

Investigation On A Bio-Sensor: A Theoretical Study On Modified Photonic Crystal Fiber Using Plasmonic Nanomaterial

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Investigation on a Bio-sensor: A theoretical study on modified photonic crystal fiber using plasmonic nanomaterial

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Abstract

A modified (HC-800) Photonic Crystal Fiber (PCF) using Gold nanoparticle as an active plasmonic material was used as bio a sensor. The Finite Element Method is used to compute numerical interpretations of sensing performance employing various liquids such as (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol). In the proposed biosensor the sample (analyte material) is placed into a core, cladding air holes, and outside of the HC fiber structure. The sensitivity was calculated before and after adding the gold layer. The maximum amplitude sensitivity was found to be $769.5749 \text{ RIU}^{-1}$ for Human blood Plasma and the best electric field was found to be 400 V/m . In the same liquid when used the deposited PCF with a gold layer the maximum amplitude sensitivity was found to be $975.5352 \text{ RIU}^{-1}$ at a best electric field of 477 V/m . And when the proposed sensor is considered as a refractive index sensor, where is it used the analyte samples only (inside the core and air holes) of PCF. The maximum amplitude sensitivity was found to be $869.8453 \text{ RIU}^{-1}$ at a best electric field of 434 V/m .

Keywords: Hollow Core- PCF, Biosensor, Surface Plasmon Resonance, Refractive index sensor, Confinement Loss, Sensitivity

I. INTRODUCTION

The photonic crystal fiber is a new type of optical fiber. The Photonic Crystal Fiber is made of a single material, such as silica glass, with air holes running the length of the fiber around a solid or hollow core. These 'air holes' serve to keep electromagnetic waves confinement within the fiber's core while also allowing them to be customized in terms of transmission properties [1]. With the possibility of filling the air holes with different liquids to enhance the optical

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properties. A wide range of sensing applications of photonic crystal fiber. Such as the Photonic biosensors have advanced significantly in recent decades in a variety of applications, including medical diagnostics, biochemical detection, and organic chemical detection [2][3].

Biosensors are used to transform a biological transition into a quantifiable signal that can be transmitted via a transducer and is widely used for biological agent detection and identification. Optical biosensors are a class of biosensors that use light as the transduced signal, and are desirable for their highly sensitive, often non-destructive analytical analysis [1]. The (PCF)-based SPR sensing technique is considered to be a possible route to miniaturization of sensors. PCF has proven its advantages as a good replacement for prism, such as small size, easier light launch, single-mode propagation and capacity to monitor evanescent field penetration [3].

Photonic crystal fiber (PCF) is an updated innovation of optical fiber that uses Photonic precious stones [4]. One important component of this kind is the number of air holes arranged [5]. Two types of PCFs exist: Solid core (SC) and Hollow core (HC) [5][6]. Each type makes use of distinctive components in light propagation [6]. There is a particular distinction between the ordinary fiber and PCF which is the required RI, since PCF uses lower RI in the layer of cladding. PCFs are used in so many applications, such as meteorology, bio-prescription, imagery, media transmission, modern equipment, etc [7].

Nanoparticles (Nps) of noble metals turned out to be extraordinarily interesting materials in many scientific areas as a result of their unique properties and important applications [12]. Metallic nanoparticles (NPs), generally gold and silver, have been created with great enthusiasm due to their SPR-related properties, which are thought to be valuable for their biological applications [13]. Control of the size, shape and surface functionality are important problems in Au NP combination [14]. Gold nanoparticles (Au-NPs) were at the focus of consideration in nano medicine because of their compound safety and noticeable optical properties [15]. Distinctive basic and morphological characteristics of created NPs can be constrained by laser fluidity, spot size, wavelength, beat width and laser beat redundancy [16].

Nanotechnology is a science that deals with nanometer-scale particles in the range of 1-100 nm[48]. Gold nanoparticles (NPs) are widely used for their unique optical and physical properties, such as surface plasmon oscillations for labelling, imaging, and sensing, as preferred materials in many fields [49]. Gold is chemically stable even in aqueous environments as an alternate plasmonic material. In addition, it demonstrates the greater shift in wavelength at the resonant wavelength, which helps to accurately detect the unknown analysis for easy detection

and increased accuracy [50]. Gold is used because it is unreactive and is not sensitive to air or light for nanoparticle applications [51]. The conventional methods to create these particles can be categorized into three types (chemical, electrical, and laser ablation methods). Evidence shows that the latter method is preferred to other methods. Different structural and morphological characters of produced NPs can be. Controlled by laser fluence, spot size, wavelength, pulse width, and repetition rate of a laser pulse [52]. Gold NPs are proved to be more effective as it has good efficacy against bacteria, viruses and other eukaryotic microorganisms.

While gold NPs can be exploited in medicine for burn treatment, dental materials, coating stainless steel materials, textile fabrics, water treatment, sunscreen lotions, etc., and possess low toxicity to human cells, high thermal stability, and low volatility. The energy density of an Au NP varies with the size and shape of the particles, resulting in a special Au NP absorption band known as the band of plasmon resonance (PR).

This absorption band results when the frequency of an incident light is resonant with the conduction electron collective in the Au NP and is referred to as particle plasmon resonance (PPR), also referred to as localized surface plasmon resonance (LSPR) [53]. Transmission electron microscopy (TEM). Can measure the size and size distribution of Au NPs in solution [54]. Scanning electron microscopy (SEM) can measure and analyze UV-vis spectroscopy and the surface coverage of Au NPs on the fiber core surface. Depending on the shape, estimation, and physical properties. In actuality, The Au nanoparticles were not circular. Subsequently, various structures were acquired, such as nanorods, nanoshells, and nanocages [49].

During the last few decades, the wide range of sensing applications and high sensitivity has gotten a lot of interest to the Surface Plasmon Resonance (SPR) phenomenon. In biosensing applications such as biomolecular analytes detection, medical diagnostics, antibody-antigen interaction, and so on, the SPR sensor has shown remarkable progress [4][5]. This paper simulated a simple HC-800 PCF biosensor based on the surface plasmon resonance phenomenon (SPR). That is will be done by preparing the PCF by etching it and then have been deposited the gold layer on the etched area (outside of the photonic crystal fiber) to enhance the sensitivity of the fiber sensor. The Gold metal was used, Because gold is chemically stable in aqueous environments and has a high resonance peak shift, it is used as the plasmonic material [6]. The properties of the sensor were studied numerically using the finite element method

(FEM) by using the COMSOL Multiphysics program, with a layer of the perfectly matched layer (PML), used to absorb the scattered light from the structure of sensors.

