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Research Article

D-shape Optical Fiber Development and Enhancement as a Refractive Indices Sensor Using Surface Plasmon Resonance

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Abstract: This article showcases the development and utilization of a side-polished fiber optic sensor that can identify altered refractive index levels within a glucose solution through the investigation of the surface Plasmon resonance (SPR) effect. The aim was to enhance efficiency by means of the placement of a 50 nm-thick layer of gold at the D-shape fiber sensing area. The detector was fabricated by utilizing a silica optical fiber (SOF), which underwent a cladding stripping process that resulted in three distinct lengths, followed by a polishing method to remove a portion of the fiber diameter and produce a cross-sectional D-shape. During experimentation with glucose solution, the side-polished fiber optic sensor revealed an adept detection sensitivity of 0.2015 au. /RIU. In order to improve sensitivity, a recent sensor was subjected to a coating process utilizing a thin film layer of gold (Au) measuring a thickness of 50 nm. The sensor was subsequently subjected to a series of tests utilizing the same glucose solutions as in previous experiments. A notable enhancement in sensitivity was observed when utilizing gold as the sensing material, with an equivalent maximum sensitivity of 3.101 au. /RIU.

Keywords: D-shaped fiber, fiber sensor, refractive index, gold nano-layer, surface plasmon.

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1. Introduction

There has been a growing interest in using optical fiber technology for refractive index (RI) measurements in recent years because of the significant benefits it offers over traditional sensor technologies. There are numerous benefits provided by this technology, such as swift reaction time, small dimensions, reliable and secure operation, adaptability, the ability to be remotely monitored, and adeptness in handling challenging conditions [1]. The main techniques used to measure RI, an optical phenomenon, are fiber Bragg gratings [2], fiber ring laser [3], tapered multimode optical fiber [4], single mode-coreless-single mode (SCS) fiber [5], fiber-based surface Plasmon resonance [6], Most fascinating strategies for detecting surface Plasmon stimulation are those based on surface plasmon resonance (SPR), which are extremely sensitive to changes in the refractive index (RI) of their surroundings [7-8]. Significant work has been expended in recent years to alter a D-shaped fiber optic to use in SPR sensors. Jing Zhao et al. (2016) The researchers examined the sensor performance reduction brought on by the degradation of the silver coating while also demonstrating a surface plasmon resonance refractive sensor based on a single-mode optical fiber that has been side-polished. The sensor was quick to react with liquids with refractive indices between 1.32 and 1.40 RIU [9]. Zakaria et al. (2017) examined the modeling and fabrication of a D-shaped fiber optic for SPR sensors. Methods for designing the SPR D-shaped fiber sensor are presented in this study, both computational and experimental, which include two setup approaches: finite element simulation and experimental methods. The experimental findings are highly correlated to the modeled results [10]. D-shaped, silver-coated, graphene-encased sensors were conceptualized and theoretically explored by Arthor A. Melo. et al. (2018). The proposed sensor achieves its best performance between 1.33 and 1.35 RIU with reduced sensing area lengths and higher polished thicknesses [10]. In 2019, Li-Ye N. et al. developed & tested a gold nanoparticle–Au layer–interacting optical fiber sensor in a D shape with a big core. In the area of refractive index (1.3332–1.3710 RIU), the SPR sensor was enhanced with gold nanoparticles (Au NPS) [12].

In this study, the goal was to enhance efficiency by applying a layer of gold 50 nm thick to the D-shaped fiber's sensing region. we develop a simple but efficient D-shape multimode fiber sensor for RI detection in a glucose solution. The samples were initially evaluated, and the findings were recorded using a D-shaped fiber sensor with a section of stripped fiber cladding as the detecting zone. After that, a 50-nm coating of gold (Au) was added to the initial sensor to increase its sensitivity. To determine the sensor's sensitivity throughout the glucose RI range of 1.334 to 1.346 RIU, the effect of the length of the stripped cladding portion is also examined. The benefits of this type of sensor are its ease of use, low cost, broad dynamic range, and good sensitivity at RI values below but near to the fiber core's RI value.

