Indonesian Journal of Electrical Engineering and Computer Science
Vol. 29, No. 2, February 2023, pp. 644~651
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v29.i2.pp644-651

Hybrid structure of u bent optical fiber local surface plasmon resonance sensor based on graphene

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Article Info

Article history:

Received Jun 24, 2022
Revised Sep 26, 2022
Accepted Oct 27, 2022

Keywords:

D-shape
Gold nano particles
Graphene
Refractive index sensor
U bent fiber sensor

ABSTRACT

In this paper, a fiber optic sensor was designed and implemented to detect the change in refractive index of sodium chloride salt solution based on the local surface plasmon resonance (LSPR) phenomenon. This sensor was manufactured using a plastic optical fiber (POF), this optical fiber was bent in a U-shape with 0.5cm bending diameter, and then the cladding and part from core of the fiber were removed by polishing at the sensor head to become as a D-shape in cross section. The sensor was coated with 30 nm thickness of gold nano particles (GNPs) by DC plasms coating technology and it was tested with sodium chloride solution, the detection sensitivity was 466.66 nm/RIU. To enhancement the sensitivity, the latest sensor was coated with 20 nm thickness of graphene nano material and retested with same samples of sodium chloride solutions. It was found that graphene improved the sensitivity by an excellent amount, where shift in wavelength was 20 nm and highest sensitivity obtained was 666.666 nm/RIU.

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1. INTRODUCTION

Due to its ability to be used in a wide range of industrial applications, such as chemical and biological detection, optical fiber sensors have sparked a lot of research interest [1]. In several disciplines of sensing, such as refractive index (RI) sensor, pH sensor, strain sensor [2], temperature sensor, curvature sensor, and humidity sensor, optical fiber sensors have gotten a lot of attention [3] .Various types of sensing methods, such as evanescent wave absorption and fiber Bragg grating, have been accomplished on the optical fiber platform [4]. Partially unclad, side-polished, tapered optical fibers, photonic crystal fiber, D-shaped optical fiber, and U-bent optical fiber sensors are just some of the optical fiber topologies that have been studied [5]. The addition of noble metal nanoparticles such as gold nano particles (GNPs) to these probes improves the field of optical fiber sensors [4]. Due to their strong optical sensitivity in the visible area of the electromagnetic spectrum, silver and gold are the most widely utilized metals [6], [7]. Due to its excellent optical qualities, gold nanoparticles (Au-NPs), a sensitive coating among metallic nanoparticles, are frequently used in optical sensing applications [8]. Free oscillating metal electrons are excited by the optical phenomena known as surface plasmon resonance (SPR). Light photons contain energy that is transferred to packets of electrons on a metal surface [9]. The SPR phenomenon was transformed to an local surface plasmon resonance (LSPR) phenomenon when metallic Nano particles were used instead of a bulk metal sheet [10]. Due to their small size, low cost, and flexibility, localized surface plasmon resonance (LSPR) sensors have piqued interest among various types of fiber optic sensing probes [11]. The refractive index variations on the sensor surface cannot be fully detected by standard optical fiber LSPR sensors, limiting their sensitivity. Graphene is added to solve this problem. Graphene is a Plasmon substance that has chemical characteristics that are stable which can extend the useful life of sensors [12].

