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Photonic Crystal Fiber Pollution Sensor based on Surface Plasmon Resonance

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Abstract

In this work, a pollution-sensitive Photonic Crystal Fiber (PCF) based on Surface Plasmon Resonance (SPR) technology is designed and implemented for sensing refractive indices and concentrations of polluted water . The overall construction of the sensor is achieved by splicing short lengths of PCF (ESM-12) solid core on one side with traditional multimode fiber (MMF) and depositing a gold nanofilm of 50nm thickness on the end of the PCF sensor. The PCF- SPR experiment was carried out with various samples of polluted water including(distilled water, draining water, dirty pond water, chemical water, salty water and oiled water). The location of the resonant wavelength peaks is seen to move to longer wavelengths (red shift) as the refractive index increases due to the transfer of maximum energy from the reflected power of the light guided through the fiber to the surface plasmons. The experimental results show that the highest sensitivity reached 4202.6nm/RIU for oiled water, the signal to noise ratio was 0.625, the resolution was $2.4*10^{-5}$ RIU, and the figure of merit was 22.8. The prepared sensor exhibited excellent performance features, making it an excellent element for detecting water pollutants.

Keywords: Photonic crystal fiber sensor, Pollution sensor, Optical fiber sensor based surface plasmon resonance, Surface plasmon resonance.

متحسس التلوث باستخدام الالياف الضوئية البلورية استنادا الى رنين بلازمون السطح

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الخلاصة

خلال هذا العمل ، تم تصميم وبناء متحسس الألياف الضوئية البلورية للكشف عن المياه الملوثة بناءً على تقنية رنين البلازموني (SPR) لتحسس معاملات الانكساروتراكيز عينات مختلفه من المياه الملوثه . يتكون التركيب الاساس للمتحسس عن طريق ربط الياف بلورية فوتونيه ذو القلب الصلب (ESM-12)على جانب واحد باستخدام الألياف التقليدية متعددة الانماط (MMF) وترسيب طبقة رقيقة من الذهب بسمك 50 نانومتر في نهايةالمتحسس . اوضحت تجربة PCF-SPR لعينات مختلفة من المياه الملوثة بما في ذلك: (مياه الصرف الصحي ، مياه البرك غير النظيفة ، المياه الملوثة كيميائياً ، المياه المزيتة ، المياه المالحة ، الماء المقطر)

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حيث لوحظ ان موقع قمم الطول الموجي عند الرنين تتحرك نحو الأطوال الموجية الطويلة حيث يزداد معامل الانكسار بسبب انتقال معضم الطاقه المنعكسه للضوء الموجه عبر الألياف إلى البلازمونات السطحية. ابدى المتحسس حساسية عالية وصلت إلى nm/RIU 4202.6 للمياه الملوثة بالزيت ، وكانت نسبة الإشارة إلى الضوضاء 0.625 ، وكانت الدقة RIU $2.4*10^{-5}$، وكانت قدرة الفصل 22.8. أظهر المستشعرالمصنع ميزات أداء ممتازة ، مما جعله عنصرًا ممتازًا للكشف عن ملوثات المياه.

1. Introduction

Photonic crystal fiber (PCF) sensors based on Surface Plasmon Resonance (SPR) have received a lot of attention in recent years because of their unique properties, such as small size, flexible design, high sensitivity, high non-linearity, and highly controllable birefringence, in addition they and do not require any additional coupling device [1,2]. PCF- SPR sensors have been widely used in a different field such as medical diagnostics [3], biochemistry, water testing, food quality detection, and environmental monitoring [4]. PCF's air hole arrangement, pitch size and air hole diameter may be modified, and a metal can be filled into its air hole or coated to its surface to produce SPR[5-7].

SPR is an optical phenomenon that describes the collective oscillation of electrons at the metal dielectric interface caused by an incident electromagnetic wave. In 1950, Ritchie introduced the theoretical concept of surface plasmon (SP) and the SPR concept [8]. Next, in 1968, Kretschmann[9] and Otto[10] presented the two main surface plasmon wave (SPW) excitation methods: attenuated total reflection (ATR) and diffraction grating. However, with a prism coupler-based approach, the structures are massively larger and more difficult to fabricate [11].