2. Fabrication of D-shaped Fiber Sensor

A schematic configuration of an optical fiber sensor in the D-shape, according to Fig.1(a). Thorlabs', step-index, and multimode silica optical fibers were used to fabricate a D-shaped fiber sensor with silica core 400 µm and fluorinated polymer cladding 25µm. In the visible spectrum, silica exhibits a refractive index of approximately 1.45, while the fluorinated polymer's refractive index is around 1.40. Initially, a collection of fiber specimens was sliced using a specialized tool to achieve 15 cm segments. In order to get ready for the polishing process, a small section in the middle of the fiber covering was taken off using an Ls sensing region (1 cm, 1.5 cm, 2 cm).

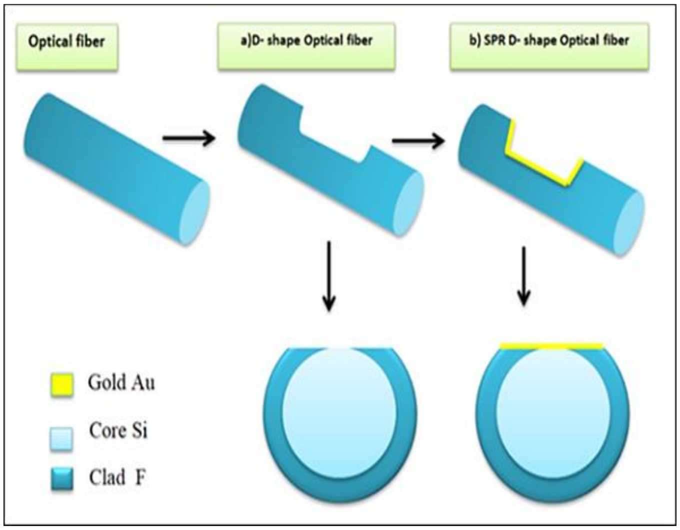

Fig.1: The steps included in the schematic design for the following sensors: a) D-shape fiber sensor; and b) SPR D-shaped fiber sensor.

This section was then fixed onto a slide that had a slot using epoxy. By repeatedly refining the sensor with 6 µm grit-sized polishing sheets (specifically Thorlabs sheets), the entire detection area of the sensor was manually polished along its entire length [15]. After each polishing stage, the sensing zone's surface was examined with a Novel NMM-800 optical microscope to estimate its average thickness. The SPR D-shaped fiber sensor has been achieved by coating Au-film on a polished fiber surface with a Quorum Tech Q150RES magnetron sputtering system. The plan is to utilize the sputter coating setup to cover thin layers of gold measuring 50 nm as shown in Fig.1(b) [16].

The refractive index of a liquid can be measured using a D-shape optical fiber sensor based on the evanescent field. As shown in Fig.1(a), the basic structure of a D-shape optical fiber sensor consists of a core, cladding, and sensing medium at the polishing area. The guiding light depends on the total internal reflection phenomenon at the core-cladding interface and produces an evanescent wave that travels along the core-cladding interface. In the sensing zone, this ephemeral field decreases at an exponential rate [20]. As a result of these characteristics. To improve the sensitivity of the D-shaped optical fibers sensor a gold nanofilm is deposited on the core-cladding interface, as shown in Fig.2(b). A D-shaped optical fiber sensor based on the SPR principle has been developed. When incident light strikes a continuous metal film at just the right angle, it will be totally reflected back into its source. Surface plasmon resonance (SPR) is excited when an evanescent wave penetrates a metal, and the location of the SPR's wavelength is dependent on the refractive index (RI) [21].