2. THE COMPREHENSIVE THEORETICAL BASIS

Optical fibers are waveguides that allow light to go through them by total internal reflection. When light travels through the fiber, a little fraction of it escapes to the cladding, which is referred to as evanescent field, which diminishes exponentially with distance. This ephemeral field is what the sensing is built on [7], due to the evanescent wave's capacity to permeate the fiber's surrounding environment and interact directly or indirectly with the analytic [13]. Because the evanescent field of a straight fiber sensor is relatively weak due to the short penetration depth, the sensor's sensitivity is restricted. By bending the fiber in a U shape, the absorption sensitivity is improved over straight probes [14]. Higher order propagation modes (guided light rays reflecting at angles near to the critical angle) reach the core-cladding interface at an a less than the critical angle and refract into the cladding at a fiber bend [15]. Due to its ease of handling and cost effectiveness, plastic optical fibers (POF) manufactured of (polymethylmethacrylate PMMA) are receiving more attention as a viable replacement to silica-based fiber optic sensors. POF is so flexible, any desired fiber probe shape such as tapered, side-polished, U-bent, coiled, or any other can be easily produced to achieve a large evanescent field at the core-cladding interface to increase light interaction with the medium and therefore improved sensitivity [16]. Due to their high surface to volume ratio and biocompatibility, two-dimensional (2D) materials (e.g., graphene and transition metal di chalcogenides) have been widely used in sensing in recent years. In comparison to traditional SPR sensors without 2D materials, SPR sensors with 2D materials are more sensitive [17]. Graphene, as a pioneer of two-dimensional materials, has made significant discoveries in fields such as materials science, biology, and medicine to apply physics, chemistry, and electronics as a result of its linear band structure and thickness of an atom [18]. In the previous studies like [5], [16], [19] the U shape LSPR sensor designed by removed the cladding of optical fiber by acetone to expose the core without removing any part from the core. In this study, we created a new LSPR sensor using a U-shaped plastic optical fiber when the cladding and part from the core were removed by polishing head sensor as D shape in cross section to produce a hybrid structure and higher sensitivity (when the U-shaped outer curvature is removed by polishing, the evanescent field's power and penetration depth in the analytic increase [20]), this sensor coated with GNPs and graphene. We showed that graphene could increase the LSPR sensor's sensitivity, and that the new LSPR sensor had good sensitivity in detecting sodium chloride solutions.

3. METHOD

Refractive index sensor based on macro-bending fiber U shape structure have been designed and constructed by using plastic optical fiber (POF), the steps of fabrication the sensor was shown in the Figure 1. Sensors were tested with (650 nm) and (5 mW) red light from a semiconductor laser source, source was connected to the U shape POF LSPR sensor and (ocean 2000) spectrometer was adopted to record the laser signal transmitted on the computer as shown in the Figure 2.

At the beginning optical fiber sensor was fabricated from a piece of POF with a length of about 20 cm with 980 µm fiber diameter and 850µm core diameter as shown in Figure 3, its microscope image shown in the Figure 3(a). POF was made of PMMA with refractive indices 1.49 and 1.41 for core and cladding respectively. Then straight POF was bent handily in U shape with 0.5 cm bending diameter, the length of the sensing area was 1.5 cm as shown in Figure 3(b) .The sensor was installed on a plastic graduated ruler and secured with thermal adhesive, then the bent region of the sensor was polished to remove the cladding of the fiber and part from the core with very smooth emery paper to get D shape in cross section with 680 µm fiber diameter, as shown in the Figure 3(c).

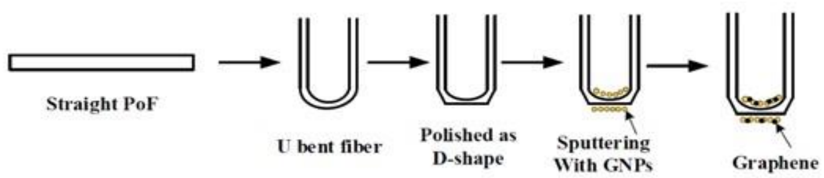


Figure 1. The steps of manufacturing the U POF LSPR sensor with 0.5 cm bending diameter

