High Performance Opening Up Dual-core Photonic Crystal Fiber Sensor Based on Surface Plasmon Resonance

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High performance opening up dual-core photonic crystal fiber sensor based on surface plasmon resonance

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Abstract:

Nowadays, plasmonic sensor based on photonic crystal fiber (PCF) attracted a great deal of attention in field of optical sensing. An opening up dual-core photonic crystal fiber based on surface plasmon resonance (SPR) are numerically demonstrated and analyzed for detecting wide refractive index (RI) range by Finite-Difference Time-Domain method (FDTD). The wavelength and amplitude integration methods, as well as figure of merit are used to investigate the sensor performance. For improving sensing performance, it is introduced a large hole between two cores in opening up section. The opening up section as a sensing channel is coated with gold film and a thin titanium dioxide ($\text{TiO}_2$) layer. By surface engineering including imposing of grating on the gold film, specification of optimized values of different layers located near the surface, sensing performance are investigated. Next, the effect of the fiber structural parameters is analyzed to enhancing of SPR and fundamental core mode coupling. The proposed sensor revealed maximum wavelength and amplitude sensitivities of $15167 \ (\text{RIU})$ and $207.19 \ (\text{RIU}^{-1})$, respectively. Due to ease of infiltrating analyte and gold coating and tanks to high wavelength and amplitude sensitivity, the sensors can be promising candidate of physical and chemical sensing.

Keyword: photonic crystal fiber, dual-core sensor, surface plasmon resonance, sensitivity, FDTD

1. Introduction

Surface plasmon resonance (SPR) refers to an electromagnetic phenomenon, which is generated by the combination of free electron oscillations and a transverse magnetic polarized electromagnetic wave on the surface between dielectric medium and metal film [1, 2]. Due to outstanding features such as label-free monitoring, high sensitivity, and real-time detection, as well as owning multifarious application such as environmental monitoring, medical diagnostics and food safety, polarization filters, and absorbers, SPR has achieved unprecedented progress in the realm of sensors [2-4]. Kretschman proposed a configuration of SPR sensor based on prism coupling [2, 3, 5]. Bulky apparatus, heavy weight, inability of remote detection, and inflexibility were major inefficiencies of this configuration, which refined by advent of photonic crystal fiber SPR sensors by Jorgenson where gold was used to create the SPR phenomenon [2-5]. Owning outstanding characteristics such as tunable effective refractive index in the fiber core, controllable birefringence, and superior light confining capabilities, PCF-SPR sensors have drawn a great deal of attentions [2, 4]. SPR based sensors, according to PCF’s properties, use several sensing configurations mainly including internal and external metal coating-based sensing approaches. In internal sensing, analyte is infiltrated in the selective micro-meter sized air holes [6, 7]. Rifat et al. proposed a SPR-PCF sensor in which introduced a large air-hole beside the core for efficient light coupling between the cores and SPR modes [8]. In addition, this large air hole will facilitate material coating and effective analyte flow. Conversely, external metal coating-based sensing method is commonly used; Not only does it provide more flexibility, but it is easier compared to covering the inner air-holes as well [8, 9]. To date, various externally coated SPR based PCF sensors, which can include D-shaped structures, have been reported. A dual-polarized spiral photonic crystal fiber based on surface plasmon resonance was proposed in ref. [9]. They showed wavelength sensitivity of $4600 \ (\text{nm RIU}^{-1})$ and amplitude sensitivity of $420.4 \ (\text{RIU}^{-1})$ in y-polarized mode. In the x-polarized mode, the maximum wavelength sensitivity is $4300 \ (\text{nm RIU}^{-1})$ and amplitude sensitivity is $371.5 \ (\text{RIU}^{-1})$. A dual-core PCF sensor using gold as a plasmonic material with high value of amplitude sensitivity but lower value of wavelength sensitivity was reported by Paul et al. [10]. In 2020, designed a large detection-range plasmonic sensor based on a H-shaped PCF with maximum wavelength sensitivity of $25900 \ (\text{nm RIU}^{-1})$ [11]. Recently, SPR based PCF sensors encounter with two main problems. First, due to micro-sized air holes, metal coating and analyte filling are challenging procedures [8, 9, 11, 12]. Second problem is about low RI or high RI PCF-SPR sensors due to their narrow RI range.
of detection [6, 11]. This problem can be solved with respect to the photonic crystal fiber uses the total internal refraction either the crystal geometric properties for light confinement.