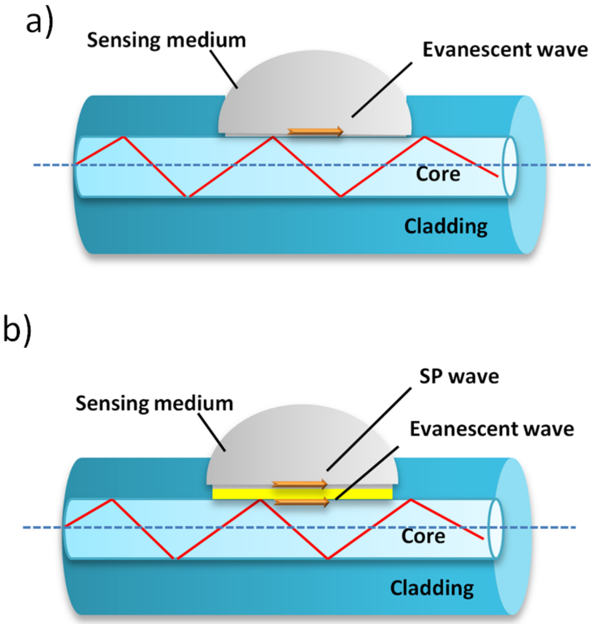

Fig.2: The schematic structure of a) D-shape fiber sensor; and b) SPR D-shape fiber sensor

3. Experiment Setup

Figure 3 depicts the test setup for RI detection using a D-shape optical sensor. The source of light for the experiment was an NKT Photonics ultra-compact white light laser. To select the 650 nm laser light, Thorlabs multi-mode fiber optic filter/attenuator was used. Thorlabs, a PM100 USB power meter was used to measure how much energy was being emitted or absorbed by the fiber optic sensor element, and the data was processed in software. The sensors' refractive index sensing experiments were performed in refractive index areas (1.334-1.346 RIU) using two sensors to compare and evaluate their sensitivity and linearity and select the most efficient sensor. The refractive indices of the investigated solutions were determined using a hand-hold "pocket" refractometer. At constant temperature, Fig.4 depicts the connection between a solution's concentration and the refractive indices of its component parts. Refractive index and concentration are directly proportional, meaning that as material solution concentration increases, so does refractive index.

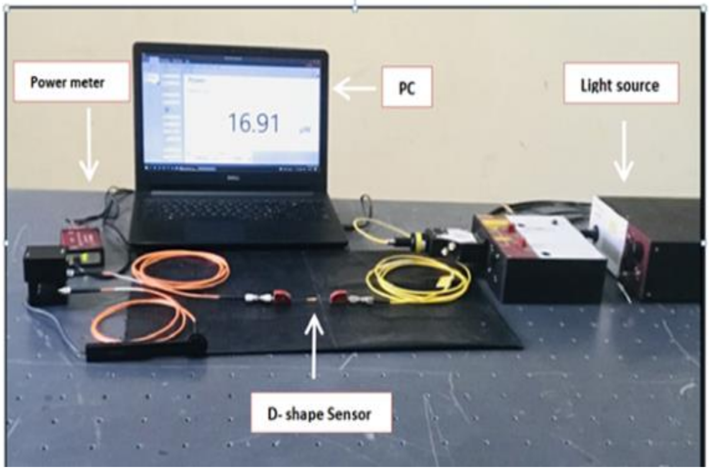

Fig. 3: Experimental setup device for IR sensor measurement.

