Fabrication of a Chemical Sensor Based on Surface Plasmon Resonance via Plastic Optical Fiber

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Abstract

In this work, a chemical optical fiber sensor based on Surface Plasmon Resonance (SPR) was designed and implemented using plastic optical fiber. The sensor is used for estimating refractive indices and concentrations of various chemical materials (methanol, distilled water, ethanol, kerosene) as well as for evaluating the performance parameters such as sensitivity, signal to noise ratio, resolution and the figure of merit of the fabricated sensor. It was found that the value of the sensitivity of the optical fiber-based SPR sensor, with 40 nm thick and 10 mm long Au metal film of exposed sensing region, was 3µm/RIU, while the SNR was 0.24, the figure of merit was 20, and the resolution was 0.00066. The sort of optical fiber utilized in this work is plastic optical fiber with a core diameter of 980 µm, a fluorinated polymer cladding of 20µm and a numerical aperture of 0.51.

Keywords: surface Plasmon resonance, optical fiber sensor, chemical samples.

تصنيع المتحسس الكيميائي المعتمد على رنين بلازمون السطح عبر الألياف البصرية البلاستيكية

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الخلاصة

في هذا العمل ، تم تصميم وتنفيذ متحسس الألياف الضوئية الكيميائية على أساس رنين بلازمون السطح (SPR)باستخدام الألياف الضوئية البلاستيكية لتقدير معاملات الإنكسارية والتراكيز المختلفة للمواد الكيميائية التالية (الميثانول ، الماء المقطر ، الإيثانول ، الكيروسين) وكذلك لتقييم معلمات الأداء مثل التحسسية ، نسبة إلاشارة إلى الضوضاء ، قيمة الكفاءة وقدرة الفصل للمتحسس المصنع. لقد وجد ان تحسسية متحسس الالياف البصرية المعتمدة على رنين بلازمون السطح بسمك 40nm وطول فلم معدن الذهب 10 mm لمنطقة المتحسس المكشوفة هو RIU / µm 3 ، نسبة الاشارة إلى الضوضاء هو 0.24 ، و قيمة الكفاءة هي 20 و قدرة الفصل هي 0.00066. نوع الالياف البصرية المستخدمة في هذا العمل هو الالياف البصرية البلاستيكية التي يبلغ قطرها الاساسي µm 980 ، والكسوة (µm20) والفتحة العددية 0.51.

1. Introduction

Optical fiber sensors have wide applications in science, environmental monitoring, and communication technology. This is due to their compact size, high sensitivity, electrical passiveness,

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immunity to electromagnetic interference, and wide bandwidth [1, 2]. For sensing techniques, the surface Plasmon's Resonance (SPR) is one of the promising optical techniques that indicate the stimulation of surface Plasmon's , due to the high sensitivity to changes in the refractive index in the surrounding medium. This technique has also a broad spectrum of applications in biology, environment, chemistry, medicine, etc.[3]. The combination of the SPR technique and optical fiber technology has been intensively used for the sensing of various entities such as refractive index of the fluid, film thickness, surface roughness, pH, temperature, as well as levels of urea, glucose, pollutions and different types of gases [4, 5]. The first study on fiber optic chemical sensors that are based on SPR was reported in 1993 by Jorgenson and Yee [6]. The field of optical fiber sensors field was increased in its research lines and possibilities with the use of nanocoating deposition techniques. Nanostructured thin films and nanocoatings were applied to the diverse optical fiber configurations for the fabrication of new sensors [7]. SPR is a high-sensitivity optical sensing method that was utilized for the real-time detection of little variations in the active refractive index of dielectric-metal interfaces. This method was dependent on the interaction between free electrons of the metallic layer and light. When the oscillation frequency of the metal's electrons equals the frequency of the incident light, the resonance takes place. Consequently, the intensity of the light reflected off the metal film is reduced significantly, and a surface plasmon wave is formed by photon energy transfer into the metal layer [8, 9]. In order to excite the surface plasmons, optical elements, such ashigh refractive index prism, optical fiber, and diffraction grating, are utilized [10]. SPR-based optical sensors are employed for different applications in life sciences, environmental safety, electrochemistry, biomedical diagnostics and chemical sciences [11]. In this work, the main purpose was to design and implement an optical fiber as a chemical sensor based on surface plasmon resonance. The sensor is employed for sensing and measuring the refractive index and concentrations of chemical samples. The sensor can be used in the fields of the production of medicinal drugs, polymers, coatings, and oils because of its higher accuracy.