II. STRUCTURE DESIGN AND SIMULATION METHOD

In the present work, use photonic crystal fiber (HC-800) with core diameter is $7.5 \pm 1 \mu\text{m}$, the region diameter of PCF is $45 \pm 5 \mu\text{m}$ and pitch of $2.4 \mu\text{m}$. As Presented in Figure (1).

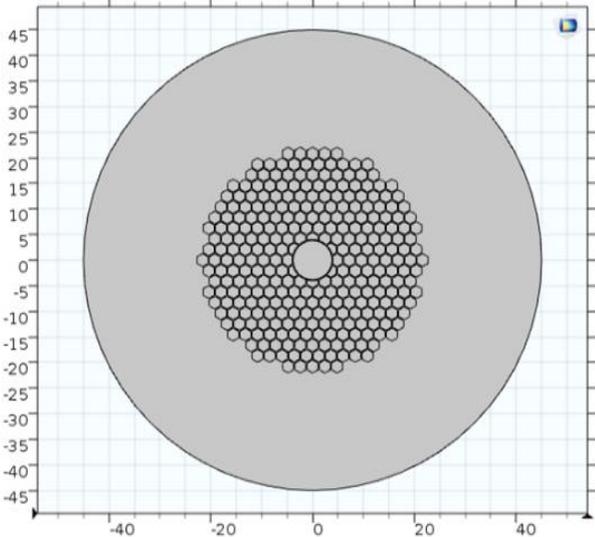


Figure (1): Geometry of the (HC-800) PCF in COMSOL Multiphysics.

In the current work, to study the performance of the proposed sensor used the Finite element method. And which depends on its work on divided The cross-sections of the proposed PCF into homogeneous triangular many subdomains. So used Maxwell’s equations to solve the neighboring subspaces of the modal analysis of the PCF structure was done in the x-y plane. Wherefore From Maxwell's equation, the vectorial wave equation can be deduced as follows [7].

$$\nabla \times (s^{-1} \nabla \times E) - K_0^2 n^2 SE = 0 \dots \dots \dots (1)$$

Where the S^{-1} the inverse of the PML matrix of 3×3 , n represents the domain's refractive index, E the electric field vector, K_0 represents the wave number in free space express it by the following equation:

$$k_0 = \frac{2\pi}{\lambda} \dots \dots \dots (2)$$

Where λ represented the wave length.

Because the cladding part of PCF has a limited number of air holes. Lead to the leakage of the light out of the structure of the fiber. So it results in the Confinement Loss (CL) can be calculated by found the imaginary part, n_{eff} . Using the following equation as a guide [8].

$$CL(\text{dB/m}) = 8.686 \times K_0 \cdot I_m (n_{eff}) \dots \dots \dots (3)$$

When the five different liquids filled the fiber, have various refractive indices as in the table below:

Table (1): different liquids filled the fiber with the various refractive indices

Liquids Materials	Refractive index
Silica [9]	1.4533
Empty fiber (Air) [10]	1.00027505
Water H ₂ O [11]	1.3290
Human Blood Plasms [12]	1.330
Colon Tissue [13]	1.3351
Liver Tissue [14]	1.3706
Pentanol (C ₅ H ₁₁ OH) [15]	1.4025

In figure (2) the refractive index is represented as a function of wavelength between (400-1200) nm. Can recognize the RI it was decreased when increasing the Wavelength. As presented below.

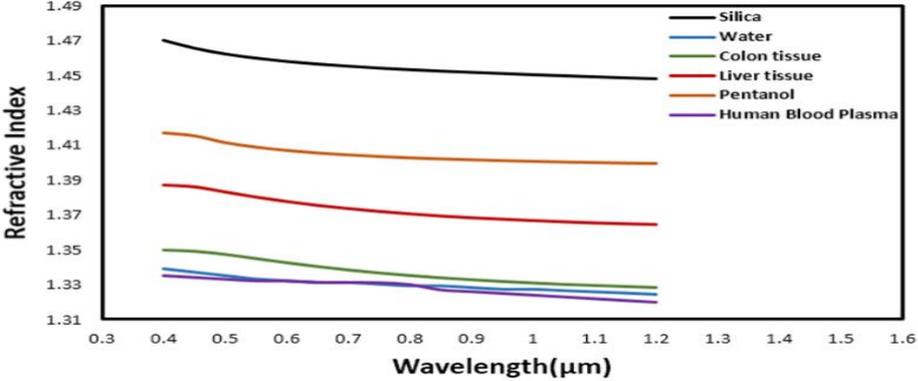


Figure (2): The refractive index (RI) of silica and (Liver tissue, Colon tissue, Human Blood Plasma, Water, and Pentanol).

III.SIMULATION AND RESULTS

HC-800 PCF without a layer of Gold: Figure (3) represents the cross-section and structure of the proposed biosensor. Was created from silica with a hexagonal pattern of air holes. Immersed and infiltrated with the external solution (Analyte material) which have different

refractive indexes (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol). On the outer of fiber a perfectly matched layer PML.

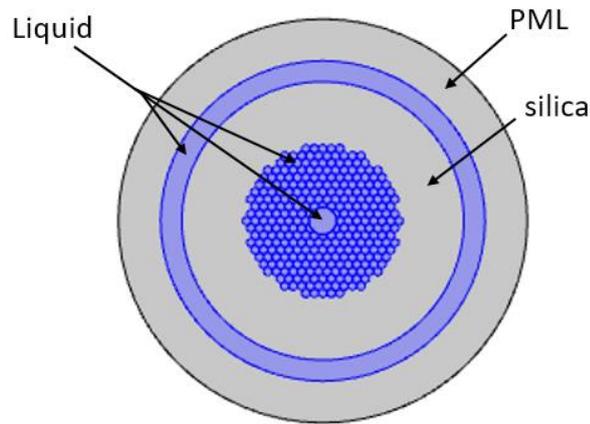


Figure (3): cross-section of the proposed biosensor without gold layer.

Firstly in figure (4.a), we calculated the optical behavior when the sensor is empty (air) at refractive index (1.00027505). The Finite Element Mesh (FEM) of PCF is shown in figure (4.b). And figure (4.c) showed the effective mode index which has two parts (real and imaginary).

