Design and Analysis of D-shaped Optical Fiber Biosensor   
for Human Teeth Disease Diagnosis

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**Abstract.** This work presents the design and simulation of a surface plasmon resonance (SPR)-based D-shaped optical fiber sensor. The sensor is designed for human dental disease diagnosis. By analyzing the refractive indices (RIs) of different parts of the human teeth and considering the various RIs, the shifts in the wavelength for a diseased tooth can be observed, which will have a different RI compared to a healthy one. The sensor’s geometry was optimized using the finite element method (FEM) by using COMSOL Multiphysics to analyze design-based parameters of the D-shaped fiber and the silver gratings. The optimized sensor demonstrated a sensitivity of 4.1247 µm/RIU, full-width half maximum (FWHM) of 0.394 µm, figure of merit (FOM) of 10.47/RIU and detection accuracy (DA) of 2.54×. This was achieved with a silver grating thickness of 45 nm, an air gap width of 10 nm, and a 12 nm thick hematite (α-Fe2O3) layer. The designed sensor has great potential for delivering accurate and effective results in detecting dental issues.

# Introduction

The early detection of dental diseases and tooth problems such as tooth decay, gum infections, and abscesses are very crucial. There are different types of sensing methods are available among them Surface Plasmon Resonance (SPR) based biosensors provide a feasible solution. SPR based biosensors provide non-invasive, high sensitive and real time solution as compared to the traditional methods often relied on visual inspection or invasive procedures. Through the detection of subtle biochemical changes and their compositions in tooth tissues, these sensors can detect dental issues quickly and accurately. This inventive technology can help in early diagnosis, upscale treatment results, and make dental health monitoring and treatment more efficiently addressable. In this work, a SPR based biosensor is developed through a D-shaped optical fiber, which contains periodic gratings, which has layered materials of silver (Ag) and a-Fe2O3 (hematite) as a part of design, monitoring the healthy refractive indices (RIs) of different layers of teeth such as enamel (1.631), dentin (1.54), and cementum (1.580) [1],[2]. A 400-micron multimode fiber optic was etched to achieve a D-shaped optical fiber structure. The model is then deposited with a thin gold layer to achieve the SPR effect. The gold-layered D-shaped optical fiber is then covalently attached with the EpCAM-targeting antibodies [3]. The stable metal-based 2D nanomaterials, especially silver and gold-enriched carbon nitrides, have exhibited improved catalytic activity and reactivity. The physical and chemical properties of these hybrid nanomaterials are utilized to advance in the fields of healthcare and medical sciences. The work was extension of previous work on essential principles for designing silver and gold coated carbon nitrides (CNs) by analyzing their structural and altered surface properties for healthcare implementations [4]. Specific details involve the usage of the D-shaped optical fibers, optimizing grating dimensions, and the geometric structure of the cladding and core. Along with the geometrical structure, material assignment is also involved wherein different materials are assigned to different regions of the sensor parts like the core, cladding, gratings, and the external medium. To ensure accuracy, mesh analysis is carried out to gain accurate geometric calculations of all the parts of the design, even further improving the performance of the system. To achieve maximum sensitivity, optimization of principal sensor parameters, including grating sizes, external refractive index (RI) and material options is done. For example, in the work being proposed, gold and other metals are utilized in place of silver, comparing their RIs to see which combination gave the maximum sensitivity. The Finite element approach was used to evaluate the D-shaped optical fiber and silver grating design parameters to optimise the SPR fiber sensor and identify the wavelength absorption dips due to the effects of SPR. The effect of the haematite sensing layer thickness on sensitivity was also investigated using the finite element method.