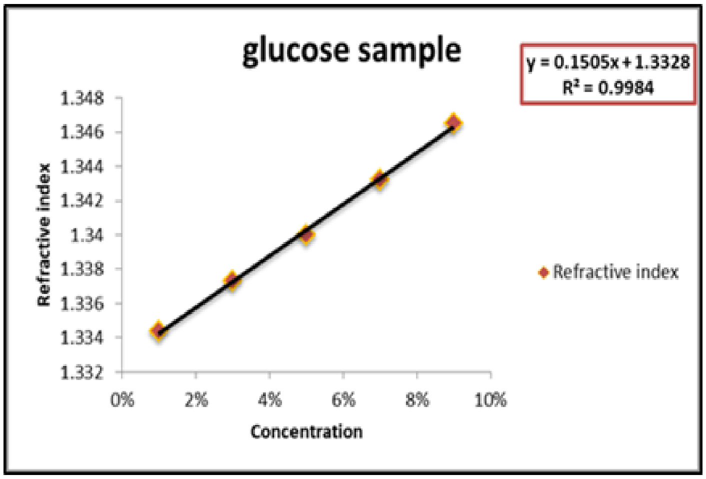

Fig. 4: The concentration of a glucose solution affects the solution's refractive index.

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4. Results and Discussion

4.1 Optical Microscope Image and Energy Dispersive Spectroscopy spectra

Figure 5 depicts the photo image and optical microscopy representations of a D-shape fiber sensor both prior to subsequent to its coating with Au, with a magnification of 5X. The SPR D-shaped fiber sensor was analyzed using energy dispersive X-ray spectroscopy (Axia Chemi) SEM. This innovative method combines the use of data from scanning electron microscopy (SEM) as shown in Fig.6, and energy-dispersive X-ray spectroscopy (EDS). Figure 7 depicts the EDS spectra, which exhibit the existence of a multitude of elements in the specimen, namely fluorine F, silicon Si, gold Au, oxygen O, and carbon C, along with their individual atomic number and mass, as illustrated in Table 1.

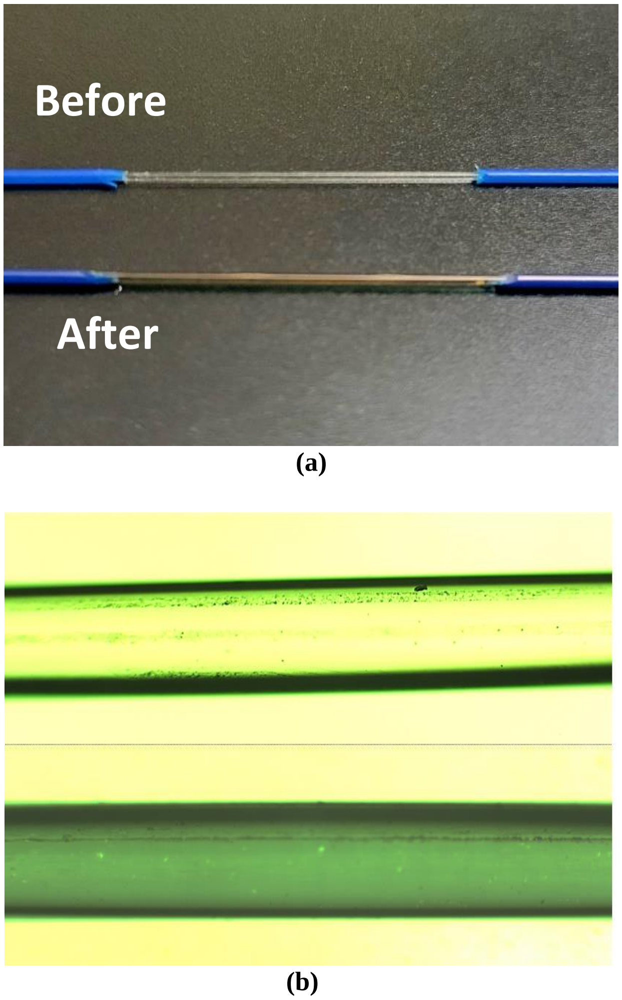

Fig.5: a) The photo image and b) Optical microscopy images, before and after Au coating, of a D-shaped fiber sensor.