2.Performance properties

Performance characteristics to be studied include sensitivity, signal to noise ratio, figure of merit, and resolution. In the case of spectral interrogation, sensitivity can be defined as the change in resonance wavelength per unit change in refractive index of the sensing medium, and it can be written as [12]:

$$S = \frac{\Delta\lambda_{res}}{\Delta n_s} \qquad \text{............... (1)}$$

where $\Delta\lambda_{res}$ and Δn_s are the change of the resonance wavelength and the change of refractive index, respectively. From this equation, the unit of the sensitivity is nanometers per refractive index unit (nm/RIU).

Signal to noise ratio (SNR) and figure of merit (FOM) are inversely proportional to the width of SPR spectral curve and can be written as [12]:

$$\textbf{SNR (n)} = \left[\frac{\Delta\lambda_{res}}{\Delta\lambda_{0.5}}\right] \qquad \text{................... (2)}$$

where $\Delta\lambda_{0.5}$ is the width of the spectral curve.

$$FOM = \frac{S}{\Delta\lambda_{0.5}} \qquad \text{.................. (3)}$$

The resolution of the sensor can be defined as the minimum of change in refractive index that is detectable by the sensor, and is given as [13]:

$$R = \frac{\Delta n_s}{\Delta\lambda_{res}} \Delta\lambda_{DR} \qquad \text{.......... (4)}$$

Where ($\Delta\lambda_{DR}$) is the spectral resolution of the spectrometer.