**SPR PRINCIPLE**

## Surface Plasmon Resonance (SPR) is a dependable optical sensing technique/phenomenon used for the measurement of biomolecular interactions with binding in real time. The principle of SPR involves interaction of light with free electrons at the metal film interface, most commonly gold or silver [4-6]. The phenomenon of attenuated total reflection (ATR) plays a critical role in the precise detection of alterations by these sensors. A surface plasmon wave (SPW) is generated in the interaction between *p*-polarized electromagnetic (EM) waves and conductive-dielectric surface in SPR, which propagates along the interface. A abrupt drop in the output signal at a specific wavelength is caused by the realization of a surface-bound wave that matches the SPW when light strikes the metal-dielectric boundary [7-11]. A thin metallic layer of gold (Au) or silver (Ag) is typically applied to the basein SPR systems. When TM-polarized light strikes the metal interface, a pronounced dip transpires at the resonance angle or wavelength, depending on the method used. By analysing this resonance, the RI of the sensor coating can be precisely measured [12-13]. The fluctuation in the resonance angle is directly related to the amount of material binding to the surface, providing a real-time, label-free detection method for molecular interactions, such as detecting biomarkers for diseases, including those in human teeth.

## DESIGN SPECIFICATION

A 400-micron multimode fiber optic, composed of a pure silica core and GeO2-doped cladding, was etched to achieve a D-shaped optical fiber structure, as shown in Figure 1. The fiber core and cladding widths of the D-shaped fiber are 4.5 µm and 62.5 µm respectively. This model is subsequently deposited with a thin gold layer to realize the SPR effect. The Sellmeier equation is applied to specify the wavelength-dependent RI of the fiber core and cladding by using Equation (1). These are used to calculate the RI of the materials such as n-Ge-doped and silica materials to introduce them in the design.

where *p1, p2, p3, q1, q2, q3* denotes Sellmeier coefficients and *λ* the denotes the wavelength. In this study these values are utilized and their corresponding values are shown in Table 1.

**TABLE 1.** Sellmeier coefficients

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Coefficients** | ***p3*** | ***p2*** | ***p1*** | ***q3*(µm)** | ***q2*(µm)** | ***q3*(µm)** |
| Cladding | 0.8974794 | 0.4079426 | 0.6961663 | 9.896161 | 0.1162414 | 0.0684043 |
| Core | 0.8974540 | 0.4146307 | 0.7028554 | 9.896161 | 00.1143085 | 0.0727723 |

To evaluate the complex RI of the hematite (α-Fe₂O₃) layer, reflectance was calculated using the given Equation (2).

where *A* denotes layer absorption. The approximation is as given by Equation (3).

where *k* represents the extinction coefficient corresponding to the absorption coefficient, α, given by *k = αλ/4.*

Using the transmission function, the transmitted power through the power monitors, *T* was evaluated and adjusted with respect to the energy source for *p*-polarized light [1] using Equation (4).

Here, indicates the plasmonic wave mode effective index, corresponding to the source light wavelength.   
*L,* which is 1mm, denotes the dimension of the sensing area. The SPR response curve represents the normalized transmitted power or transmission coefficient with respect to the operating wavelength. Wave coupling between the surface plasmon mode and core mode of the optical fiber produces wave interaction. The SPR response exhibits a drop when this coupling condition is fulfilled. The efficacy of an SPR sensor is influenced by two factors: Sensitivity (S) and Full Width at Half Maximum (FWHM). If *Δn* denotes the variation in the RI of the sensor layer, and *Δλ*resdenotesthe wavelength shift, then the sensitivity of the SPR is expressed as in Equation (5).

To evaluate the FWHM, the maximum wavelength , minimum wavelength were obtained from the graph. The difference of those wavelengths is reduced to half to give the FWHM, as in Equation (6).

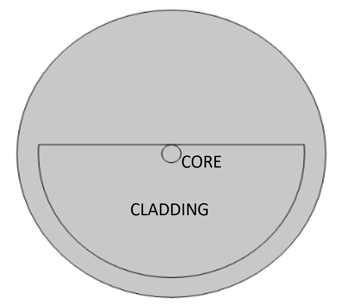
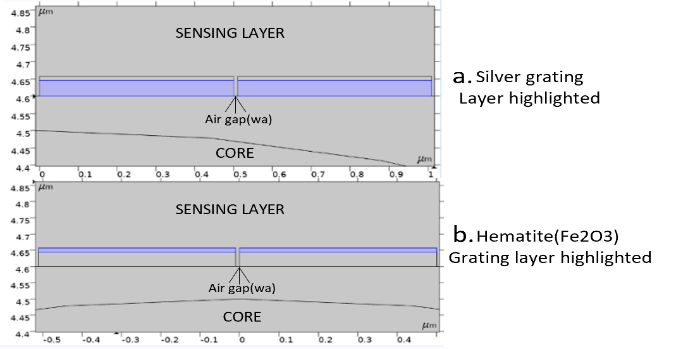
After obtaining Sensitivity (S), FWHM, the Figure of Merit (FOM), which is one of the important performance parameters, which is given by Equation (7). The detection accuracy is given by Equation (8).