The working principle of PCF-SPR sensors is based on the evanescent wave created by light propagation through the region of core-cladding interface, resulting in the interactions between light and plasmonic surface. Because the refractive index of the infiltrating analyte changed together with that of the guided light mode, a shift in resonant wavelength was produced, which allowed the particles or molecules to be recognized by sensing the shift in resonant wavelength [12]. Plasmonic materials, such as gold and silver, can be employed to enhance the sensor sensitivity. Silver has a high resonance peak; however, it becomes chemically unstable when exposed to air [13]. In contrast, the chemical stability and strong resonance peak of gold make it a favored plasmonic material [14]. In this work gold has been chosen as a plasmonic material to prevent the oxidation of silver due to the infiltration of air holes with water samples. To date. Jassam suggested a chemical sensor using a plastic optical fiber, with a sensitivity of 3.3030m/RIU [15]. Rahim created an optical fiber biomedical sensor with a sensitivity of 7.5m/RIU employing surface plasmon resonance [16]. Ali and Al-Bassam designed and implemented a no-core optical fiber with a sensitivity of 11.11m/RIU for monitoring contaminated water [17]. In the same year, 2021, Khatar and Bassam designed and implemented a chemical sensor with a sensitivity of 4.4 m/RIU using a multimode plastic optical fiber [18].

The major goal of this work was to design and construct a photonic crystal fiber, based on surface plasmon resonance, that may be used as a pollution sensor. The sensor is used to detect and measure the refractive index and concentrations of polluted water samples which were dirty pond water, chemically contaminated water, oiled water, drainage water and sodium chloride water.

2. Performance parameter

Performance of PCF-SPR sensors can be estimated through some parameters such as sensitivity, resolution, signal-to-noise ratio, and figure of merit: Sensitivity (S) is defined as the change in the resonance wavelength for a unit change in the refractive index (RI) of two neighboring analytes, and this can be expressed as [19]:

$$S_\lambda \left[\frac{nm}{RIU}\right] = \frac{\Delta\lambda_{\text{peak}}}{\Delta n_a} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where: $\Delta\lambda_{peak}$ and Δn_a is the difference in the wavelength resonance peak and difference in the RI of the two neighboring analytes, respectively.

The resolution (R) of a sensor indicates how much minor variation in analyte RI can be observed which may be calculated from the equation [20]:

$$R[RIU] = \Delta n_a \times \frac{\Delta\lambda_{min}}{\Delta\lambda_{peak}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where: $\Delta\lambda_{peak}$ is the resonance wavelength difference between the two adjacent analytes resonance peaks and n_a is the RI difference between the two adjacent analytes.

The Signal-to-Noise Ratio (SNR) measures the sensor performance and is represented by the equation [21]:

$$SNR = \frac{\Delta\lambda_{peak}}{FWHM(nm)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where FWHM is the Full Width at Half Maximum

Another important parameter is the figure of merit (FOM), which is defined as the ratio of sensor sensitivity to spectral curve width. A good sensor has a high FOM value, which indicates that it has a sharp (FWHM) spectrum and a good sensitivity. FOM is expressed as [22]:

$$FOM[RIU^{-1}] = \frac{Sensitivity(\frac{nm}{RIU})}{FWHM(nm)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

3-The fabrication of the photonic crystal fiber sensor

The morphology of the Photonic Crystal Fiber (PCF) (ESM-12, NKT Photonics) was determined with a scanning electron microscope (SEM), as shown Figure 1. It can be seen that it has six layers of hexagonal air holes surrounding a solid silica core. The fiber has a core diameter of 10.2μm, holes with diameters of 2.46m, a pitch of 7.8μm, and an outside diameter of 125μm. The coating from a stub of PCF (ESM-12) and (MMF) was mechanically removed. The PCF and MMF were then cleaved using a fiber cleaver in the second stage. The stub of a commercial PCF (10 mm) was then fusion spliced with (MMF) on one side using a splicing machine (FSM-60S). Finally, a gold sensing layer of 50 nm thickness was deposited on the end face of PCF using a Sputter Coater (Quorum Q150R ES, UK) which worked with a gold target bombarded using ions of argon gas. The coating process was achieved inside the chamber at a pressure of 3×10^{-3} Torr, sputter current of 20 mA and sputter time of 147 sec.

