Influence of Optical Fiber Diameters on the Performance of Surface Plasmon Resonance Sensor

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Abstract:

In this research, a sensor for chemical solutions was designed and formed using optical fiber-based on a surface Plasmon resonance technology. A single-mode optical fiber with three different diameters (25, 45 and 65) µm was used, respectively. The second layer of the low refractive fiber was replaced by gold, which was electrically deposited at 40 µm thickness. For each of the three types of optical fiber, different saline concentrations (different index of refraction) were used to evaluate the performance of the refractive index sensor (chemical sensor) by measuring its sensitivity and resolutions. The highest values we could get for these two parameters were 240mm/RIU, and $6*10^{-5}$ RIU respectively, when the diameter of an optical fiber was 25µm.

Keywords: Chemical optical fiber sensor, Chemical etching, Single mode optical fiber, Surface Plasmon Resonance.

Introduction:

There have been major developments in recent times in the field of sensors, particularly those involving biological and chemical sensors, where appropriate solutions have been found to overcome many of the problems in this field, as well as the addition of new features to detection. Most of these problems were due to the size of the sensor, the number of samples being tested, the ability to detect small changes, and the cost factor by improving the high sensitivity performance[1,2].The most important of these characteristics is the speed of response, the need for a small amount of material to be tested, real-time analysis, remote sensing, also the low cost of manufacturing it, in addition to having distinct performance parameter. The surface Plasmon is the excitation of free electrons in the interference boundary zone between dielectric and metal material. These excitations are transverse magnetic waves transmitted throughout the district area. The field associated with it vanishes in the dielectric and metal, the cause of the magnetic field for these surface waves that have been excited by the light has parallel polarized on themetal surface[3-5].

When the transmission constant of the incident light is equal to that of the surface SPR will be occur, light energy will be transferred from the incident rays to the surface wave of Plasmon. The propagation constant of the Plasmon wave depends on the constant of the dielectricof the external medium, which is in contact with the surface metal. A variation in the value of the dielectric constant causes a variation in the constant of propagation of light incident wave which has (p-polarized) at resonance. The variation in the wave constant of propagation of incident light when resonance occurs determines the value of the dielectric constant of the external medium. For the Plasmon resonance technique there are several optical elements that must be employed such as a prism ata high refractive index, a diffraction grating and an optical fiber[5-7].

Theoretical concepts

Surface Plasmon sensor sensitivity is based on attenuation of the signal entering the optical fiber, which is transmitted by the principle of total internal reflection (TIR). The basic structure of this sensor consists of three layers, an optic fiber core, a

thin layer of chemically stable metal such as gold, and a third layer represented by the material being tested, as shown in Fig.1.
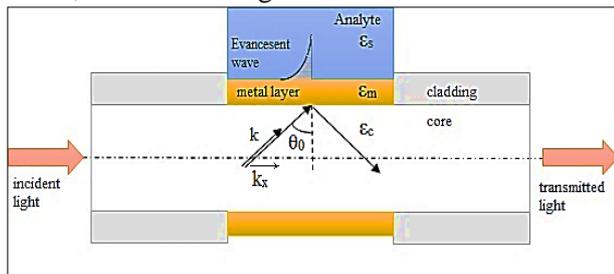
Figure 1. Shows the sketch of the sensor components: the silica fiber core, the metal layer and the analyzed medium[5].

This sensor is fabricated by removing the low refractive index of the second layer and then substituting it with specific metal precipitation directly onto the core of the optical fiber. When a certain light is inserted at the entire end of the optical fiber and then detected at the output end using an optical spectrum analyzer (OSA).

At specific wavelengths the intensity of the output light detected from another end has been a sharp dip and a resonance occurs because a high absorption of these wavelengths under surface Plasmon resonance condition [8-10].

Any variation in the refractive index of the third medium under the sensing process will result in a shift in the value of the wavelength at which resonance occurs (λ_{res}). To study and evaluate this sensor main four key parameters must be calculated, the sensitivity, signal-to-noise ratio, figure of merit and the resolution precision. Sensitivity is defined as the ratio of the change in resonance wavelength to the corresponding change in the index of refraction. The equation can be written as follows [7,11].

$$S_n = \frac{\delta\lambda_{res}}{\delta n_s} \text{ ------- 1}$$

Where S_n represents the sensitivity, $\delta\lambda_{res}$ the variation in resonance wavelength, δn_s and the variation in analytes refractive indices.