The intensity of SPR response curve is dependent on the sensitivity, whereas the detection accuracy depends on the its width. A constricted full width at half maximum (FWHM) enhances detection precision. Consequently, the sensor's performance is significantly reliant on both sensitivity and detection accuracy, facilitating the determination of Plasmonic wavelength. Several factors influence the sensitivity and detection accuracy of SPR sensors including material roughness, residual cladding thickness, grating period, metal layer thickness. To accurately determine the resonance wavelength, the transmission dip must be well-defined.

## METHODOLOGY

The first step is to define the various parameters that will be used in building the model. This includes specifying values such as the core radius, cladding radius, air gap width, operating wavelength, and other relevant factors. For the theoretical modelling, a step-index mono-mode fiber was employed, with high purity silica as the outer layer (cladding) and a GeO₂-doped silica core. To determine the RI of the core and cladding, the wavelength-dependent Sellmeier dispersion relation is applied. The implementation of the different materials is through introducing different refractive indices of different materials according to the design and material allotment. The two-dimensional geometry of the design is created by introducing the shapes of the structure and arranging them according to the specifications. The core and cladding, structures shown in Figure 1 are introduced according to the specified parameter value, while the D-shaped fiber is created as part of the design. Additionally, the minute gratings, which are a series of consecutive patterns separated by width of air shown in Figure 2, are positioned in the design over the D shaped cladding. There are 20 consecutive gratings which are 0.5m each. The lower layer is of the Silver and the upper layer is of Fe2O3(Hematite). Different configurations were implemented tested by removing the Hematite layer and trying different materials in the place of Silver such as gold and copper. In the mode plot distribution, blue surrounding area represents regions of lower field intensity, primarily in the cladding and beyond as shown in Figure 3

Materials are assigned to the different parts of the model, silica glass is used for the core, while the cladding is made from n-Ge-dop material. The external medium is also defined, along with the materials that are vital to the performance, such as silver for the gratings and hematite for other structural elements. This careful material allotment is crucial for accurately simulating the sensor’s behavior and performance. The primary focus is on the RI of the materials, as this property directly influences how light interacts with them. Other material properties are not considered in this study. The main emphasis is on how different materials affect the behavior of light, particularly in terms of refraction, which is instrumental to the sensor’s performance. This approach ensures that the simulation accurately reflects the optical characteristics of the materials used. Mesh involves breaking down the model’s geometry into smaller, simpler elements, allowing the software to perform detailed calculations. The mesh helps the program analyse how different physical properties, like the RI or electromagnetic fields, behave across the model. The quality and size of the mesh affect both the accuracy and speed of the simulation. A finer mesh provides more precise results but requires more computing power, while a coarser mesh speeds up the process but may reduce accuracy. Adding a study is key to defining the simulations and results you need. It sets the physics, conditions, and desired outcomes, ensuring the right methods are used. Without a study, the simulation lacks direction, making it hard to draw useful insights, A Parametric sweep lets you adjust key parameters, like wavelength or material properties, to see how changes affect the results, Mode analysis is important for understanding how light or waves travel through your structure, Global Evaluation makes it easy to pull out important results from your simulations, like averages or totals.



**FIGURE 1.** Geometry of D shaped optical fiber **FIGURE 2.** Grating structure

# RESULTS AND DISCUSSION

The mode field distribution plot is obtained by computing mode analysis. This is a mode field distribution plot, showing how light is distributed in a D-shaped optical fiber. The bright central region corresponds to the core shown in Figure 4, where most of the light is confined due to the high RI of the core compared to the cladding. In the case of a D-shaped fiber, the flat side exposes part of the core, allowing some light to leak out as an evanescent field. This unique structure enhances light matter interaction, making it suitable for sensing applications. The plot helps analyse the propagation characteristics and field distribution within the fiber to optimize its design and performance.