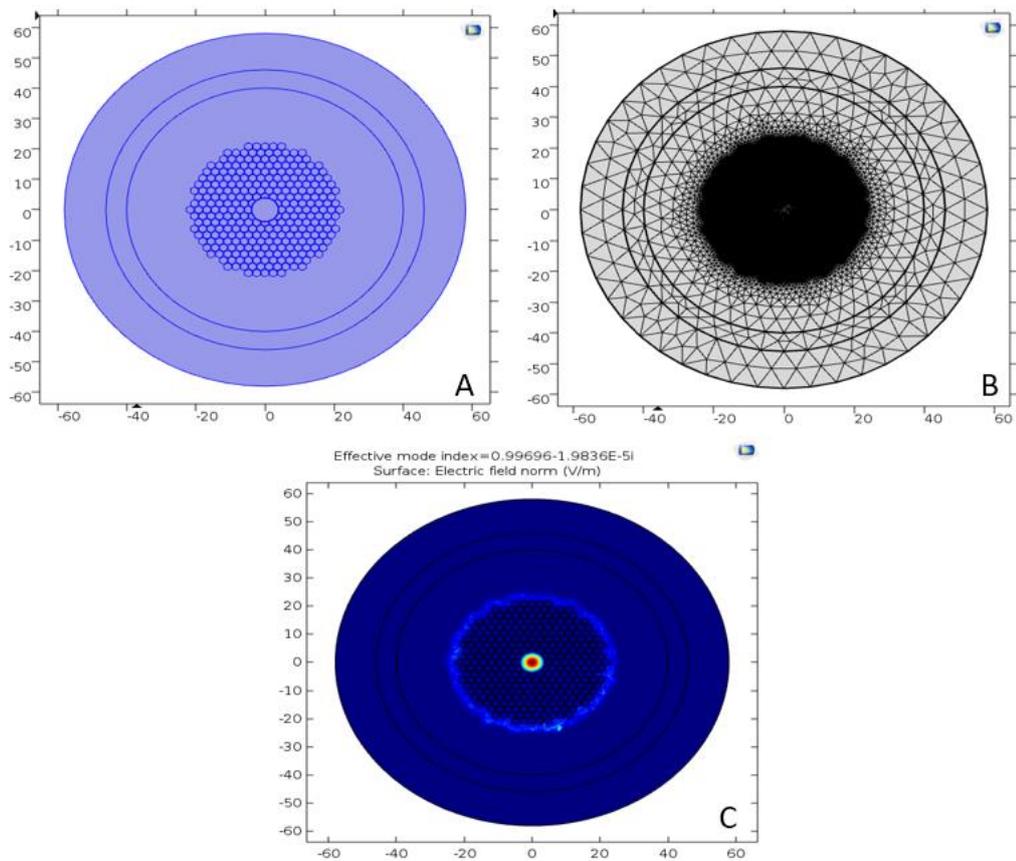


Figure (4): (A) The structure of HC-800 PCF was empty at the air refractive index = (1.00027505) (B), HC- PCF FE Mesh (C) The fundamental mode.

From the real part of the effective index can observe the change of it with the wavelength for the HC-800 PCF, It was noted when wavelength increased the effective index decreased as in figure (5) below.

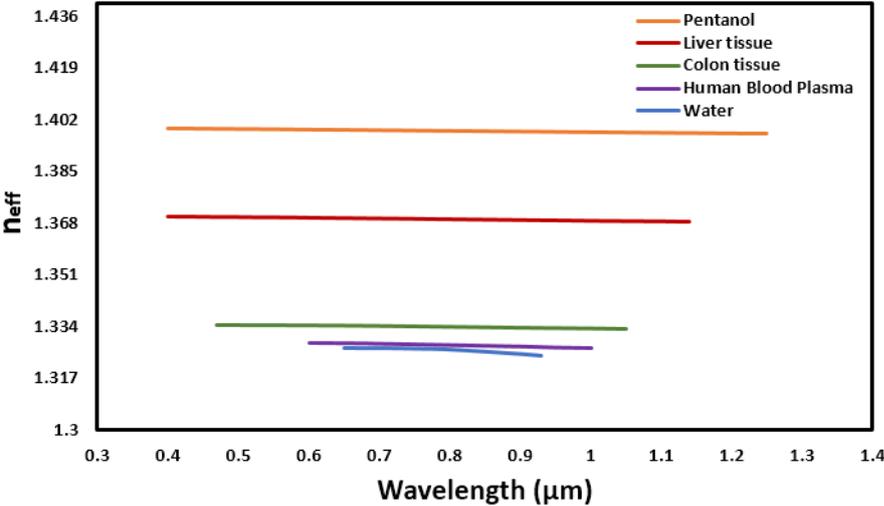


Figure (5): The real part of effective index for (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol).

Figure (6) explains the confinement losses (CL) of light from the HC-800 PCF that was Immersed and infiltrated with various liquids (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol). It can be calculated based on equation (3), and the imaginary part of the fundamental modes.

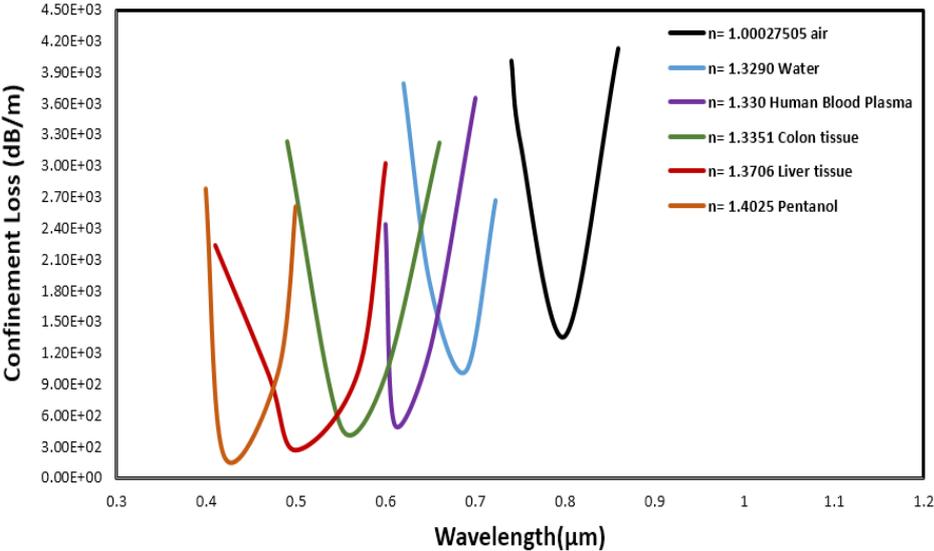


Figure (6): Confinement loss for different liquids (Water, Human Blood Plasma, colon tissue, liver tissue, and pentanol) immersed and infiltrated in HC-800 PCF.

Eventually observed the compare the confinement loss for different liquids, it was decreased when the refractive index of liquid increasing As a result. The position of the band gap peak depends on the most appropriate wavelength with the least amount of confinement loss.