The sensor spectral resolution(R)can be determined by the ratio between the minimum variation in the refractive index of the medium tested by the sensor and the change in the peak of the resonance wavelength multiplied by the optical resolution of the spectrum analyzer(OSA) device used in these experiments, as follows [12-14]:

$$R = \frac{\delta n_s}{\delta\lambda_{res}} \delta\lambda_{DR} \text{-------- 2}$$

Where $\frac{\delta n_s}{\delta\lambda_{res}} = 1/Sn$ and ($\delta\lambda_{DR}$) is the spectral resolution of the spectrometer which is equal to 0.1 nm.

Preparing sensor and setup:

The Fabrication process of the MMF-SMF-MMF structure of optical fiber refractive index sensors was done via a few experimental procedures at room temperature. First, a suitable length of single-mode fiber had been used of standard core/ cladding diameters 10 /125 μm. About 3 cm in the middle region of the fibers had been stripped and cleaned very well. After that, the stripped region was immersed in a hydrofluoric acid (HF) with an original concentration of 42%. The acid had been diluted with distilled water {1(HF):3(Distilled Water)} ml. The immersion time was 60, 120, 180 seconds to get different optical fiber diameters. After that, the resulted optical fiber had to be cleaned very well to remove all the acid reside and stop the chemical reaction. This is done by dipping the fibers into distilled water for a few minutes in three stages. The outer diameter of the sample was then measured using an optical microscope (Nikon Eclipse ME600) with a magnification of 100X. The resulted final diameters resulted from the chemical etching with different dipping times were 65, 45, and 25 μm respectively Fig.2, shows the resulted tapered optical fibers. To fabricate the surface Plasmon layer, gold nanoparticles were deposited on the surface of the three tapered sensors. A method called "sputtering" is among these and has become one of the most common methods to produce thin films. Sputtering is a physical vapor deposition (PVD) system used in a high vacuum setting to deposit materials onto a substrate by ejecting atoms from those materials and condensing the expelled atoms onto a substrate. The thickness of the gold layer is about 40 nm. After this stage both ends of the sensor were spliced by multimode the optical fiber using optical fiber splicer machine Fujikura (FSM-60S Japan).

The sensing medium is sodium chloride (NaCl) solution. Different concentrations were prepared to get different refractive index solutions. Concentrations range from 0.05 - 0.45 mol/liter. The refractive indices of the resulted solution were measured using a Refractometer ((BOECO Digital ABBE Refractometer).
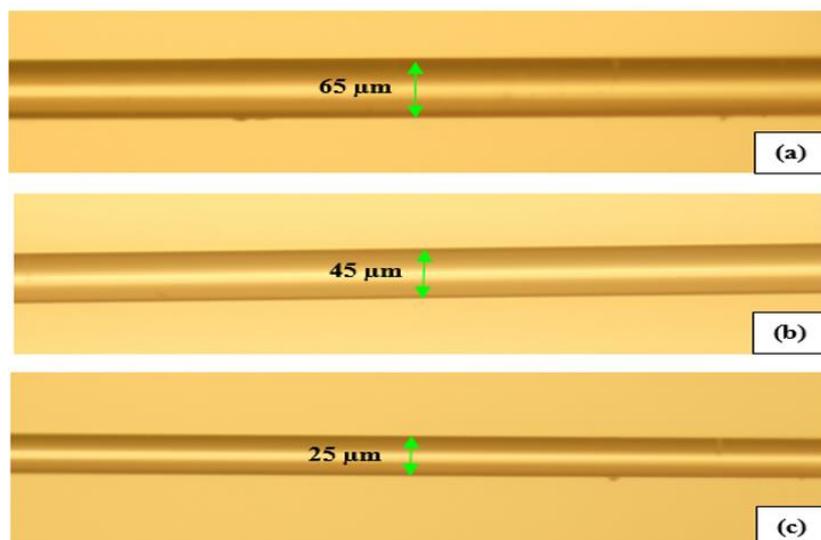
Figure 2. The microscopic image of the resulted tapered fiber with diameters (a) 65µm, (b) 45 µm, and (c) 25µm

The refractive index characteristics of the submitted sensor were tested at room temperature (25 ˚C). In this paper the influence of sensor diameter on the sensor performance will be studied and analyzed.