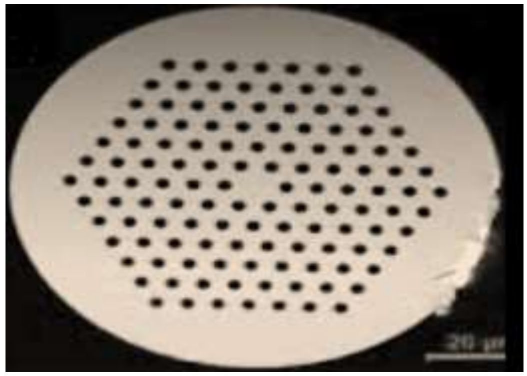


Figure 1: scanning electron microscope of PCF (ESM-12)

4-Experimental devices and setup

The experimental setup of the PCF-SPR pollution sensor is presented in Figures 2 and 3.

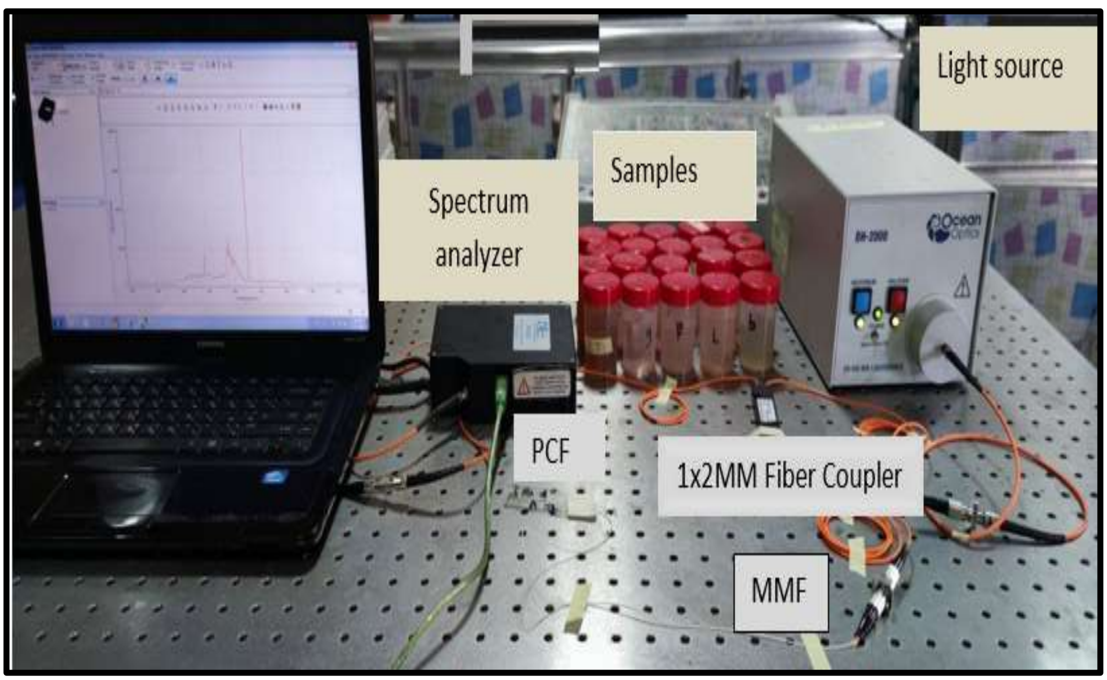


Figure 2: Photographic picture of experimental setup of PCF-SPR sensor.