3. Experimental work and setup

The experimental setup for measuring the transferred light spectrum consists of the light source (halogen lamp), plastic optical fiber from Thorlabs Company, and the optical spectrum analyzer (OSA) from Thorlabs Company. The spectrometer is lastly associated with a computer. The SPR curves along with data values are displayed online on the computer screen and saved by and advanced software provided by Thorlabs. Figures- 1 and 2 demonstrate, respectively, a photograph and a scheme of the experimental setup for the optical fiber chemical sensor based on SPR.
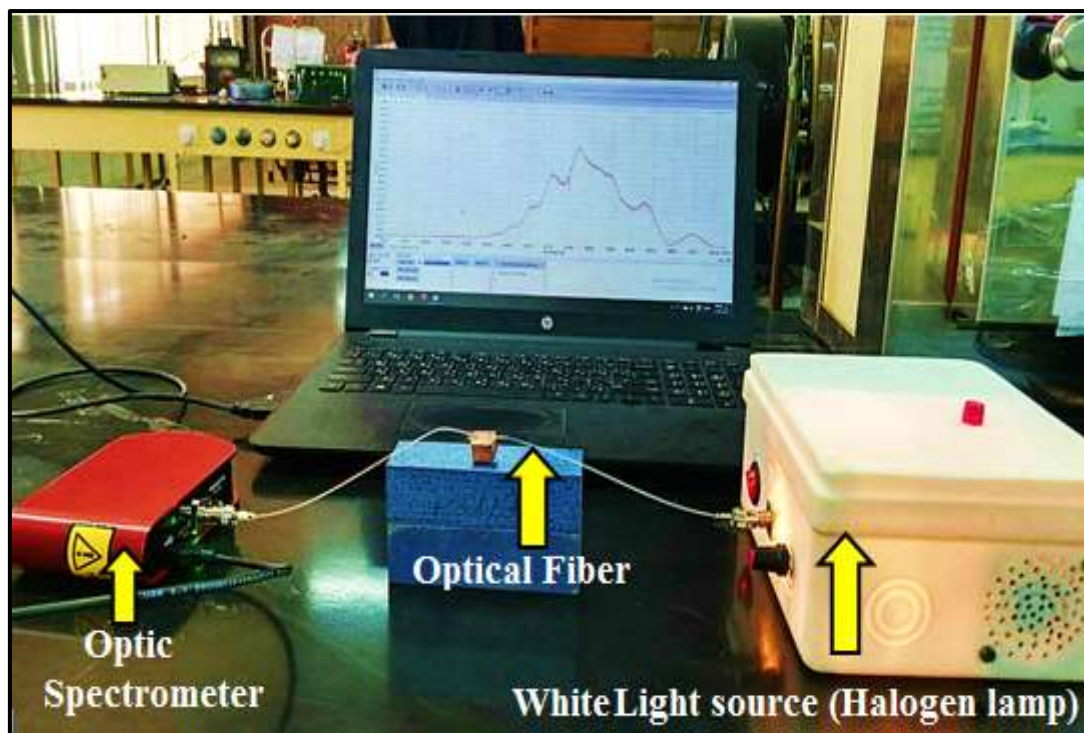
Figure 1-A Photograph of the experimental setup for the optical fiber chemical sensor based on SPR.
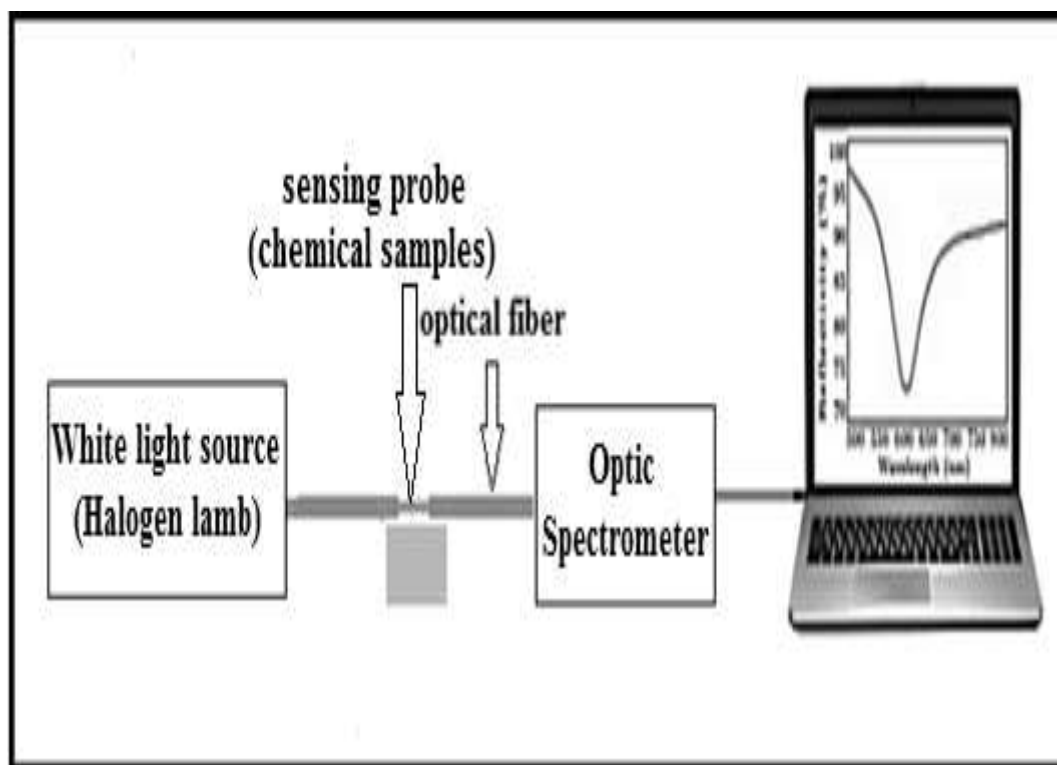
Figure 2-An outline of the experimental setup of the optical fiber chemical sensor based on SPR.

3.1. Optical Sensor Systems

The optical grade plastic optical fiber, with a core diameter of 980µm, a numerical aperture of 0.51 without a jacket, and a small part (10mm) of optical fiber in the middle, is embedded in a resin block as shown in Figure-3. Thereafter, the polishing process is performed. The removed clad part is cleaned