However, there are other important calculations to measure the optical behavior of the HC-PCF it as the amplitude sensitivity, resolution, the wavelength sensitivity. So the amplitude sensitivity can be computed by the following equation [16]:

$$S_A(\text{RIU}^{-1}) = -\frac{1}{\alpha(\lambda, n_a)} \frac{\partial \alpha(\lambda, n_a)}{\partial n_a} \dots \dots \dots (4)$$

Where, $\alpha(\lambda, n_a)$ represented the propagation loss at refractive index (RI) n_a , and $\partial \alpha(\lambda, n_a)$ is the loss different between two loss spectra. The sensitivity of wavelength interrogation computed by the following formula [17].

$$S_\lambda \left(\frac{\text{nm}}{\text{RIU}} \right) = \frac{\Delta \lambda_{\text{peak}}}{\Delta n_a} \dots \dots \dots (5)$$

Where, $\Delta \lambda_{\text{peak}}$ represented the difference between to wavelength peak shifts, and n_a is the difference between tow refractive index (RI). Where a change in the analyte refractive index (RI) are (1.3290-1.33), (1.33-1.3351), (1.3351-1.3706) and (1.3706-1.4025), and then calculated the wavelength sensitives are (80000, 11764.705, 1408.45, and 2507.836) nm/RI for (Human Blood Plasma, colon, liver, and pentanol). And the resolution of the proposed sensor is given by the following equation [18]:

$$R(\text{RIU}) = \Delta n_a \times \frac{\Delta \lambda_{\text{min}}}{\Delta \lambda_{\text{peak}}} \dots \dots \dots (6)$$

Where, Δn_a represented the difference between the two refractive index, $\Delta \lambda_{\text{min}} = 0.1$ [19] (the a standard assuming value for the minimum spectral resolution), $\Delta \lambda_{\text{peak}}$ is the difference between two peaks of wavelength. So the resolution of the suggested sensor is $(1.25 \times 10^{-6}, 8.5 \times 10^{-6}, 7.1 \times 10^{-5}, \text{ and } 3.98 \times 10^{-5})$.

The figure (7) illustrate the amplitude sensitivity of the HC-PCF, Without gold layer. We found that the maximum value of amplitude sensitivity is 769.5749 RIU⁻¹ at 0.61μm for refractive index (RI) of (1.330) for Human blood Plasma.

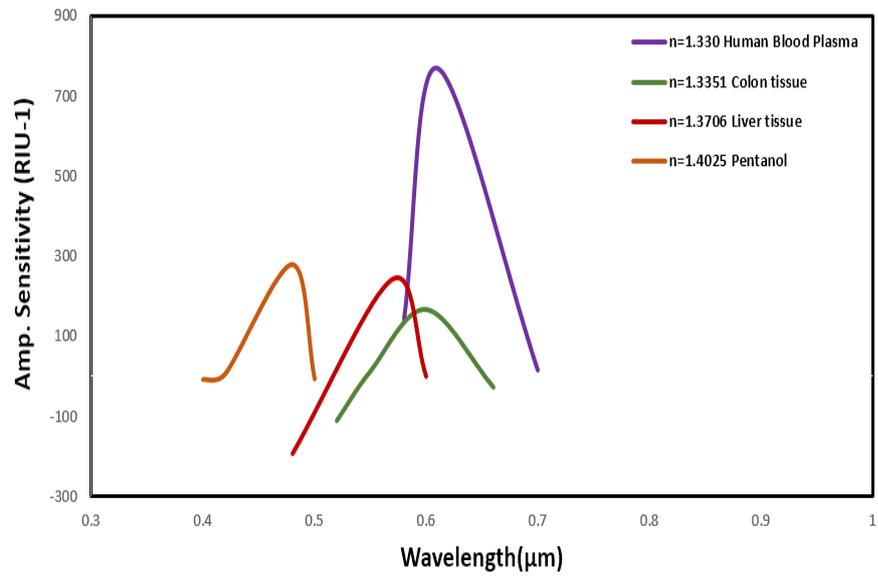


Figure (7): Amplitude sensitivity for different refractive index analytes.

Now, as shown in Figure (8), we observed by comparing the results of a fundamentals mode for the various liquids with their electric fields. So The Human Blood Plasma has a best electric field than other liquids equal to 400 V/m which leads to high sensitivity than other liquids.

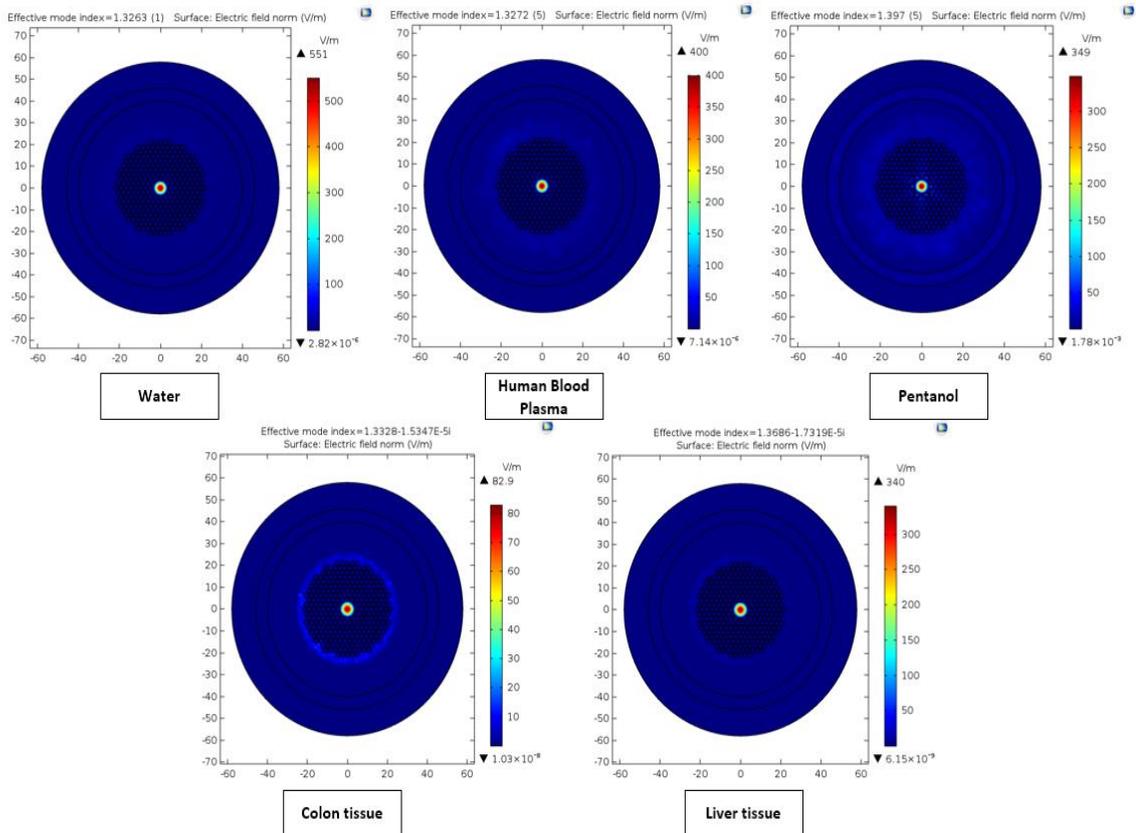


Figure (8): Fundamentals mode for different liquids of HC-800 PCF (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol).