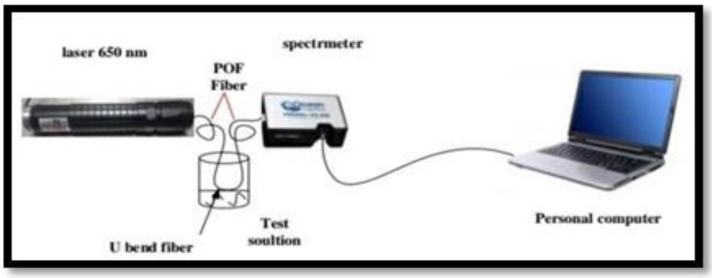
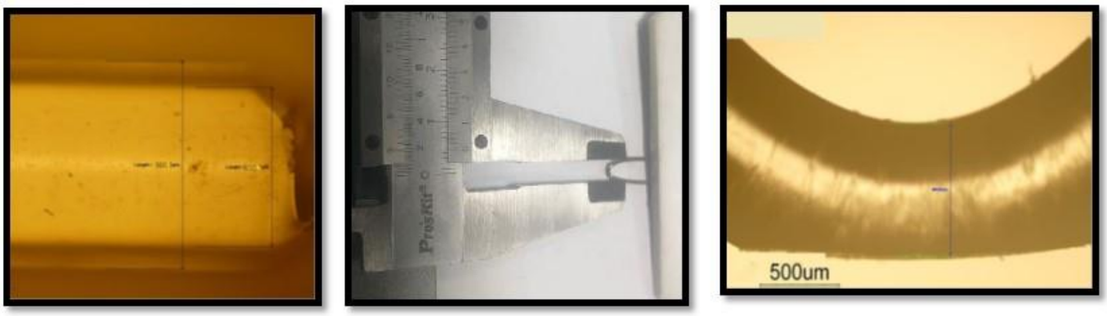


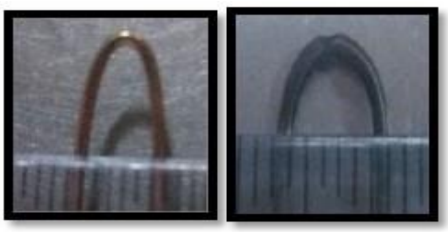
Figure 2. Schematic diagram of U shape LSPR sensor measurement setup



(a) (b) (c)

Figure 3. Images for Plastic optical fiber (POF), (a) microscope image for straight POF with 980 µm fiber diameter and fiber core diameter is 850 µm, (b) photographic image of U shape POF sensor with 0.5 cm bending diameter without coating, and (c) microscope image for U bent polished fiber with 680 µm diameter

The test samples were prepared with different concentrations of sodium chloride solution dissolved in distilled water and the refractive index of each sample was measured using abbe refractometer where the refractive index ranges from 1.333 to 1.363. The testing process is done by immersing the manufactured sensor in the prepared saline solution and before each test process the sensor is washed with distilled water. The next step was the U shape fiber sensor with 0.5cm bending diameter shown in Figure 4 was coated with 30 nm thickness of gold nanoparticles by using DC Plasma coating device as shown in Figure 4(a). Gold target with a thickness of (1 mm) a diameter of (5 cm), and a purity of (99.9%) was utilized to sputter deposited GNPs upon the head sensor to build the U shape POF LSPR sensor. Finally, to enhance the sensitivity of the sensor, it was coated with 20 nm thickness of graphene with the same DC Plasma coating device, as shown in Figure 4(b). The sensor was retested using the same samples solutions.



(a) (b)

Figure 4. U POF sensor with 0.5 cm bending diameter, (a) coated with 30 nm thickness of GNPs and (b) coated with 30 nm GNPs + 20 nm graphene

Scanning Electron Microscopy image for the latest sensor (U shape POF with 0.5 cm bending diameter coated with 30 nm of GNPs + 20 nm of graphene) was shown in Figure 5. Energy Dispersive Spectroscopy (EDS) spectrum to show the materials excite on the latest U LSPR POF head sensor (U shape POF with 0.5 cm bending diameter coated with 30 nm of GNPs + 20 nm of graphene) was shown in Figure 6.