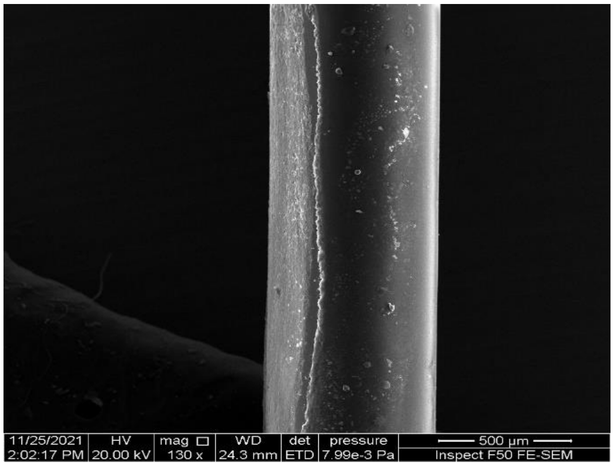

Fig.6: D-shaped SPR fiber sensor SEM image.

Table 1: EDS data for SPR D-shape fiber sensor elements.

Element	Atomic %	Weight %
C	62.7	53.8
O	23.6	27.0
F	13.7	18.6
Au	0.0	0.6
Totals	100.0	100.0

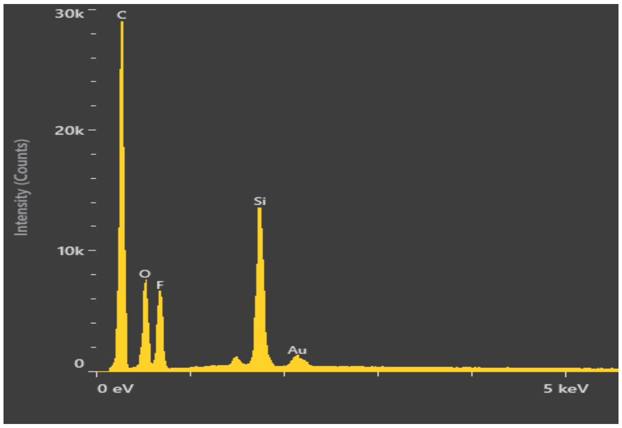

Fig.7: Sensor EDS spectra for SPR D-shaped fibers.

4.2 A D-shape fiber sensor's performance

Figure 8 plots the normalized intensity against the glucose solution's refractive index for all the D-shape fiber sensors that were examined as the sensors interact with the surrounding medium outside the fiber core, the normalized intensity rises linearly with increasing RI in the range of (1.334 to 1.346) RIU.

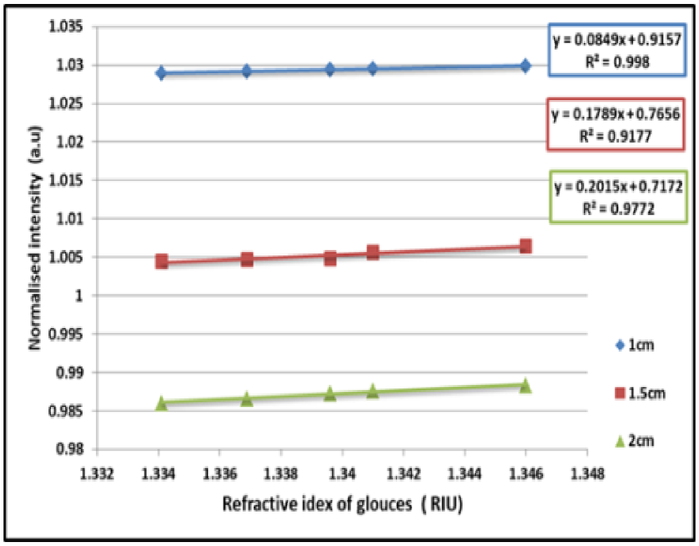

Fig. 8: Intensity normalized by sensing length for D-shaped fiber sensors.

The glucose solution will stop the evanesces wave from exiting the fiber because the surrounding medium's refractive index has increased, which acts as an optical fiber cladding .