HC-800 PCF with a layer of Gold: Figure (9) expresses the structure and cross-section of the proposed biosensor when adding the gold layer at a thickness (39.55 nm). Also, it is made from silica with a hexagonal pattern of air-holes. And submerged from the outside and inside (core, cladding air holes) with different liquids (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol). On the outer the gold layer of fiber the PML is used to absorb scattered light from the proposed sensor.

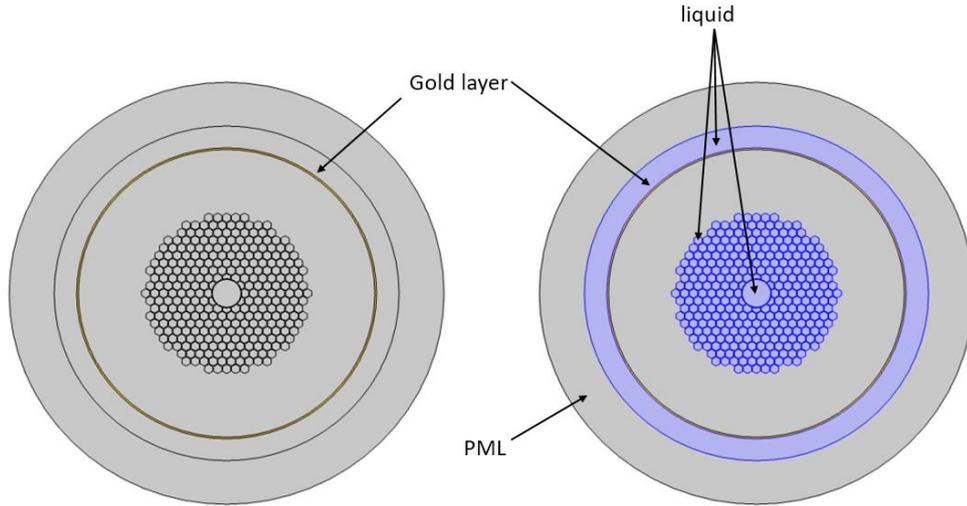


Figure (9): Cross-section of the proposed biosensor with gold layer.

Figure (10.a) explains The Finite Element Mesh. And figure (10.b) illustrates the fundamental mode when the proposed sensor (HC-800 photonic crystal fiber with a layer of gold), is empty (air) at refractive index (1.00027505).

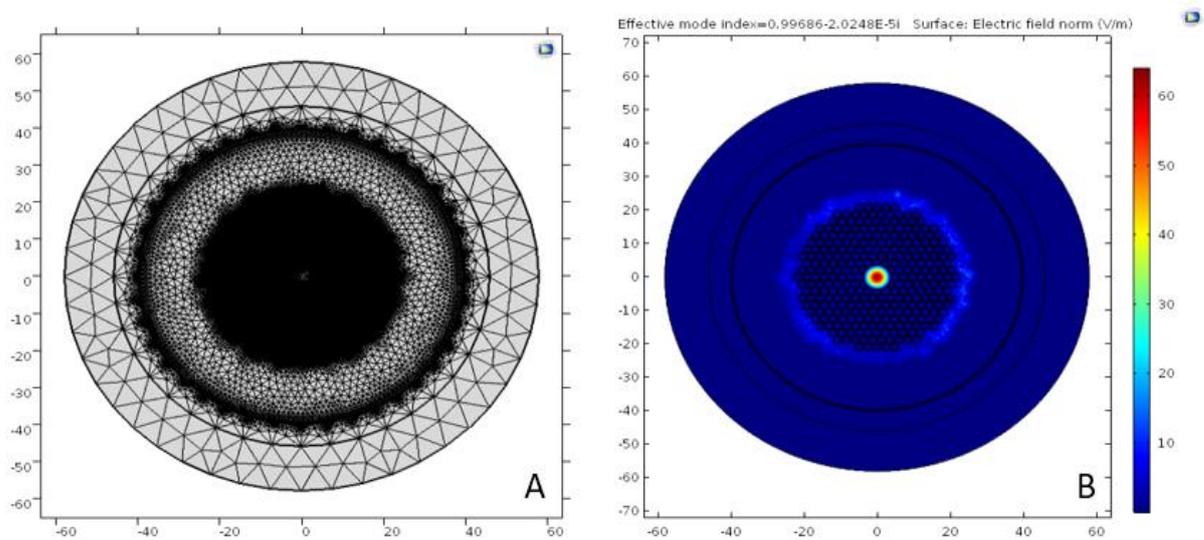


Figure (10): (A) FE Mesh of HC-800 PCF (B) The fundamental mode for an empty PCF with a layer of gold.

Figure (11) represented the confinement losses were computed by using the equation (3). When the proposed biosensor with a layer of gold, Was Immersed and infiltrated with various liquids (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol).

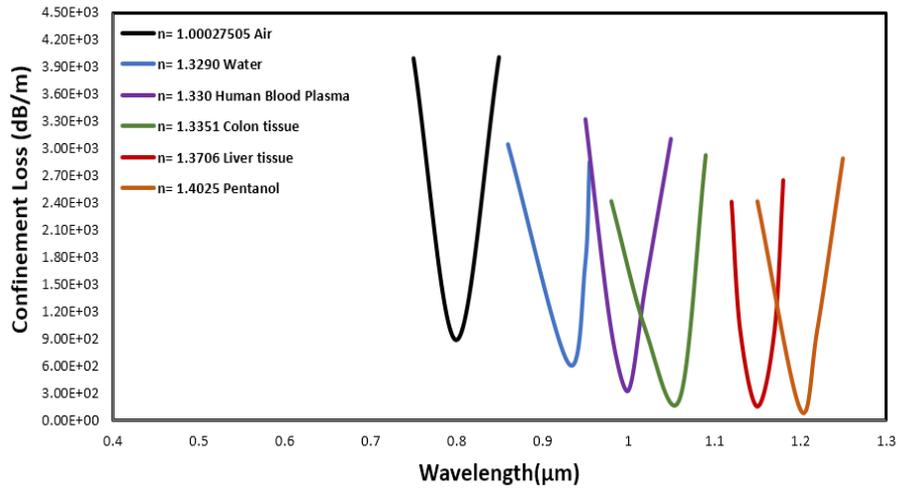


Figure (11): Confinement loss of HC-800 Photonic Crystal Fiber with a gold layer, when immersed infiltrated with different liquids (Water, Human Blood Plasma, colon tissue, liver tissue, and pentanol).