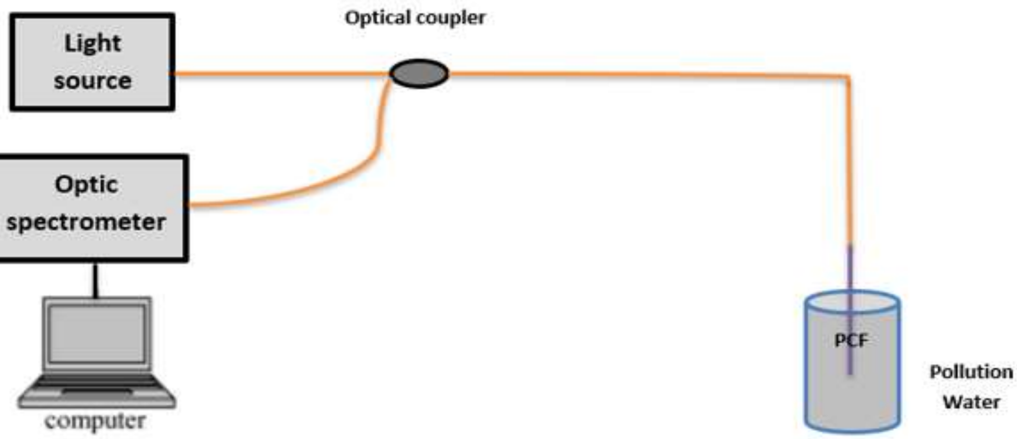


Figure 3: Schematic diagram of the proposed sensor set up.

Initially, a halogen light illuminates the PCF-SPR sensor (Ocean Optics Inc., DH-2000-BAL). When the sensor was immersed in the target solution, the white light in the sensing area was modulated by external environmental solutions. Finally, the reflector reflects the modulated light and is collected by the Ocean Optics optical spectrum analyzer (USB4000+UV-VIS-NIR), which is connected to a computer and collects the modulated light with Ocean Optics software. The sensor was cleaned with distilled water after each measurement to ensure that the sensing sensitive region is clean.

5-Results and discussions

The sensitive area of the sensor was immersed in sucrose solutions of different concentrations i.e. different refractive indices (ns) to construct a calibration curve of refractive index versus concentration for the prepared sensor which is a linear relationship, as shown in Figure 4. The solution's refractive indices were measured using an Abbe refractometer (Hilger type). The working principle of this type of the refractometers is based on the critical angle.