with distilled water and then deposited with about 40nm thickness of gold metal using ION _COATER. The conditions adopted to deposit the 40nm thickness of gold were 7mA current and 300 sec time of deposition. The thickness of the metal layer was determined as shown in Figure- 4. The used machine was of the Model KIC-1A from COXEM Company, Korea.
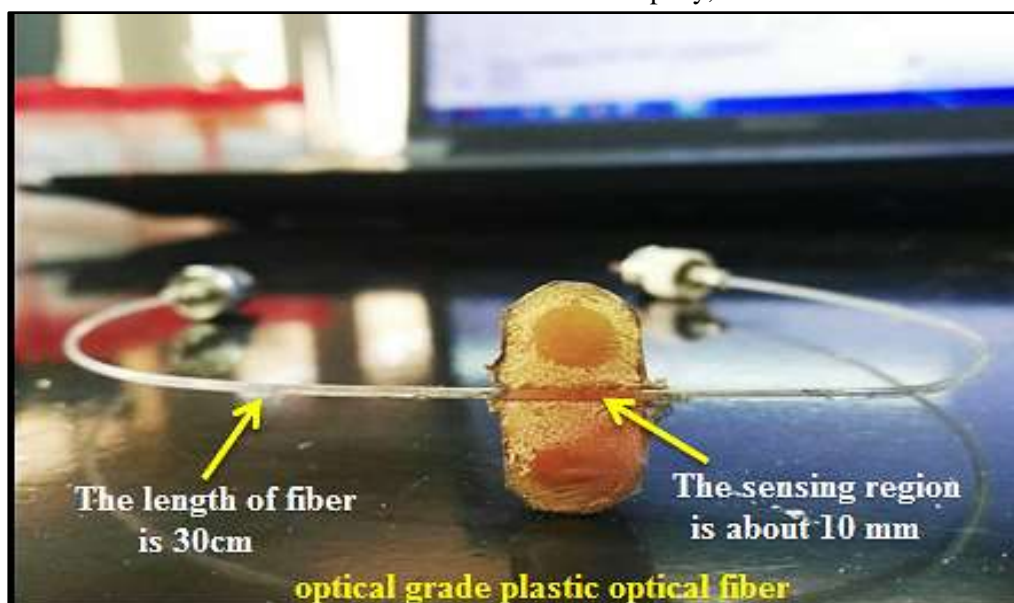

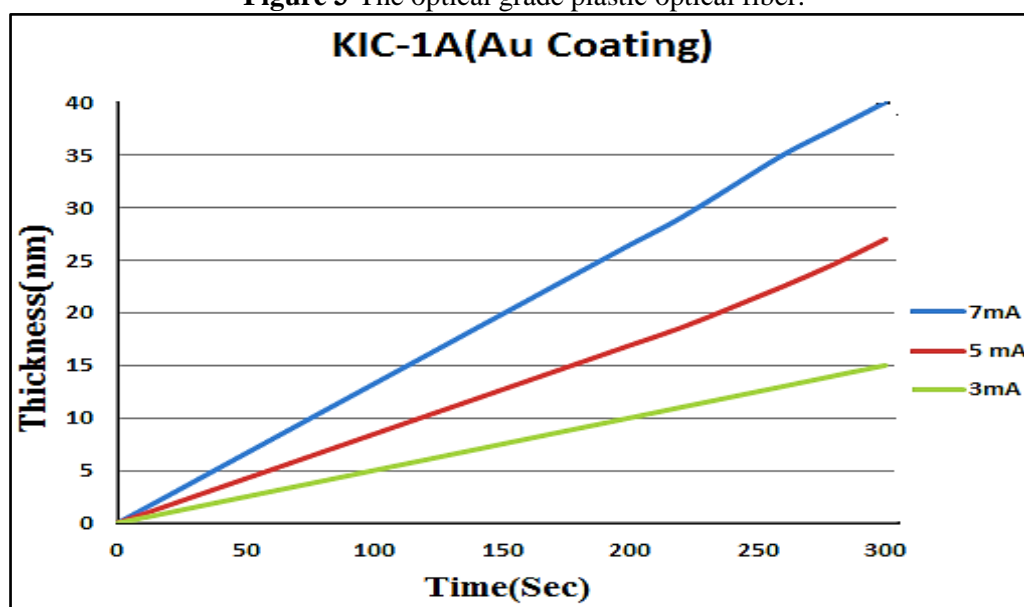**Figure 3**-The optical grade plastic optical fiber.

Figure 4-The thickness of the gold layer as a function of time in sec.