In figure (12) was computed the maximum amplitude sensitivity from equation (4) is $975.5352 \text{ RIU}^{-1}$ at $1 \mu\text{m}$ for an analyte material (Human Blood Plasma). Also used equation (5) to calculate the wavelength sensitivity is (70000, 11764.705, 2535.211, and 1567.39) nm/RI for (Human Blood Plasma, colon, liver, and pentanol). Moreover, was computed the resolution of the proposed biosensor from equation (6) is (1.428×10^{-6} , 8.5×10^{-6} , 3.94×10^{-5} , and 6.38×10^{-5}).

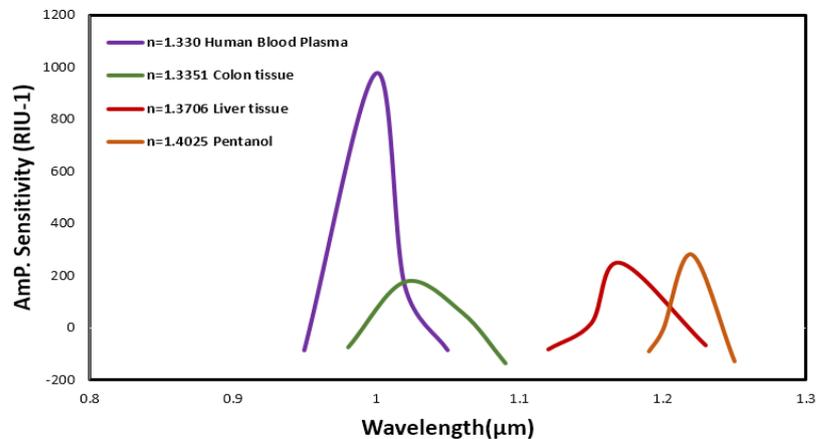


Figure (12): Amplitude sensitivity for different refractive index (RI).

In figure (13) we note The fundamental mode of liquids as compared to their electric field. So we found the best electrical field for Human Blood Plasma equal to 477 V/m. which leads to it have high sensitivity best than other liquids.

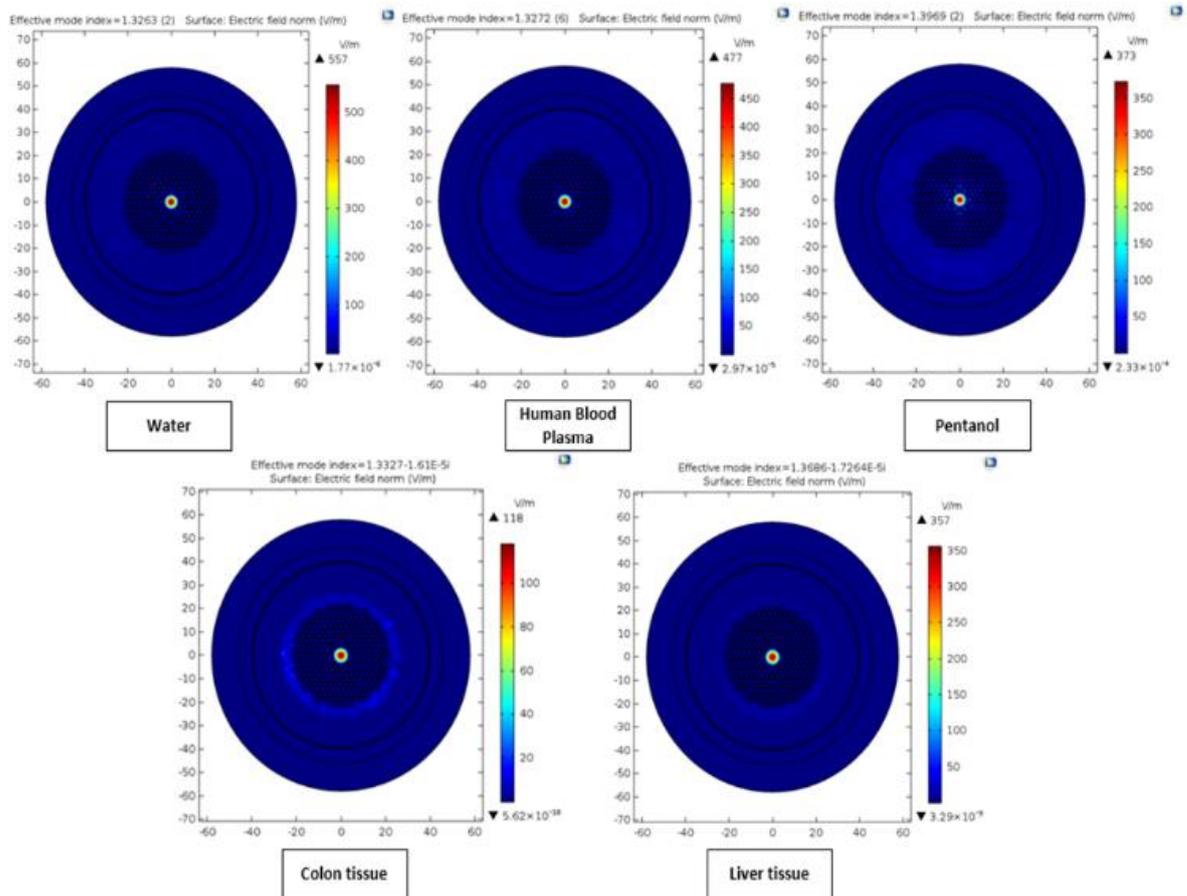


Figure (13): Fundamentals mode for different liquids of HC-800 PCF with a layer of gold.

Table (2): Electric fields of the HC-800 PCF With a layer of gold as a biosensor for different liquids (water, Human Blood Plasma, Colon, Liver and Pentanol).