4.3 SPR D-shaped fiber sensor performance

Here, a D-shaped fiber covered with Au nanofilm senses the refractive index (RI) of the glucose solution. A gold nano-film is required for a surface plasmon resonance-based detection technique. This film must be exposed to both incident and absorbed light for detection to be possible, and detection is defined by the detected light intensity.

Normalized intensity and corresponding refractive indices for increasing glucose concentration are shown in Figure 9 for the SPR D-shaped fiber sensor. As the glucose RI rises, so does the sensitivity of the proposed sensor. The decrease in the refractive index difference between the two media may be responsible for this influence on the SPR D-shaped fiber structure [13].

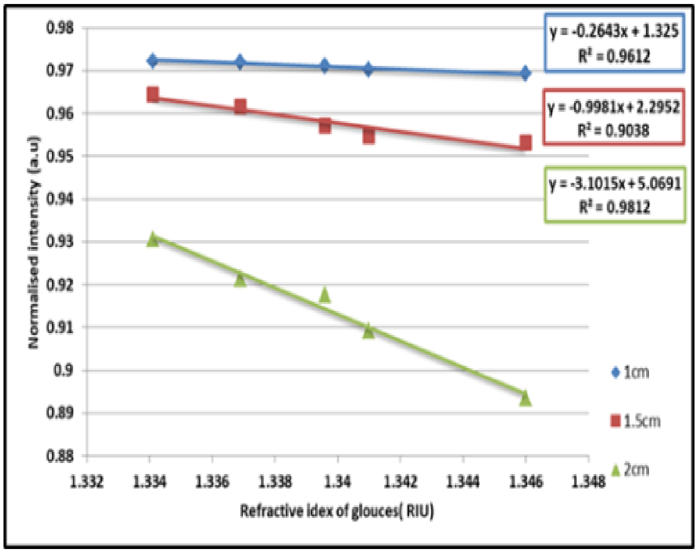

Fig. 9: Intensity normalized by sensing length for SPR D-shaped fiber sensors.

5. Sensitivity analyses and enhancement

The suggested D-shape fiber sensor and SPR D-shape fiber sensor performance have been evaluated in this study for glucose materials which have a range of 1.334 to 1.346 RIU for their refractive indices.

The sensitivity for each sensor at various sensing lengths is the absolute number obtained by the slope of the line fitting. By using the following equation to compute the sensitivity S:

$$S = \left|\frac{\Delta\ I_N}{\Delta\ n}\right| \tag{1}$$

Where ΔI_N is the variation in the normalized intensity and Δn indicates the material's fluctuating refractive index [14]. Table 2 displays the calculated sensitivity using eq. (1). Figure 10 shows the sensitivity vs. sensing length relationship for D-shape fiber sensors and SPR D-shape fiber sensors. An SPR D-shape fiber sensor with a 2 cm detecting length was used to obtain the high sensitivity of 3.1 au. / RIU.

The addition of an Au nanolayer to the D-shaped fiber sensor improves its sensitivity. The results of the experiments show that the SPR D-shaped fiber sensor has ~ a 15% enhancement in sensitivity compared with the D-shape fiber sensor.

Table 2. Sensitivity comparator and enhancement.

Sensing length	D-shape fiber sensor	SPR D-shape fiber sensor	Enhancement
	S	*S*	*En*
Ls = 1 cm	0.0849	0.2643	3.11 %
Ls =1.5 cm	0.1789	0.9981	5.58 %
Ls = 2 cm	0.2015	3.1	15.39 %

Table 3. Comparison of different fiber sensors for measuring refractive index.