3.2. Preparation of Solutions of different refractive indices

The sensitive region of the sensor is covered with various sucrose /water solutions with various concentrations and ,thereby, different refractive indices n_s. We measured the refractive indices of the solutions by using the Abbe refractometer. Figure- 5 demonstrates the linear relationship between the refractive index and the solution concentration.
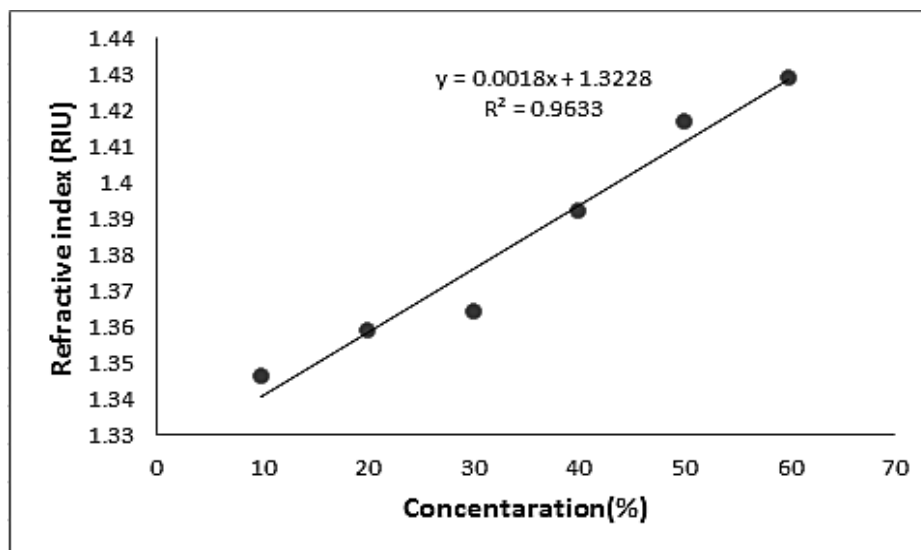
Figure 5-Refractive index of sucrose /water solutions as a function of the solution concentration.

4. Results and Discussion

The values of the parameters used in the numerical calculations as well as in the experimental study included fiber optic numerical aperture (NA) =0.51, fiber core diameter (D) =980μm, sensing length (L) =10mm, metal layer thickness (d) =40nm and different values (1.346, 1.359, 1.364,1.392, 1.417 and 1.429) of refractive index from sucrose /water solutions.

The spectra are obtained by recording the transmission curves T of light through an optical fiber. T is calculated from the ratio of the intensity I measured in the existence of a sample (sensing medium) and the intensity of the optical signal I_0 measured with air (without the chemical samples). The transmission (T) is a function of wavelength in (nm). The T-wavelength curve is called the SPR curve and, at a particular wavelength, named resonance wavelength. A sharp dip happens in T because the energy of the incident light is transferred to the electrons of the metal and thus lessens the reflected light intensity. The location of this dip depends on the refractive index (n) to the sensing medium. The resonance wavelength, that is the wavelength at which a resonance occurs between the incident light and the SPR wave, increases with the increase in the refractive index of the sensor medium. This takes place because the energy decreases and thus the sharp dip of the resonance wavelength will be shifted to the longer wavelength side (red shift), as shown in Figure-6.
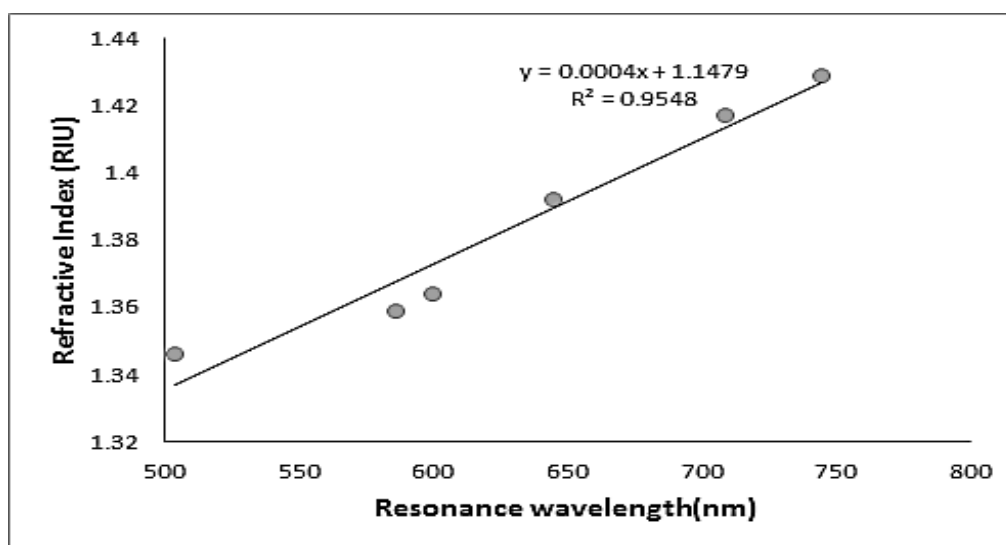
Figure 6-Refractive index as a function of resonance wavelength for the sensor with gold layer.