Liquids	Electric Fields V/m	Amp. Sensitivity R/U ⁻¹
Water	557	-
Human Blood Plasmas	477	869.8453
Colon Tissue	118	172.5254
Liver Tissue	357	239.5760
Pentanol (CSH11OH)	373	274.4483

HC-800 PCF with a layer of Gold as a refractive index sensor: In this type of proposed sensor we have used an analyte material just into (core, cladding air holes) of HC-800 PCF without immersed the fiber by external liquid, without the SPR phenomenon, it occurs. On the outer of gold layer use a Perfectly Matched layer (PML).as a figure (13) below:

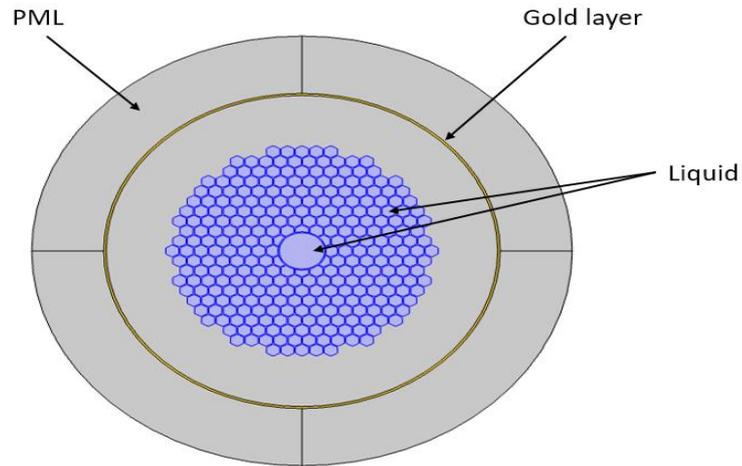


Figure (13): The cross-section of the proposed RI sensor with gold layer.

Figure (14) shows The fundamental mode of the proposed RI sensor when the PCF empty. And The Finite Element mesh.

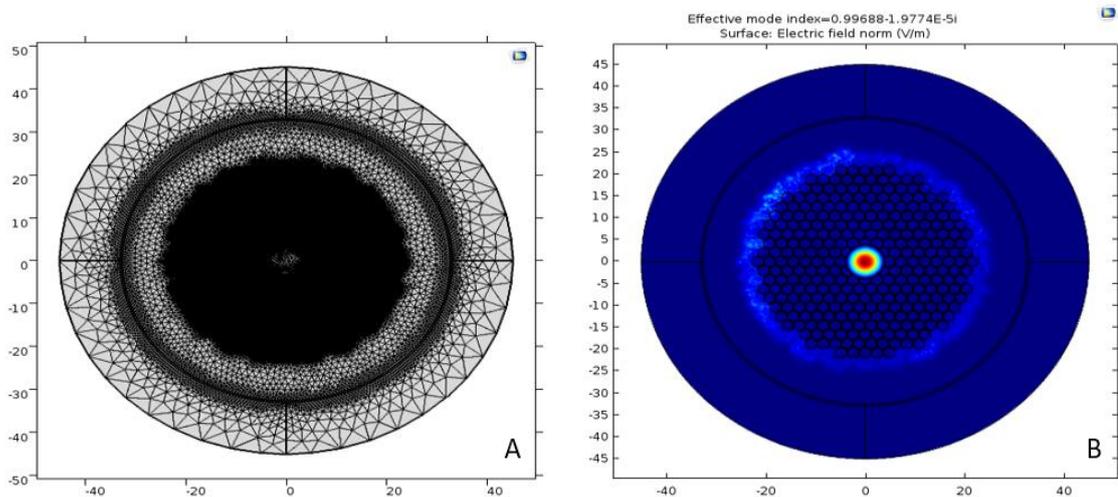


Figure (14): (A) Finite Element mesh of HC-800 PCF (B) The fundamental mode for an empty HC-PCF with a layer of gold.

The confinement losses explain in figure (15) by using eq (3). When the proposed RI sensor infiltrated by different liquids (Liver Blood, Colon Blood, Human Blood Plasma, Water, and Pentanol).

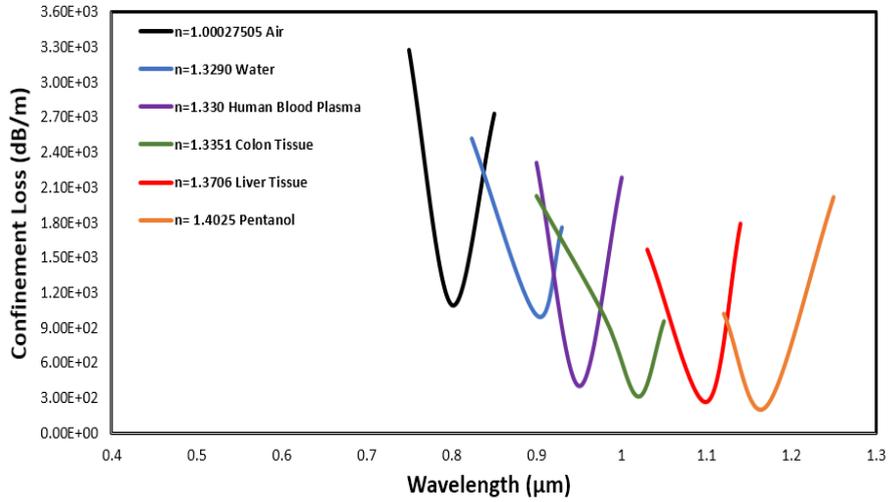


Figure (15): The Confinement loss of proposed Refractive index sensor

In figure (16) was calculated the wavelength sensitivity from the equation (5) is (50000, 13725.49, 2253.52, and 2194.35) nm/RI for analyte materials (Human Blood Plasma, colon, liver, and pentanol). also, was found the maximum amplitude sensitivity from equation (4) is 869.8453 RIU⁻¹ at 0.95μm for Human Blood Plasma. Finally was computed the resolution of the proposed RI sensor from equation (6) is (2×10^{-6} , 7.285×10^{-6} , 4.437×10^{-5} , and 4.55×10^{-5}).

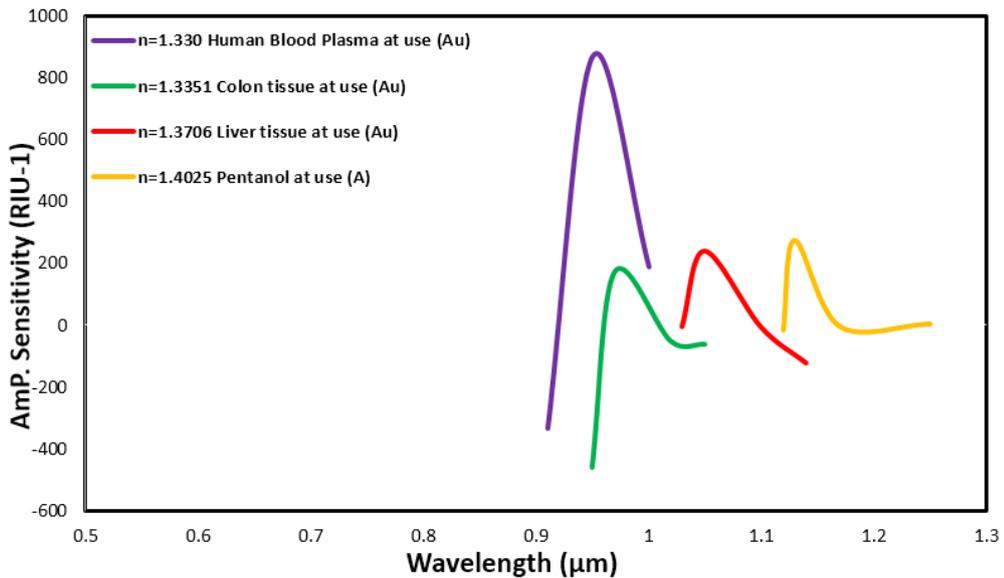


Figure (16): Amplitude sensitivity of proposed Refractive index sensor.