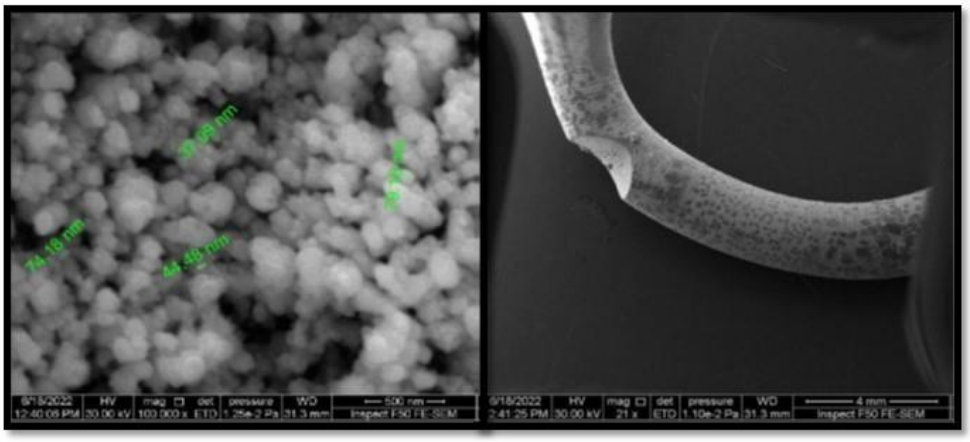


Figure 5. The SEM image for U LSPR POF sensor with GNPs + Graphene in two different scales (500 nm, 4 mm)

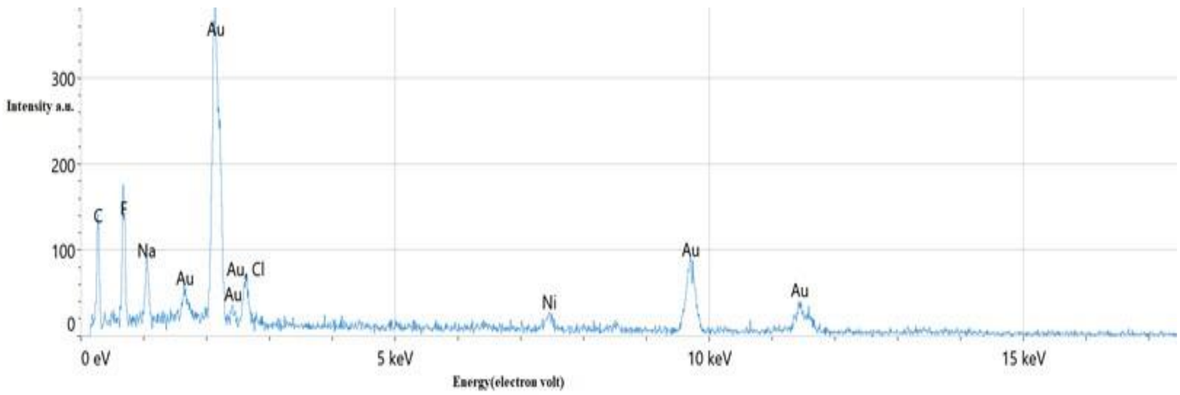


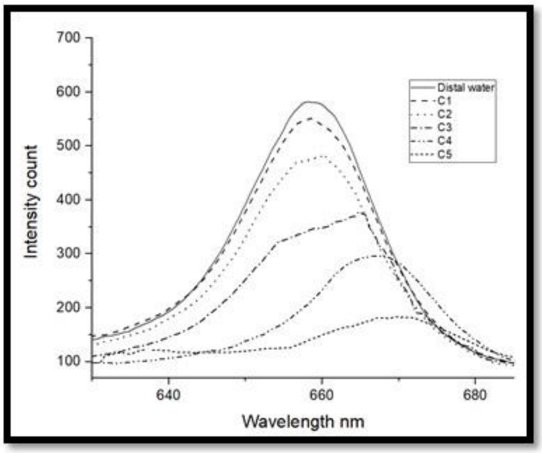
Figure 6. Energy dispersive spectroscopy (EDS) spectrum for materials present on U LSPR POF head sensor (The EDS image was taken at the end of the experiment, where there are some traces of the NaCl solutions that were used in this experiment on the sensor head)