Figure-7 shows the SPRfor the fabricated sensor with gold layer at various refractive index values of the chemical samples (sensing medium). It is obvious that the width and dip position of each SPR response curve is changed to the sensor, with each sample having a different refractive index. Also, the magnitude of shifting of the dip position increases as the refractive index increases. These variations make the performance parameters, which depend on the surface plasmon resonance (SPR) curve width, the value of the shifting, and the position of dip, change with changing the resonance wavelength and refractive index of the sensing medium. These changes occur because the performance parameters depend on the changes in the resonance wavelength, the refractive index, and the width of the spectral curve. Table 1 shows the experimental performance parameters for the simulated and fabricated sensor with the gold layer. Table 2 demonstrates the values of the refractive index and the concentration for each sample of chemical at different resonance wavelengths. The concentration of the samples increases as the refractive index increases and hence the resonance wavelengths increase. This occurs because of the shift of the sharp dip to the red wavelength.

Table 1-Experimental performance parameters of the gold based sensor.

Metal	Sensitivity (S_n) [μm/RIU]	Signal to noise ratio (SNR)	Figure of merit (FOM)	Resolution [RIU]
Gold	3	0.24	20	0.00066

Table 2-Resonance wavelengths for different values of concentration and refractive index.

Samples	Resonance Wavelength (λ_{res})(nm)	Refractive Index (n) (RIU)	Concentration (C) (%)
Methanol	450	1.3279	2.833
Distilled Water	459	1.3315	4.833
Ethanol	531	1.3603	20.8
Kerosene	736	1.4423	66.38

(a) Methanol   **(b) Distilled Water**
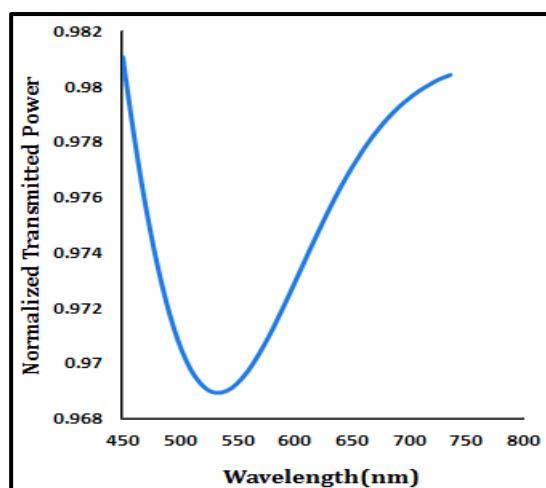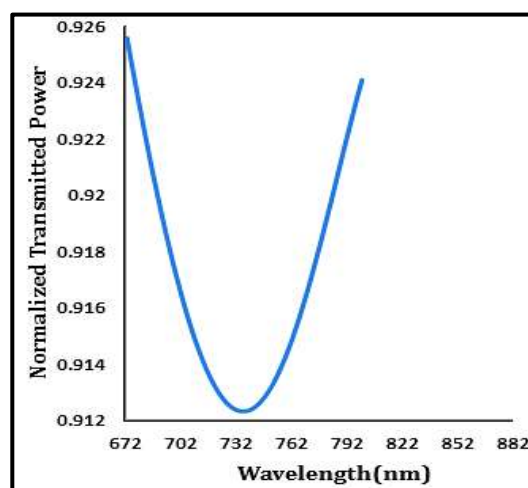
(c) Ethanol   **(d)Kerosene**

Figure 7-SPR curve of the optical fiber sensor with a gold metal for different samples of chemicals (a) Methanol, (b) Distilled Water, (c) Ethanol, (d) Kerosene**.**

5. Conclusions

The change of the SPR response curve for each sample was recorded in this work and exhibited a dip in the position of resonance. A change in the value of the resonance wavelength occurs for each change in the refractive index and hence for different values of the concentration of chemical solutions. The magnitude of shifting of the dip position increases as the refractive index increases. The sensitivity of the plastic optical fiber based surface plasmon resonance (SPR) sensor, with 40nm thick Au metal film of exposed sensing region, had a value of 3 μm/RIU, while the signal to noise ratio was 0.24.

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