Opening up microstructured optical fiber (MOF) structures, such as D-shaped or exposed-core MOF-SPR sensors [13-15] are the promising approaches to evade of infiltrate analyte. Opening up dual-core microstructure optical fiber-based plasmonic sensor with large detection range and linear sensitivity is proposed in [14] and showed the maximal sensitivity of 4900 $\frac{nm}{RIU}$ when the RI of the analyte is close to that of the fiber background material. To overcome the problems aforementioned, in this paper we propose an opening up plasmonic sensor based on dual-core PCF which can be operated in range from 1.42 to 1.46. For improving sensing performance, it is introduced a large hole between two cores in opening up slot. The opening up section as a sensing channel is coated with gold film where a thin titanium dioxide ($TiO_2$) layer is placed between gold and analyte in only this hole part. Next, with imposing changes in surface of this part including applying grated gold film and sandwiching thin layer of $TiO_2$ between fiber surface and gold, we investigate effect of these structure variations on sensing performance. Recently, investigation revealed that gold layer coated on fiber can be flaked off from the fiber [6]. $TiO_2$ accompanied by gold layer can conquer the adhesion problem of gold to fiber [16]. Regard to sensitivity, this sensor shows high sensitivity value better than that of [14]. The opening up part directly fills with analyte and supports possibility for real-time sensing.

2. Design and numerical method

Figure 1(a) illustrates the schematic representation of our proposed sensor, comprises open slot which is coated by a gold layer. This part acts as a sensing channel and can be directly in contact with analyte. In addition, to improve the sensing performance, we introduce a large hole with diameter of $2r_c$ between two cores in sensing channel. Since, evanescent waves can enhance resonance effect, which may improve the sensitivity significantly. This dual-core SPR-PCF sensor has been designed by arranging the air-holes in hexagonal lattice with pitch size of $\lambda$. These air-holes with radius of $r$ work as a low refractive index cladding, enabling mode guidance in the fiber core. Furthermore, we applied a shift by a distance $d_x$ in the center of four selected air holes which is situated neighborhood of the large hole from their original position. Shifting holes lead to achieve optimum structure which is needed to get high sensitivity. With the purpose of increasing the plasmon excitation, a thin layer of $TiO_2$ with the thickness of $t_{TiO_2}$ is deposited on gold.
Fig. 1 Cross-section view of DC-PCF-SPR sensor magnifying of central large hole a with Au and TiO$_2$ thin layer between Au and analyte b with Au nano-continues gratings layer and thin TiO$_2$ layer between fiber material and Au

Our sensor is modeled using the following parameters: $\lambda = 2.26 \mu m$, $r = 0.4 \mu m$, $dx = 0.3 \mu m$, $r_c = 1.85 \mu m$, $t_{Au} = 40 nm$, $t_{TiO_2} = 7 nm$, $w = 1 \mu m$, $h_1 = 7.5 \mu m$, $h_2 = 4.75 \mu m$. The refractive indices of background material and air-holes are supposed to be 1.45 and 1 respectively, and gold permittivity is modelled from Johnson and Christy data [17]. The RI of TiO$_2$ is calculated by [18]:

$$n_{TiO_2}^2 = 5.913 + \frac{0.2441}{\lambda^2 - 0.0803},$$  \hspace{1cm} (1)

$\lambda$ is in $\mu m$ unit.

Perfectly matched layer (PML) is applied as scattering boundary condition. FDTD method is employed to investigate the sensor performance. Figure 1(b) shows the same structure associated with some changes in the surface of the proposed sensor. Indeed grating Au is used as a plasmonic material in large hole part and TiO$_2$ thin layer is deposited between fiber and gold due to assist adhesion. The optimized parameters are as follows: segmented Au film thickness $d_1 = 25 nm$ and continuous Au films thickness $d_2 = 15 nm$, total segment number $N = 28$, $t_{TiO_2} = 5 nm$. Other geometric parameters are the same as mentioned before.

The key factor to analyze the performance of PCF-SPR sensors is calculation of the confinement loss of the fundamental core mode. The imaginary part of the effective refractive index ($n_{eff}$) is used to determine the confinement loss and can be expressed as [19]:

$$\alpha_c \left( dB/cm \right) = 8.686 \times \frac{2\pi}{\lambda(\mu m)} Im(n_{eff}) \times 10^4,$$ \hspace{1cm} (2)

where $\lambda$ is the operating wavelength. The proposed sensor has two guiding modes (a) x-polarization and (b) y-polarization. In the dual-core PCF-SPR sensors, for x-polarization and y-polarization, the odd and even modes are excited simultaneously. But here the confinement loss of the odd mode for y-polarization is the largest, which means that SPR mode couples with odd mode for y-polarization more strongly than the other polarization. Hence, we focus on odd core mode for y-polarization in the following numerical analysis.