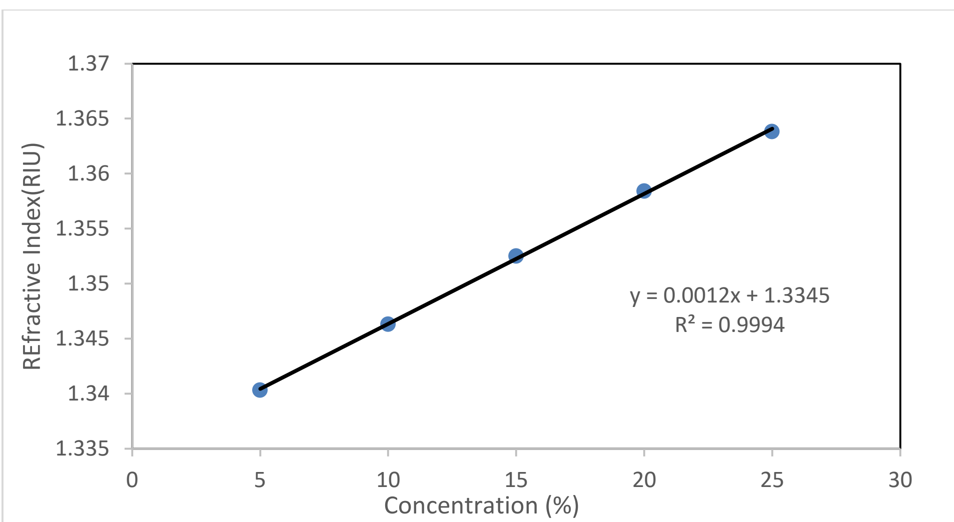
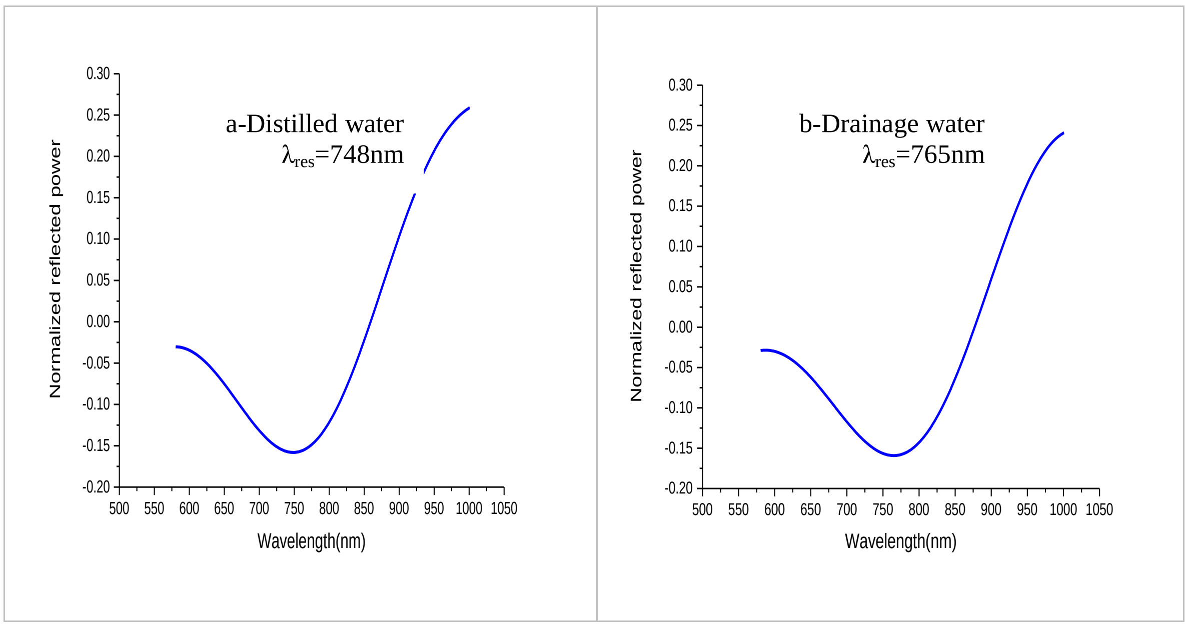


Figure 4: PCF-SPR calibration curve using sucrose/water solution.

Figures (5 a-f) shows the plasmon resonance curves of the different polluted water samples (sensing media) of different refractive indices. All these figures are in terms of the normalized reflected power. This normalized reflected power was plotted as a function of the incident wave wavelength (in nanometer). The response of prepared sensor explained in Figure 5. As shown in the SPR curves, the resonance appears as a dip. The dip occurs at the resonance wavelength due to the transfer of maximum energy from the reflected power of the light guided through the fiber to the surface plasmons. Increasing the refractive index of a sensing medium i.e. increase of the concentration raises the resonance wavelength to a longer wavelength (red shift), which may be explained by the resonance condition of surface plasmon waves. When the refractive index of the sensing medium is high enough, surface plasmon waves are able to resonate at longer wavelengths because the real component of their propagation constant is higher. Figure 6 shows a linear relationship between the resonant wavelength and the refractive index of the polluted water samples. Table 1 shows the performance parameter values for the sensor with the gold layer. Sensitivity, resolution, signal to noise ratio and figure of merit were calculated according to Equations (1), (2), (3) and (4), respectively. Table 2 shows the resonance wavelengths, the refractive index, and the concentration of polluted water samples.