A blue circle with a red dot in the center

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## A colorful circle on a blue background AI-generated content may be incorrect.

**FIGURE 3.** Mode plot distribution of D-shaped fiber **FIGURE 4.** Mode plot distribution of core

Different transmittances are shown in Figure 5 corresponding to varying thicknesses of the sensor’s metallic layer, i.e, Silver (Ag), ranging from 40 nm to 65 nm. The resonance dip in transmission shifts with changes in thickness, indicating a strong dependency on layer thickness. Thinner layers (e.g., 40 nm) have resonance dips at shorter wavelengths, while thicker layers (e.g., 65 nm) shift the resonance to longer wavelengths. The depth and sharpness of resonance dips vary, suggesting sensitivity changes with layer thickness. Different transmittances corresponding to Fe2O3 layer (Hematite) thicknesses ranging from 5 nm to 14 nm is shown in Figure 6. Increasing Fe2O3 thickness results in sharper and more pronounced resonance dips, indicating higher sensitivity. Resonance peaks are well-defined, showing the sensor’s wavelength-tunable characteristics. This behavior is indicative of a high-performance plasmonic sensing mechanism. Figure 7 corresponds to air gap widths (wa) of 10, 20, 40 and 60 nm. The resonance dip positions shift toward longer wavelengths as the air gap width increases. Narrower air gaps (e.g., 10 nm) produce dips at shorter wavelengths, while wider gaps (e.g., 60 nm) shift the dips significantly. Table 2 shows the performance metrics of the sensor.

A diagram of a spectrum of different colors

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**FIGURE 5.** Transmission spectrum for different Silver thickness **FIGURE 6.** Transmittance of varying thickness of

Fe2O3 vs grating

**TABLE 2.** Key performance metrics of the sensor

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sensor Parameters** | **Sensitivity** | **FWHM** | **FOM** | **DA** |
| Values obtained | 4.1247  µm/RIU | 0.394 µm | 10.47/RIU | 2.54× |

Figure 8 shows refractive indices 1.54, 1.582, and 1.631, which represent the different layers of teeth. As RI increases, the transmission coefficient decreases consistently across all wavelengths. The peak positions shift slightly with higher RI, and the valleys become more pronounced. The graph’s shape reflects distinct spectral characteristics for each RI, which can help in monitoring disease progression based on optical properties. Table 3 presents the comparative results with the existing work.

A graph of different colored lines

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**FIGURE 7.** Transmittance of varying width of air gap (wa) **FIGURE 8.** Transmittance of varying human teeth RI

# CONCLUSION

The work presents the design and analysis of SPR based biosensor for detection of dental diseases. In order to achieve good sensitivity D shaped fiber with silver gratings and hematite (α-Fe2O3) as the top layer is selected. Sensor dimensions are optimized and achieved a sensitivity of 4.1247 µm/RIU, FWHM of 0.394 µm, FOM of 10.47/RIU and detection accuracy of 2.54× which makes it feasible to detect even the smallest changes in the oral health. The sensor has the ability to offer label free, real time monitoring of dental healthcare. By appropriate experimental validation and clinical trials this method can be used for the improved diagnostic accuracy and eliminate the need of radiographing imaging by supporting faster and safer decision-making.

**TABLE 3.** Comparative analysis of the proposed work

|  |  |  |  |
| --- | --- | --- | --- |
| **Sl. No** | **Sensitivity** | **Papers** | **Citation** |
| 1 | 6.5 um/RIU | Highly Sensitive D-Shaped Optical Fiber Surface Plasmon Resonance Refractive Index Sensor Based on Ag–Fe2O3 Grating | [1] |
| 2 | 83.219 deg/RIU | Human Teeth Disease Detection Using Refractive Index Based Surface Plasmon Resonance Biosensor | [2] |
| 3 | 72 deg/RIU | Surface Plasmon Resonance Based Titanium Coated Biosensor for Cancer Cell Detection | [3] |
| 4 | **4.1247 um/RIU** | Design And Analysis of D-shaped Optical Fiber Biosensor for Human Teeth Disease Detection | **Present Work** |

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