4. RESULTS AND DISCUSSION

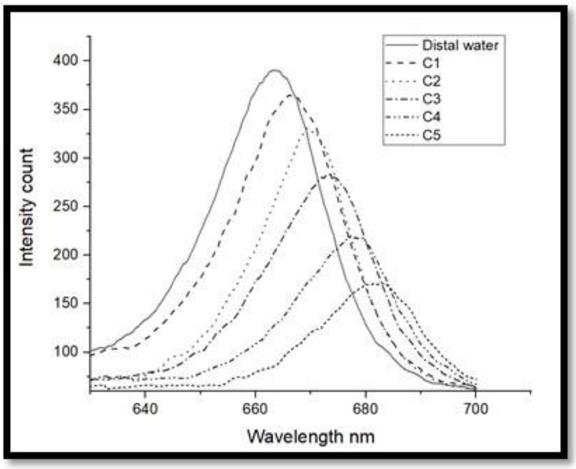
In the following study the sensitivity of the U bent POF LSPR sensor was measured by immersing it in the Sodium chloride solution with RI changes from 1.333 to 1.363 was investigated, then this sensor coated with graphene Nano material to improve the sensitivity towards RI changes from 1.333 to 1.363. The results shown in the following Figures 7 and 8 were obtained.

It can be observed the response intensity of U shape LSPR sensor as shown in Figures 7. In Figures 7(a) that 14 nm red shift of LSPR wavelength with increase the sodium chloride solution concentrations at room temperature, the change in resonance wave length with change in refractive index of sensing media can explained by the operating principle of SPR is based on the interaction between an evanescent field and a surface electron that a Plasmon metal emits. An evanescent field is produced at the location of the U bend by the light wave propagating in the fiber's core. Surface plasmon waves (SPWs), which travel through metal-dielectric surfaces, are created when the evanescent field collides with a metallic surface. When the energy of light photons exactly matches the energy level of the surface plasmon, the surface Plasmon is excited at the metal/dielectric interface, which results in the transfer of energy from incident light to surface Plasmon electron. This lowers the output light's intensity [9]. As observed in Figures 7(a) that as the concentration of sodium chloride solution increase the peak intensity reduced gradually with the RI increasing because increase absorption of light power by the solution. The sensitivity obtained from this sensor was 466.66 nm/RIU (sensitivity is the ratio of shift wavelength to RI change [21], [22]). This sensor exhibits a good linear regression coefficient R^2=0.98 as shown in the linear fitting curve in Figure 7(c). The RI sensitivity is further enhanced with the coating of graphene on the GNPs coating as shown the response intensity of U shape LSPR sensor coated with 30 nm thickness of GNPs + 20 nm graphene in Figures 7(b). A red shift of 20 nm in LSPR wavelength is observed with 0.03change in RI, the red shift of the local resonance wavelength get larger due to the addition of graphene. Higher sensitivity of 666.66 nm/RIU was obtained; the optical property of graphene leads to an increase in sensitivity. The peak intensity decreasing with increase the concentration of sodium chloride solution due to transfer energy of light to the metal electrons. This sensor exhibits a good linear regression coefficient R^2=0.99 as shown in the fitting curve in Figure 7(c). These findings is agreement with results of the study in reference [5], [17]. Graphene is a dielectric material, it has been shown that applying a dielectric layer on the gold surface of the SPR sensor would change how the sensor's electric field is distributed [17], so the graphene will cause more shift in wavelength that increase the sensitivity. The normalized transmission spectra obtained for U shape POF LSPR sensors as shown in Figures 8.