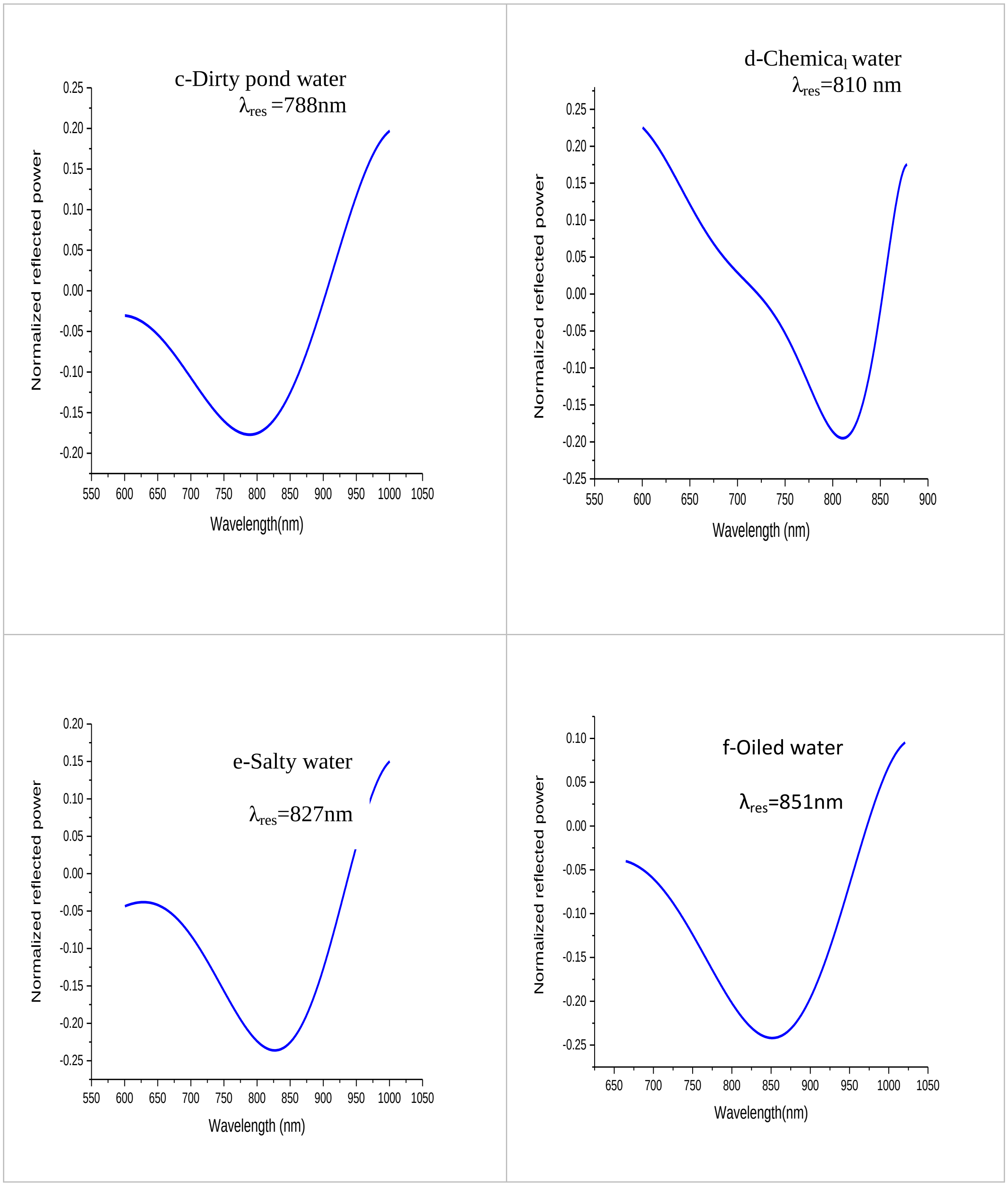


Figure 5: SPR curves of PCF-SPR sensor with 50 nm thickness gold layer for different polluted water samples:(a) Distilled water, (b) drainage water, (c) Dirty Pond water, (d) Chemical water, (e) Salty water and (f)Oiled water.