3. Results and discussion

Different structural parameters such as radius of central large hole ($r_c$), width of slot ($w$), distance between center to end of slot ($h_2$) and the position of the neighboring holes of central hole ($dx$) are examined and optimum parameters are selected throughout this work. Performance of the proposed sensor is numerically carried out by FDTD method in wavelength range of 0.975-1.7 $\mu m$ and fundamental core mode, SPR mode and dispersion relation are investigated for the proposed sensor. First part of results is associated with the configuration of figure 1(a). The electric field profile of odd fundamental core, SPR and coupled core-SPR modes at resonance wavelength are depicted in figure 2(a)-(c), respectively. Obviously, in resonance condition most of the energy is confined in core regions, and only a small part of energy penetrates to metal film surface, see panel (c). This penetration causes a peak in loss spectrum which can be analyzed by the dispersion relationship between the fundamental core mode and SPR mode as it is shown in panel (d). In fact, coupling between the core and plasmonic modes occurs when propagation constant and wavevector of two modes become equal. This condition is known as phase matching.
Fig. 2 Electric field distribution of the a y-polarized odd core mode, b odd SPP mode, c resonance condition, and d dispersion relation of core mode (green), SPR mode (blue), and loss spectrum (red) of core mode for \( n_a = 1.43, \ t_{TiO_2} = 7 \text{ nm}, \ t_{Au} = 40 \text{ nm} \)

As it is clear from this panel, the real part of \( n_{\text{eff}} \) of both modes coincides at the wavelength of 1.4589 \( \mu \text{m} \), called resonance wavelength where corresponding loss is 89.97 \( \text{dB/cm} \).
The real part of the effective index of the plasmonic mode is highly dependent on the small variation of analyte RI. When RI of analyte is changed, it leads to the resonance wavelength shifts. Using the mentioned optimized parameters, the loss curves of the proposed dual-core SPR-PCF sensor for different RI of analyte ranging from 1.42 to 1.46 in the absence of TiO₂ layer are plotted and shown in Figure 3.

As it is clear from the figure 3, with increasing \( n_a \) up to 1.45, red shift of resonance wavelengths is found, and the loss spectra noticeably increases. But, when \( n_a \) changes from 1.45 to 1.46, resonance wavelength shifts towards longer wavelength, while loss decreases. Next, we have examined the loss curves of proposed sensor by introducing extra over layer of TiO₂. Interestingly it can be observed that by applying TiO₂ layer, monotonic increasing trend in resonance wavelength and its intensity is achieved, as it is shown in figure 4.
Fig. 4 Loss curves as a function of operating wavelength of the proposed sensor for different analyte for $t_{TiO_2} = 7 \text{ nm}$, $t_{Au} = 40 \text{ nm}$

With increasing RI of analyte $n_a$, the peak of loss shifts toward longer wavelength and confinement loss increases, too.

It is convenient to investigate the sensor performance from the loss curve by using the wavelength and amplitude interrogation methods. The ratio of peak wavelength change to refractive index is known as the wavelength sensitivity and it is computed as bellows [20]:

$$S_\lambda = \frac{\partial \lambda_{\text{peak}}}{\partial n_a} \left[ \frac{\text{nm}}{\text{RIU}} \right]. \quad (3)$$

Also, the amplitude sensitivity can be evaluated by the following equation [20]:

$$S_A = -\frac{1}{\alpha(\lambda, n_a)} \times \frac{\partial \alpha(\lambda, n_a)}{\partial n_a} \quad [\text{RIU}^{-1}]. \quad (4)$$

where $\alpha(\lambda, n_a)$ is the confinement loss at different RI. With these definitions, the proposed sensor shows a wavelength sensitivities of 15167, 6894, 3158 and 2179 $\text{nm RIU}^{-1}$, respectively, when the analyte’s RI changes from 1.42 to 1.46 with a step of 0.01. The maximum wavelength sensitivity is 15167 $\text{nm RIU}^{-1}$ which is higher than that of previously proposed in [14] which is a similar work and also it is higher than the maximum wavelength sensitivity of proposed sensor in absence of $TiO_2$ (13024 $\text{nm RIU}^{-1}$). Furthermore, the amplitude sensitivities are obtained 207.19, 62.55, 35.40, and 22.91 $\text{RIU}^{-1}$, correspondingly.
Fig. 5 a Loss variation for different thickness of gold layer of the proposed sensor and b amplitude sensitivity for different thickness of gold layer with $t_{TiO_2} = 7 \text{ nm}$