Fiber sensor	Method	Analyte	Sensitivity	Ref
Un-cladding fiber	LSPR	sucrose solution	1.612 au/RIU	[17]
hetero-core structure	LSPR	glycerin solutions	2.93au/RIU	[18]
D-shape fiber	--	glycerin solutions	2.827 au/RIU	[19]
D-shape fiber	SPR	sucrose solution	3.101 au/RIU	This work

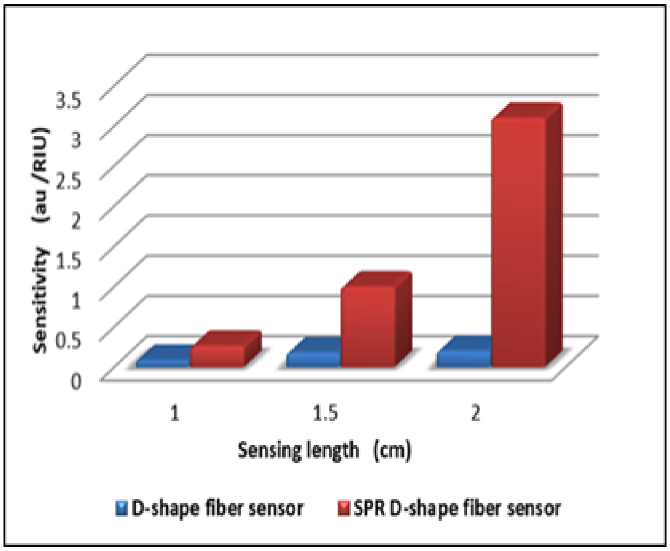

Fig. 10: The relationship between sensitivity and sensing length for IR fiber sensors.

The D-type optical fiber structure increases the effective detection area of the sensor by increasing the polishing depth of the fiber, resulting in improved sensitivity. The gold film on the flat section of the fiber structure enhances the field intensity of the local electric field, leading to improved sensor performance.

Finally, the results of the present work's SPR D-shaped fiber sensors are compared to those of other existing fiber sensor architectures in Table 3. Since the D-shape structure simply requires the side polishing of the multimode fiber, its manufacture is easy to fabricate and low cost from the others.

6. Conclusions

The current research describes the creation and design of a side-polished optical fiber sensor that is both straightforward and efficient in measuring values for the RI of glucose solutions. The sensor's sensing region is located within the uncoated section of the optical fiber cladding. The present study also examines the influence of the length of the exposed cladding section on the sensor's ability to monitor variations in refractive index at a reasonable range. The sensor underwent development and refinement through the utilization of surface plasmon resonance (SPR) characteristics. The experimental results of the developed sensors demonstrate that the SPR D-shape fiber sensor has ~15% enhancement in sensitivity compared with the D-shape fiber sensor.

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تطوير الألياف الضوئية على شكل D وتحسينها كمستشعر لمؤشرات الانكسار باستخدام رنين البلازمون السطحي

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الخلاصة: تعرض هذه المقالة تطوير واستخدام مستشعر الألياف البصرية المصقول جانبياً الذي يمكنه تحديد مستويات معامل الانكسار المتغيرة داخل محلول الجلوكوز من خلال تنفيذ تأثير رنين البلازمون السطحي. تم إنشاء الكاشف باستخدام ألياف السليكا الضوئية، والتي خضعت لعملية تجريد الكسوة التي أسفرت عن ثلاثة أطوال متميزة ، تليها طريقة تلميع لإزالة جزء من قطر الألياف وإنتاج مقطعي عرضي على شكل حرف D . أثناء تجربة محلول الجلوكوز ، كشف مستشعر الألياف البصرية المصقول جانبياً D- shaped fiber عن حساسية كشف تبلغ (0.2015 au./RIU). من أجل تحسين الحساسية ، تعرض جهاز الاستشعار لعملية طلاء باستخدام طبقة رقيقة من الذهب (Au) بسمك 50 نانومتر. خضع المستشعر SPR D- shaped fiber لاحقا لسلسلة من الاختبارات باستخدام نفس محاليل الجلوكوز كما في التجارب السابقة. لوحظ تحسن ملحوظ في الحساسية عند استخدام الذهب كمادة استشعار ، حيث بلغت حساسية المستشعر (3.101 au / RIU).