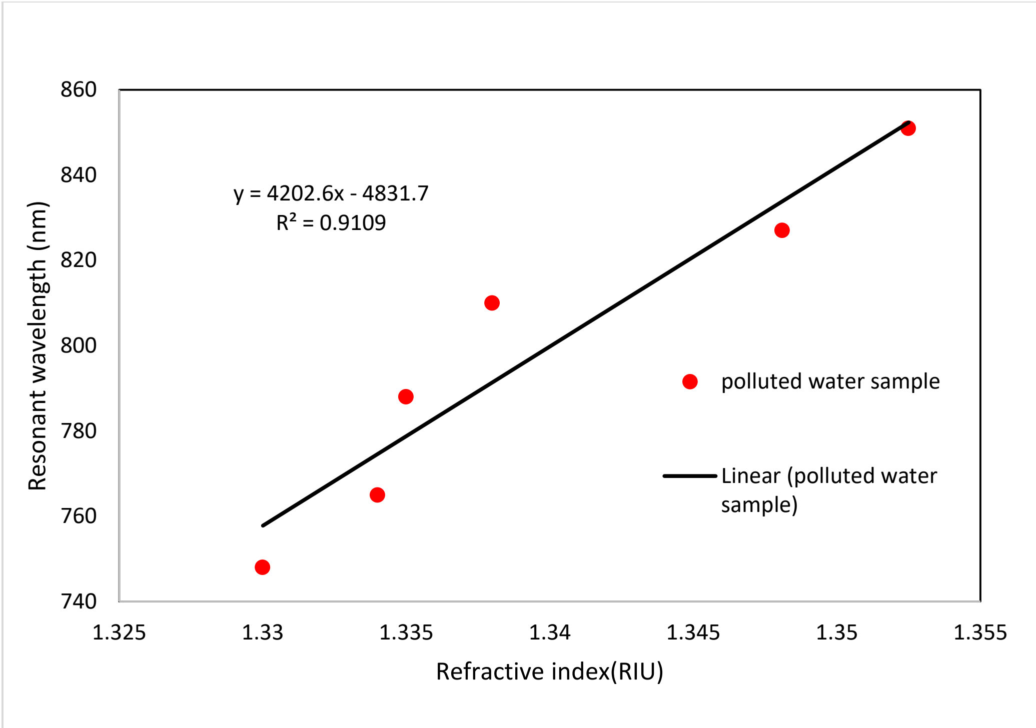


Figure 6: The resonant wavelength as a function of the refractive index of the polluted water samples.

Table 1: Experimental performance parameters of the sensor

Metal/(thickness)	Sensitivity [nm/RIU]	Figure of merit (FOM)	Signal to noise ratio (SNR)	Resolution [RIU]
Gold /(50nm)	4202.6	21.8	0.625	$2.4*10^{-5}$

Table 2: Refractive index, concentrations and resonance wavelengths of the polluted water samples.

Sample	(λ_{res}) (nm)	Refractive index (n) (RIU) by abb refractometry (laboratory method)	Concentration by the sensor (C) %
Distilled water	748	1.33	0.4
Drainage water	765	1.334	1.3
Dirty pond water	788	1.335	2.1
Chemical water	810	1.338	2.9
Salty water	827	1.3481	5
Oiled water	851	1.3525	15

5-Conclusion

This work presents a reflection type Photonic Crystal Fiber sensor (PCF) based on Surface Plasmon Resonance (SPR) technology to be exploited for sensing of polluted water. The value of the resonant wavelength varies with the refractive index and the concentration of the polluted water. The prepared sensor shows maximum sensitivity of oiled water sample reaching 4202.6nm/RIU, signal to noise ratio 0.625, resolution $2.4*10^{-5}$ RIU and figure of merit 21.8. The reflection-based photonic crystal fiber plasmonic sensing probe is compact, low cost, and has potential application in biomedical applications, chemical testing, the monitoring of environmental pollutants, and water testing.

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