The schematic diagram and photographic image of the experimental work are shown in Fig.3.
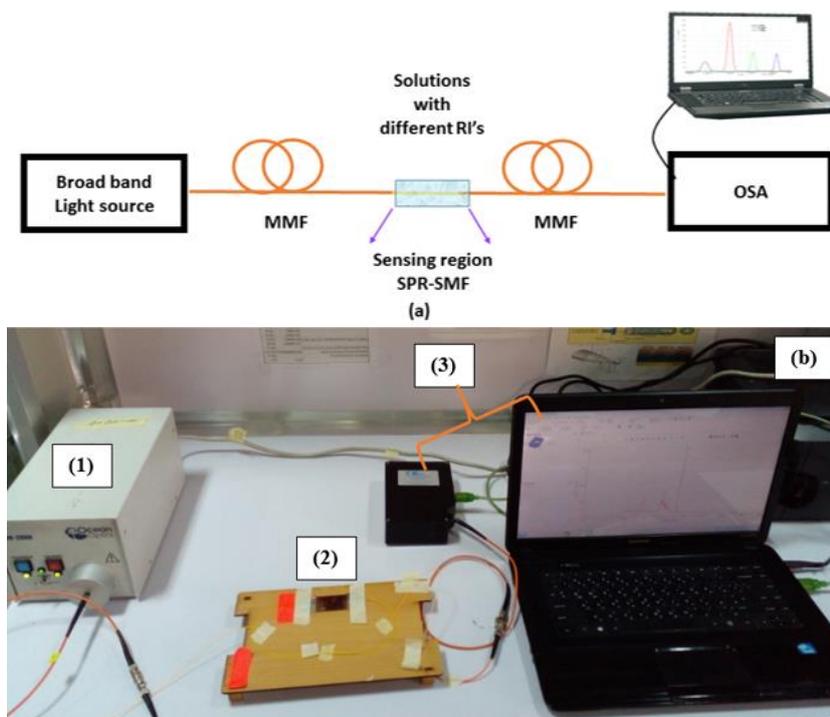
Figure 3. (a) The schematic diagram and (b) the photographic image of the experimental setup. Where (1) represents the light source, (2) the sensing region, and (3) the OSA with PC.

The input arm of the sensor is connected to the UV-VIS light source (DH-2000 Ocean optics) with a range 200-1100 nm as a transmitting signal passing through the sensors. The visible range of the spectrum chosen for this experiment is the deuterium. The output side of the sensor is connected to the Optical Spectrum Analyzer (OSA) (Ocean Optics USB- 2000) with a range 200-1100 nm. The active (sensing) region of the prepared sensors of diameter 65, 45, and 25 µm wasimmersed in the NaCl solution with different refractive indices. The absorption spectrum for each case was collected and analyzed online using the optical spectrum analyzer.

Results and Discussion:

Determined the resonance wavelength:

In the wavelengths and absorbance of the light source, the resonance wavelengths were determined for each of the refractive parameters for different saline solutions. Then this step was repeated for the three different types of optical first step, was after the optical spectrum analyzer (OSA) curves between the different bars whose diameters are 65, 45, and 25 μm respectively. When observing the different curves, we find that there are dipsat specific wavelengths, these values represent the wavelengths of Plasmon resonance that correspond to a specific index of refraction, Fig.4, shows these relationships.
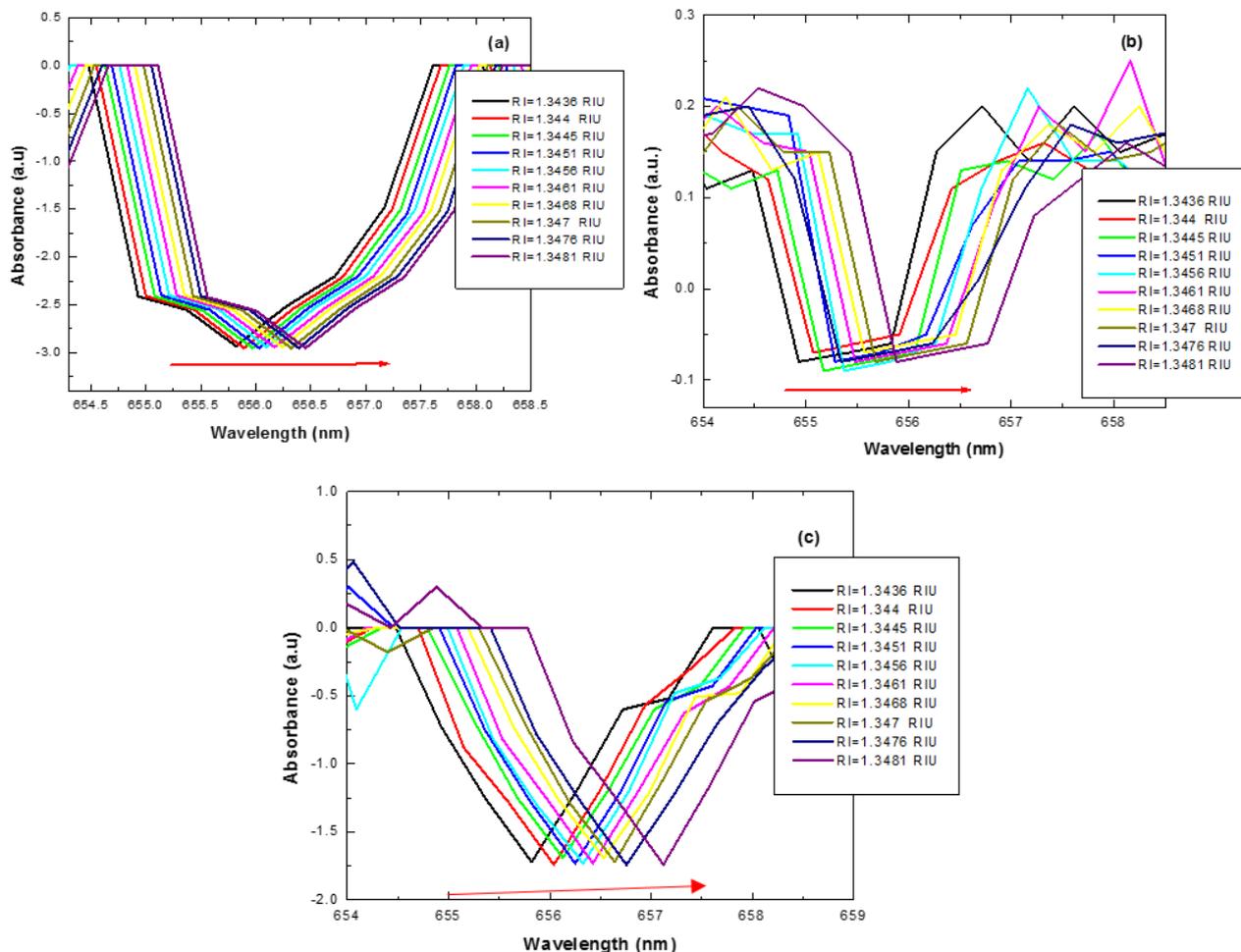
Figure 4. Illustrate the resonance curves SPR for three different types of optical fibers (a:65 –b:45, c:25) μm and with 40nm thickness gold layer at different refractive indices of sensing media

Influence of Refractive index onresonance wavelength:

Using the curves representing the relationships between wavelength and absorbent in the previous step, and after determining the values of the Plasmon resonance wavelengths corresponding to the refraction coefficients of different saline solutions, the relationships between these variables had been drawn, and for three different types of optical fiber diameters. Fig.5 illustrates these relationships along with Tables. 1 and 2. In the three figures below, there is adirect relationship between the increase in refractive index and the wavelengths of resonance. The curves shift towards the large wavelengths with a greater index of refraction of the medium to be tested (redshift).
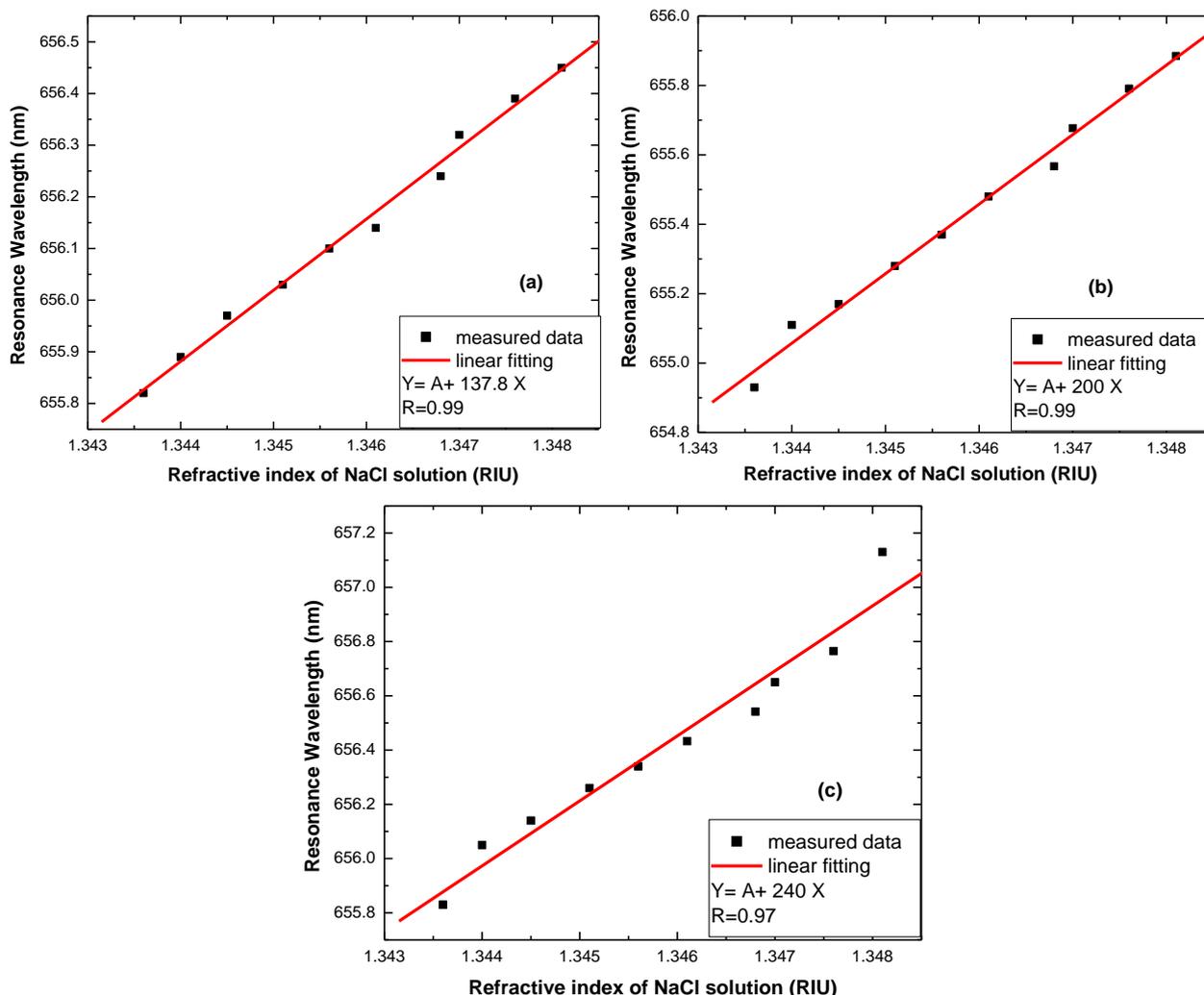
Figure 5. Illustrates the resonance wavelengths as a function of refractive index for three different types of optical fiber.

Table1. Illustrate the refractive indices and evaluated resonance wavelengths for three types of fibers

RI of NaCl solution(RIU)	Resonance Wavelength for sensor diameter 65 µm(nm)	Resonance Wavelength for sensor diameter 45 µm(nm)	Resonance Wavelength for sensor diameter 25 µm(nm)
1.3436	655.82	654.93	655.83
1.344	655.89	655.11	656.05
1.3445	655.97	655.17	656.14
1.3451	656.03	655.28	656.26
1.3456	656.1	655.37	656.34
1.3461	656.14	655.48	656.433
1.3468	656.24	655.567	656.542
1.347	656.32	655.677	656.65
1.3476	656.39	655.791	656.765
1.3481	656.45	655.885	657.13