Figure (17) explains The fundamental mode of liquids as compared to their electric field. And found the best electrical field also for Human Blood Plasma equal to 434 V/m which leads to high sensitivity than other liquids.

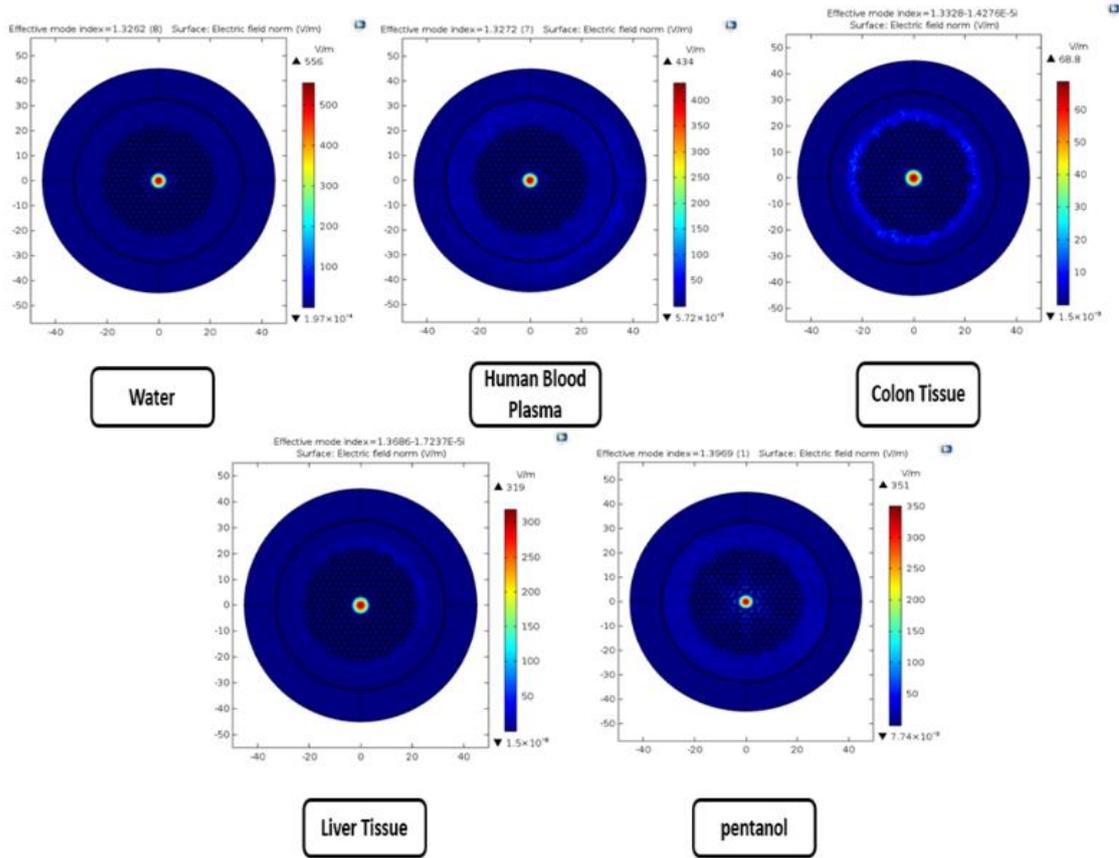


Figure (17): Fundamentals mode for different liquids of proposed Refractive index sensor.

Table (3): The electric fields of the HC-800 PCF as refractive index sensor for different liquids (water, Human Blood Plasma, Colon, Liver and Pentanol).

Liquids	Electric Fields V/m	Amp. Sensitivity R/U ⁻¹
Water	556	-
Human Blood Plasmas	434	869.8453
Colon Tissue	68.38	172.5254
Liver Tissue	319	239.5760
Pentanol (CSH11OH)	351	274.4483

CONCLUSION

This article displays A practically simple HC-800 PCF as a biosensor and RI sensor. We performed three calculations of the confinement losses and the sensitivity of the proposed sensor. As it has been studied numerically using (FEM). In the first case, before the gold layer was deposited on the fiber, the fiber was immersed with the analytical material from the outside and (inside core and air holes), and we noticed when the refractive index of the sample (analyte) increased, the confinement losses decreased. And the maximum amplitude sensitivity for (human blood plasma) is $769.5749 \text{ RIU}^{-1}$ and the best electric field was found to be 400 V/m . And in the second case of the same type of fiber, a plasmonic sensor was proposed when depositing the gold layer on the fiber from the outside, and also immersed by the analytical material, outside and (inside core and air holes) so we noticed the highest increase in the sensitivity of the sensor for the same analytical substance (human blood plasma), where it was equal to $975.5352 \text{ RIU}^{-1}$ at the best electric field was found to be 477 V/m . In the third case, the same type of fiber was used, and also the same layer of gold was deposited on it from the outside, but it was considered as a refractive index sensor because the analytical material was only placed inside the fiber (inside the core and air holes) and the maximum sensitivity of the proposed sensor was calculated and found to be equal to $869.8453 \text{ RIU}^{-1}$ for (human blood plasma) at the electric field 434 V/m .

Declarations

1- Funding

The research reported in this manuscript has been done at the University of Technology, Baghdad, Iraq. Fully funded of our own financial support.

2- Conflicts of interest/Competing interests

We wish to draw the attention of the Editor to the following facts, We confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

3- Availability of data and material

All our data presented in the manuscript

4- Code availability

COMSOL Multiphysics® version 4.3b

5- Authors' contributions

Our manuscript creates a paradigm for future studies to encourage researchers to focus on this area and all Authors were aware of about the paper content and approved its submission.

6- Consent to participate

We confirm that if accepted, the article will not be published elsewhere in the same form, in any language, without the written consent of the publisher.

7- Consent for publication

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

8- Ethics approval

I am the undersigned on behalf of the authors declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere and not submitted to more than one journal for simultaneous consideration.

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Thank you for your consideration

Sincerely,

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Assoc. Prof. Dr. Makram A. Fakhri

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