut	1.4705	660.659	1.2×10^{-9}	77.489
Corn	1.4719	661.373	1.2×10^{-9}	77.665
Canola	1.4728	660.068	6.473×10^{-9}	79.932
Sunflower	1.4739	660.219	1.158×10^{-9}	80.159
Sesame	1.47615	661.329	1.199×10^{-9}	77.565

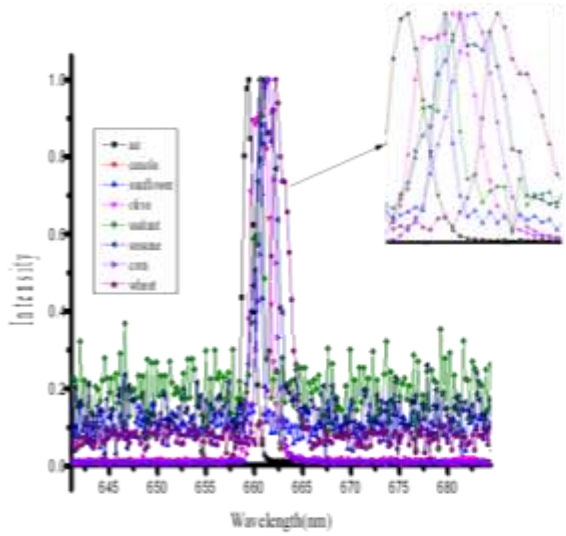


Figure (4): Relation between wavelength and intensity for the different seven editable oils

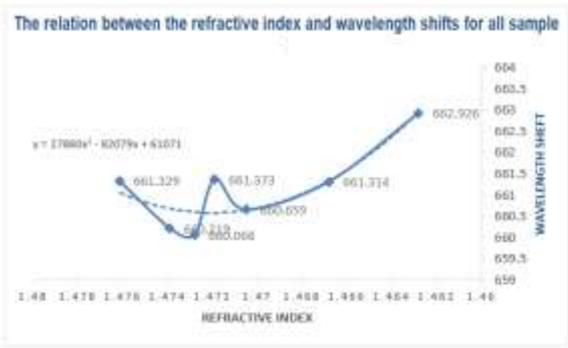


Figure (5): The relation between the refractive index and wavelength shifts for all sample

The refractive index of the filling material significantly influences the light propagation characteristics within the HC-PCF. Generally, a higher refractive index leads to stronger light-matter interaction, which affects both the wavelength shift and the sensitivity of the fiber. Air is used as a reference material due to its minimal refractive index and interaction with light. Although the edible oils have similar optical properties—with refractive indices ranging approximately between 1.46 and 1.48—

even minor differences can impact the HC-PCF's performance.

The wavelength shift refers to the change in the transmitted wavelength when the HC-PCF is filled with different oils. This shift is primarily driven by the refractive index and its interaction with the photonic crystal structure. For example, the wavelength shift ranges from 660.068 nm (canola oil) to 662.926 nm (wheat oil), as illustrated in Figures 3, 4, and 5, and detailed in Table 2. Although these shifts are relatively small, they are measurable and indicate the HC-PCF's potential for precise sensing applications.

The reproducibility of the sensor's performance is essential for real-world applications. Since the sensor relies on manual oil filling and precise alignment, small deviations in the fabrication or handling process may lead to performance variation. This study used a standardized HC-PCF (HC-800B), but variations in manufacturing (e.g., core diameter, air hole size) could affect sensitivity and confinement losses. Future work should involve batch testing of sensors fabricated under different conditions to quantify robustness. Design modifications that tolerate slight fabrication variances, such as using anti-reflective coatings or automated alignment systems, can improve the sensor's reproducibility and long-term performance.

5 -Conclusions

Edible oils are necessary in everyday life, yet their similar appearance makes distinguishing between them difficult. This work proved the ability of a Hollow-Core Photonic Crystal Fiber (HC-PCF) sensor to detect edible oils based on their distinct optical properties. The sensor demonstrated good performance in terms of sensitivity and low confinement losses across a range of oil types. While the oils had equal refractive indices, the sensor efficiently detected minor changes. These findings indicate that HC-PCFs can be a dependable and unique alternative for edible oil detection. This work is a first step toward building fiber-based sensors for food analysis, with further research expected to improve and modify the design for specific uses.

6 -Reference

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