Table 2. Illustrate the calculated main sensors parameter for three types sensors

Sensor Diameter (µm)	Sensitivity (nm/RIU)	Resolution (RIU)
65	137.8	0.9×10^{-5}
45	200	5×10^{-5}
25	240	6×10^{-5}

Sensitivity as a function of sensor diameter:

The most important variable that can describe a sensor's performance is its sensitivity to small changes in the medium being tested. By observing the curves and tables above, we can draw the relationship between sensitivity as a function of the diameter of the sensor on the three types of optical fibers used. Once the relationship has been drawn, one can observe the inverse relationship

between an increase in thediameter and sensitivity of the fiber, which leads to an increase in the accuracy of the resolution when decreasing the fiber diameter, as shown in Fig .6.
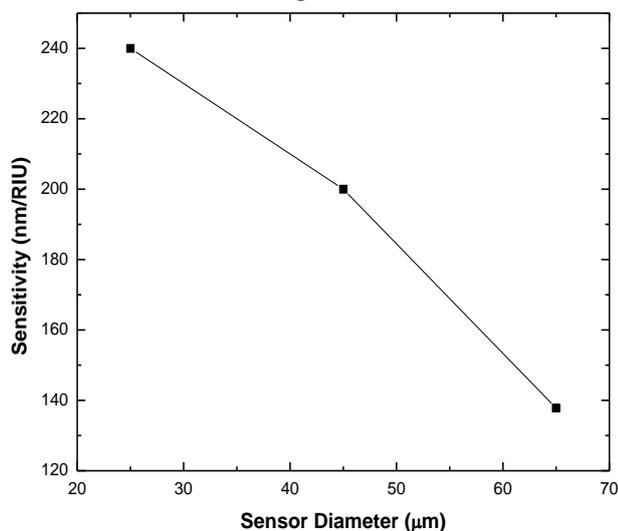
Figure 6. The sensitivity of sensor as a function of fiber diameter

Conclusions:

After studying all the results that have been reached, we can conclude the following: The surface Plasmon resonance sensor is very sensitive to the slightest changes that occur in the samples. The resonance wavelengths of high concentration solutions (high refractive index) shift toward the larger values (red shift) and what is about sensitivity and resolution of the sensor we see increase in both variables with decreasing diameter. Finally, it can be said that this sensor can be used in different chemical application fields, depending on how the refractive index of the sample is altered.

Authors' declaration:
- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for re-publication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in University of Baghdad.

Authors' contributions statement:

T.J.M. the first author carried out the studies needed to do this research, made the measurements, and wrote the results, made the calculations, and discussed them. As for H.Y.H. the second author, his role was to propose the subject of the research and formulate a plan for its implementation, with a contribution to supervising the implementation of the researcher's experiments and offering assistance if required. Also contribute to the analysis of the results.

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تأثير قطرالألياف الضوئية على أداء متحسس استشعار رنين البلازمون السطحي

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الخلاصة:

في هذا البحث صمم وشكل متحسس كيميائي باستخدام الليف الضوئي وبالاعتماد على تقنية رنين البلازمون السطحي. حيث استخدم ليف بصري من نوع النمط الاحادي ولثلاث اقطار مختلفة هي (25, 45, 65) مايكرومتر وعلى التوالي. ازيلت الطبقة الثانية لليف الضوئي ذات الانعكاسية الواطئة واستبدلت بطبقة رقيقة من معدن الذهب كهربائيا وبسمك 40 مايكرومتر. اجريت التجارب لثلاثة انواع من المتحسسات وباستخدام تراكيز ملحية مختلفة (محاليل ذات معاملات انكسار مختلفة) في تقييم اداء المتحسس الكيميائي(متحسس لمعاملات الانكسار), وذلك من خلال قياس التحسسية ودقة التحليل . ان اعلى قيم تم الحصول عليها كانت 240 نانومتر/ وحدة معامل انكسار و 6 * 10⁻⁵ وحدة معامل انكسار على التوالي , وعند استخدام اليف البصري ذو القطر 25 مايكرومتر.

الكلمات المفتاحية: متحسس ليف بصري كيمياوي، الحفر الكيمياوي، ليف ذو نمط مفرد، رنين البلازمون السطحي

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