Generally, geometric parameters have a dominant effect on the sensor performance. The effect of changing of $Au$ and $TiO_2$ thickness on loss spectra are depicted in figures 5 and 6, respectively. As it is seen from figure 5 (a) with increasing the gold thickness from 30 to 50 nm, loss increases and wavelength redshifts. Panel (b) shows amplitude sensitivity; the maximum $S_A$ of $411.1 \text{ RIU}^{-1}$ is obtained for $t_{Au} = 40 \text{ nm}$ with $n_a$ varying from 1.42 to 1.43. This results summarized in table 1 which included both wavelength and amplitude sensitivity for proposed sensor with various thickness of gold. Considering wavelength and amplitude sensitivity, $t_{Au} = 40 \text{ nm}$ is chosen as optimum thickness of $Au$ in our calculations.

Table 1. Effect of gold thickness on the $S_w$ and $S_A$

| Au thickness (nm) | Wavelength sensitivity($S_w \frac{nm}{RIU}$) | Amplitude sensitivity($S_A \frac{1}{RIU}$) |
|-------------------|---------------------------------------------|----------------------------------------|
| 30                | 8728                                        | 292.3                                  |
| 40                | 15167                                       | 411.1                                  |
| 50                | 14768                                       | 263.2                                  |

By this value of $t_{Au}$, the effect of different $TiO_2$ thicknesses on loss curves is illustrated in figure 6 where wavelength sensitivity can be calculated by its data.
Fig. 6 Loss curves for thickness variation of $TiO_2$ for $n_a = 1.43$, $t_{Au} = 40$ nm

The obtained $S_w$ for given $TiO_2$ thicknesses are 13024, 12538, 15167, and 14157 $\text{nm RIU}^{-1}$ respectively in which $t_{TiO_2} = 7$ $\text{nm}$ shows better sensitivity. Titanium dioxide has not only diminished adhesion problem but because of its high refractive index, it strongly attracts the field from the core mode, and causes strong coupling between core and plasmonic mode [21].

Besides of sensitivity, another factor for analyzing sensor performance is figure of merit (FOM) which can be defined as the ratio of sensitivity to full width at half maximum (FWHM) as [22]:

$$FOM(\text{RIU}^{-1}) = \frac{sensitivity(\text{nm} \text{RIU}^{-1})}{FWHM(\text{nm})}.$$  \hspace{1cm} (5)

Now then, sensitivities and FOM of the proposed sensor are investigated for the wide range of analyte RI which are summarized in table 2.

Table 2. Performance analysis of the proposed sensor by varying the dielectric RI.

| Dielectric RI | $S_w$ (nm RIU$^{-1}$) | $S_A$ (RIU$^{-1}$) | FOM (RIU$^{-1}$) | Resolution (RIU) |
|--------------|------------------------|--------------------|------------------|------------------|
| 1.42-1.43    | 15167                  | 411.1              | 207.19           | 6.6 × 10$^{-6}$  |
| 1.43-1.44    | 6894                   | 314.5              | 62.55            | 1.4 × 10$^{-5}$  |
| 1.44-1.45    | 3158                   | 59.95              | 35.40            | 3.1 × 10$^{-5}$  |
| 1.45-1.46    | 2179                   | 19.8               | 22.91            | 4.6 × 10$^{-5}$  |

The proposed sensor shows the best performance in RI range of 1.42-1.43 with respect of wavelength and amplitude sensitivities and FOM. By increasing of $n_a$, these sensing factors decrease monotonically.

Resolution of the sensor is also essential to determine detection capability of offered sensor and can be computed by [22]:

$$R(\text{RIU}) = \Delta n_a \times \frac{\Delta \lambda_{min}}{\Delta \lambda_{peak}},$$  \hspace{1cm} (6)

where $\Delta \lambda_{min}$ is assumed to be 0.1 $\text{nm}$. The maximum resolution of proposed sensor is obtained as high as $6.6 \times 10^{-6}$. Therefore the smallest change in analyte IR in order of $10^{-6}$ can be detected with a high degree of accuracy.