Figure 8(a) shows the higher concentration of the solution, the greater depth of the transmittance curves with red wavelength shift because the LSPR phenomena was occurred, the sensitivity of the transmission (change of transmission with change of refractive index) was determined from the linear fit relation ΔT/RIU=18.86. Figure 8(b) shows due to the addition of graphene, the transmission overall significantly decreased, the sensitivity of the transmission is ΔT/RIU= 20.55.



(a)



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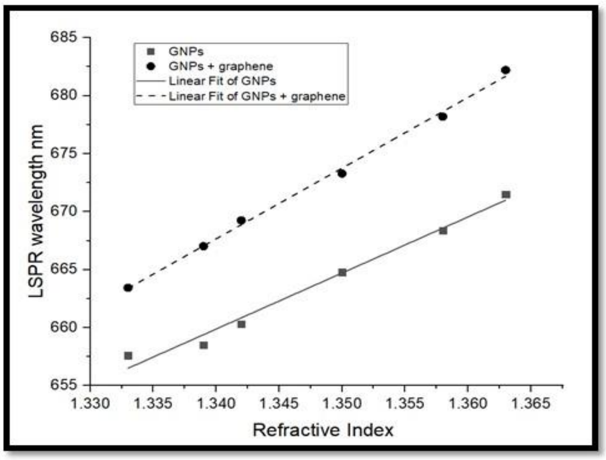
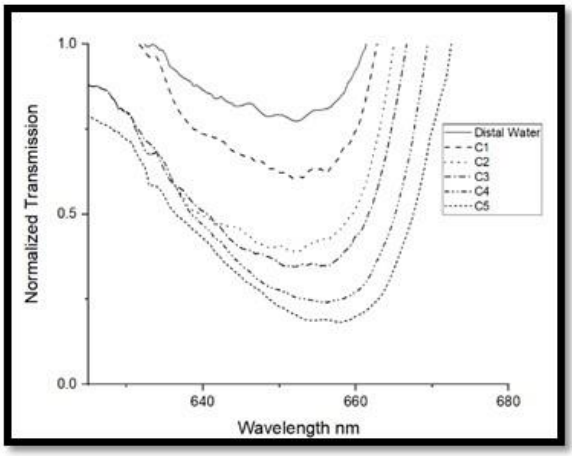
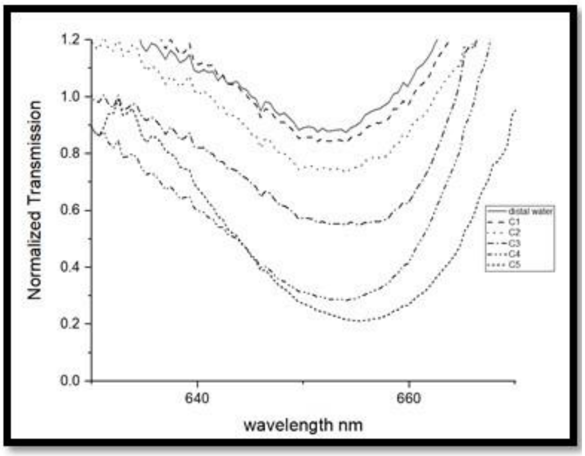


(c)

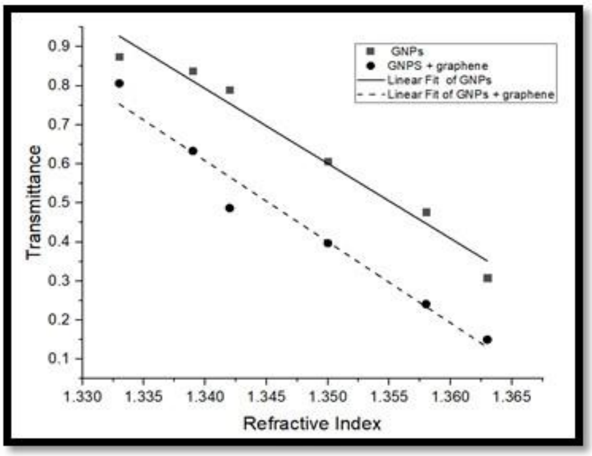
Figure 7. Response Intensity of U shape POF LSPR sensor, (a) with 30 nm GNPs in different RI solutions, (b) with 30 nm GNPs + graphene in different RI solutions, and (c) linear fitting curve between the RI change and LSPR wavelength