Last part of this work devoted to effect of grating on the surface of structure corresponding to the second configuration, figure 1 (b). A similar calculation are done for this configuration in the presence of grating for various structural parameters such as segment number, segmented metal film thickness and thickness of continuum part of metal layer. A typical SPR mode profile for grated dual-core PCF-SPR sensor is presented in figure 7. Simultaneously localized SPR and propagated SPR in the neighborhood of segment part are clearly observed.
Fig. 7 Electric field distribution of the SPR mode for grated structure for \( n_a = 1.43 \)

The wavelength sensitivity, amplitude sensitivity and figure of merit for grated structure are computed and tabulated for different thicknesses of TiO\(_2\) and also in absence of TiO\(_2\) layer. Evidently, as shown in table 3, in all case of the presence of extra TiO\(_2\) layer, the proposed sensor shows better results in comparison with the bare one, the absence of TiO\(_2\) layer. Thus, TiO\(_2\) has the definite effect on improving sensor detection sensitivity. It is seen that the maximum values of \( S_W \), \( S_A \), and FOM belong to grating configuration associated with 5 \( nm \) of TiO\(_2\) thickness. Therefore, we continue our simulation with 5 \( nm \) thickness of TiO\(_2\).

| \( t_{TiO_2} \) (nm) | Maximum \( S_W \) (RIU\(^{-1}\)) | Maximum \( S_A \) (RIU\(^{-1}\)) | FOM (RIU\(^{-1}\)) |
|----------------------|-------------------------------|-------------------------------|-------------------|
| 0 nm                | 12397                         | 302.9                         | 84.91             |
| 3 nm                | 12068                         | 408.4                         | 150.85            |
| 5 nm                | 13295                         | 511.4                         | 166.18            |
| 6 nm                | 9116                          | 320.8                         | 99.08             |
| 7 nm                | 12638                         | 260.8                         | 133.03            |
| 10 nm               | 11931                         | 326.9                         | 80.07             |

The sensing parameters for different analyte refractive index of grated structure with \( t_{TiO_2} = 5 \) \( nm \), \( t_{Au} = 40 \) \( nm \) and segment number of 28 are came up in table 4. It can be concluded from this table that the \( S_W \), \( S_A \) and FOM reach their maximum value when IR varies between 1.43-1.44.

| Dielectric RI | \( \lambda_{peak} \) (um) | \( S_W \) (RIU\(^{-1}\)) | \( S_A \) (RIU\(^{-1}\)) | FOM (RIU\(^{-1}\)) |
|---------------|---------------------------|-------------------------|-------------------------|-------------------|
| 1.42          | 1.4046                    | 5790                    | 234.9                   | 75.19             |
| 1.43          | 1.4625                    | 13295                   | 511.4                   | 166.18            |
| 1.44          | 1.5954                    | 6282                    | 124.5                   | 73.90             |
| 1.45          | 1.6582                    | 2655                    | 16.27                   | 39.04             |
| 1.46          | 1.6848                    | -                       | -                       | -                 |

Figure 8 shows the effect of N, segment number, on the wavelength sensitivity with and without TiO\(_2\) layer. Also in table 5 the effect of this parameter on the other sensing factors are tabulated.
This figure depicted that the existence of TiO$_2$ layer has considerable role on $S_w$ behavior. In fact, in the absence of TiO$_2$, when N increases, sensitivity varies in a zigzag form where it has smooth behavior with a single peak value in the presence of TiO$_2$. Peak value in both cases occurs in $N = 28$. It is worth mentioned that, the similar calculation for N values smaller than 20 is done which gives sensitivities lower than the obtained peak value. Consequently the sensitivity can be effectively tuned by the segment number. We consider $N = 28$ as an optimized segment number.