(a)



(b)



(c)

Figure 8. Normalized Transmission spectra obtained from U shape POF LSPR sensor (a) with 30 nm GNPs immersed in different RI solutions. (b) with 30 nm GNPs + graphene, sensor immersed in different RI solutions, and (c) linear fitting curve

The well sensitivity between transmittance and RI change can be ascribed to graphene, which has relatively high surface-to-volume ratio thus allowing it to have a better surface contact with the analytic and absorb more molecules, and tunable RI of the graphene with the concentration increase of the solution which leads to a more significant absorbance variation [12]. The sensitive RI change of the sensing area with graphene is introduced by the molecular enrichment properties of graphene [23]. these results agreement with the result in the previous study in reference [5] and [17] With the addition of graphene layer, the SPR spectrum's resonance wavelength will more shift, the RI sensitivity will be improved by using graphene. Beside the sensitivity the FOM (Figure Of Merit) used to evaluate the performance of LSPR sensor, FOM given by the ratio of sensitivity to FWHM (full width at half maximum) [22], Signal to noise ratio (SNR) is the ratio of shift wavelength to FWHM and Resolution is the ratio of minimum spectral resolution to Sensitivity [24]-[26]. The characteristics for the sensor that coated with 30 nm thickness of GNPs and sensor that coated with 30 nm thickness of GNPs + graphene is shown in Table 1. In Table 2, the sensitivity of the latest sensor is compared with the sensitivity of the sensors made in previous studies.

Table 1. The characteristics for the LSPR RI sensors manufactured in this study

Sensor Type (U bent LSPR sensor)	Sensitivity nm/RIU	FWHM nm	SNR	FOM RIU^{-1}	Resolution mRIU	R^2(regression coefficient)
30 nm GNPs	466.66	17	0.824	27.45	0.214	0.98
30 nm GNPs + Graphene	666.66	19	1.05	35.08	0.150	0.99

Table 2. Comparison sensitivities between some optical LSPR sensors

Structure	Material	Sensitivity nm/RIU	reference
U bent fiber	Ag + graphene	1116.8	[27]
U bent fiber	Mos_2 + GNPs	6184.4	[28]
D shape fiber	GNPs	580	[29]
End reflection	GNPs+ graphene	611	[30]
U bent fiber	Ag+PVA+graphene	1198	[31]
U bent fiber	GNPs+ graphene	666.66	Current study

5. CONCLUSION

In this article U bent LSPR optical fiber sensor was designed by using plastic optical fiber with 980 µm fiber diameter was bent in U shape with 0.5 cm bending diameter, the cladding and part from the core were removed by polishing from the head sensor to increase the evanescent wave and improve the sensitivity, the optical sensor was immersed in sodium chloride solutions with RI range from 1.333 to 1.363. In this study, it was concluded that when GNPs were deposited on the head sensor, the obtained sensitivity was 466.66 nm/RIU for wavelength shifting and 18.86 ΔT/RIU for transmittance respectively. While when graphene is deposited over the GNPs on the head sensor, the sensitivity becomes 666.66 nm/RIU for wavelength shifting and 22.55 ΔT/RIU for transmittance respectively, this improvement in sensitivity occurred due to the addition of graphene, this supports previous studies. This sensor is simple, has good detection specificity and excellent reliability, it can be used in bio/chemical applications.

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