Table 5. Effect of Au grated with 5 nm thickness of TiO$_2$ on $S_w$, $S_A$, FOM and average sensitivity for different N.

| Segement number N | maximum $S_w$ (nm/RIU) | maximum $S_A$ (RIU$^{-1}$) | maximum FOM (RIU$^{-1}$) | Average sensitivity |
|------------------|------------------------|-----------------------------|--------------------------|-------------------|
|                  | Without TiO$_2$ | with TiO$_2$ | Without TiO$_2$ | with TiO$_2$ | Without TiO$_2$ | with TiO$_2$ | Without TiO$_2$ | with TiO$_2$ | Without TiO$_2$ | with TiO$_2$ |
| 20               | 10467    | 8722     | 285.4       | 301.3      | 73.71      | 96.91      | 5026        | 4899.3     |
| 24               | 9613     | 10036    | 273.4       | 409.8      | 99.10      | 145.44     | 6101.6      | 6525.6     |
| 28               | 12397    | 13295    | 302.9       | 511.4      | 130.5      | 166.18     | 8193        | 8455.6     |
| 34               | 8373     | 11235    | 283.4       | 472.5      | 64.90      | 160.5      | 5501.3      | 7521.6     |
| 38               | 11438    | 9400     | 225.1       | 400        | 105.9      | 110.58     | 7503.3      | 6862.6     |
From table 5, it can be observed that when N varies from 20 to 38, the maximum obtained wavelength and amplitude sensitivity, FOM, and also average sensitivity are 13295 $\frac{nm}{RIU}$, 511.4 $RIU^{-1}$, and 166.18 $RIU^{-1}$ in presence of $TiO_2$ layer. The corresponding values decrease to 12397 $\frac{nm}{RIU}$, 302.9 $RIU^{-1}$, 130.5 $RIU^{-1}$ in absence of $TiO_2$. It is worth noting that these maximum values allocate to $N = 28$.

Considering the optimized values of $t_{Au} = 40 nm$, $t_{TiO_2} = 5 nm$, and $N = 28$, the effect of $d_1$ and $d_2$ on the sensor performance is considered simultaneously, with the condition of $d_1 + d_2 = 40 nm$ ($d_1 + d_2 = t_{Au}$). Results are illustrated in figure 9 which shows the loss spectra for different arrangement of $d_1$ and $d_2$. For arrangement of $d_1 = 30 nm$ and $d_2 = 10 nm$ when $n_a$ changes from 1.42 to 1.45, the wavelength sensitivities are 7432, 10467, 5805, 3205 $\frac{nm}{RIU}$, while the corresponding values are 6379, 12397, 5805 $\frac{nm}{RIU}$ for the arrangement of $d_1 = 25 nm$ and $d_2 = 15 nm$.

![Fig. 9 Loss spectra as a function of different arrangement of $d_1$ and $d_2$](image)

As a result, when $d_1 = 25 nm$ and $d_2 = 15 nm$ the maximum wavelength sensitivity is higher than that of when the sensor is set with $d_1 = 30 nm$ and $d_2 = 10 nm$.

**Conclusion**
In summary, two different configuration of highly sensitive opening-up dual-core photonic crystal fiber sensors based on surface plasmon resonance have been introduced and numerical analyses have been performed by using of FDTD method. The opening up structure not only simplifies analyte infiltrating and gold coating but also offers the capacity for real-time sensing. The results reveal that the odd mode for y-polarization coupled with odd SPR mode more strongly due to its largest confinement loss in two structures. Additionally, a comparison was made in each configuration with presence of TiO₂ and in absence of TiO₂ in terms of the sensitivity and FOM. As regards applying TiO₂ layer improve the sensitivity about 16% for first configuration and about 7% for second configuration it was observed that dual-core SPR-PCF sensor with TiO₂ thin layer without grating structure shows the highest sensing performance. Surprisingly this sensor has capability to detect higher or lower RI than the RI of the background material. Owning to highly sensitive response, the proposed sensor can be considered ideal for refractive index detection.

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Conflict of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data

The datasets generated during the analysis of current study are available from the corresponding author on reasonable request.

Author contributions

Soghra Ghahramani: Conceptualization, Methodology, Formal analysis and investigation, Writing - original draft preparation.

Jamal Barvestani: Supervision, Project administration, Writing - review and editing.

Bahar Meshginqalam: Writing - review and editing.

Ethics approval

This study is not involved human participants, their data or biological material.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent to publish

Authors give consent for the publication of identifiable details within the text to be published in the Plasmonics journal.

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Figure 1

Cross-section view of DC-PCF-SPR sensor magnifying of central large hole a with Au and TiO$_2$ thin layer between Au and analyte b with Au nano-continues gratings layer and thin TiO$_2$ layer between fiber material and Au
Figure 2

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Figure 3

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Figure 4

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Figure 5

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Figure 6

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Figure 8

please see the manuscript file for the full caption
Figure 9

Please see the manuscript file for the full caption.