The Reinforced Optical Fiber Sensing with bilayer AuNPs/SiC for pressure measurement: Characterization and Optimization

Marwan Hafeedh Younus1*, Ghazwan Ghazi. Ali1, Hesham Anwar Salih1

1Physics Department, College of Education for Pure Science, University of Mosul, Iraq.

*Corresponding author email: marwan.hafed@uomosul.ude.iq

Abstract. A cladding modified multimode optical fiber sensor reinforced with bilayers Au:SiC is designed and fabricated for pressure sensing in this presented. The Au thin film was used to enhanced the sensitivity of the sensor while the SiC thin film has been investigated as the reinforced layer at the sensing part to measure the wide range of applied pressure. The data acquisition interrogated using an optical time-domain reflectometer (OTDR). The results showed that the performance of the optical fiber sensor coated with bilayers Au:SiC coating is significantly improved in the measurement of applied pressure at the sensing part. Additionally, the sensor coated with bilayer Au:SiC exhibits linear variation in the return losses measured from OTDR trace with the wide range of applied pressure compare to the sensor coated with Au thin film. Where the maximum value in the sensitivity is equal to 35% dB/um of the sensor coated with bilayers SiC:Au compared to the sensitivity of the sensor coated with Au which equal to 30% dB/um. The high performance showed in results demonstrating that the fabricated optical fiber sensor has the excellent potential application as a sensor to measure a wide range of applied pressure without deform the sensing part.

Key words: Reinforce Optical Fiber, Pressure Sensors, Thin films, Bilayer Coating

1. Introduction

The dependable sensors with highly sensitive to measure a large range of parameters of interest is needed as the one of a vital detection device in recent times. The research lines in the fields of optical fiber sensors have considerably improved and capability with the use deposition techniques to deposit the nanocoating films. A various configuration of optical fiber sensors being achieved using nanostructured thin films and nanocoating to produce a new sensor. Moreover, many optical fiber based sensors have been established to use in detection and monitoring of different physical parameters such as a gases [1-4], pH [5,6], temperature [6], humidity [7, 8], ions [9,10], biomolecules [11-13] and micro-bending [14-16]. The advantages of optical fiber sensors such as cost effective, remote monitoring. Data acquisition and the flexibility were clearly apparent in applications over the traditional sensors where pressure and strain are required over long distances or large areas [17-21].

In several practical applications, optical fiber sensors have exhibited its ability to sense a variety of parameters. Optical fiber have been developed successfully as sensors to measure the displacement, acceleration, acoustic or vibration and pressure. The general advantages of optical fiber pressure sensors such as, inexpensive, dependable, noncomplex which they can be applied for use in distributed sensing along the fiber. [22-24].

In diverse new researches, it has been demonstrated that the gold nanoparticles (AuNPs) embedded coatings enhance some parameters of optical fiber sensor, for example, dynamic range,
lifetime and sensitivity [25, 26]. However, the optical fiber sensor remains problematic to pressure measurement because it is very fragile. On the other hand, silicon carbide (SiC) is widely used as reinforcement materials because of their effective toughening mechanisms such as, high strength and good chemical stability [27,28]. So we considered to use SiC to reinforcement the optical fiber sensor coated with AuNPs in order to improve its properties toward the wide range of pressure measurements.

In the present work, we fabricated and characterized an optical fiber coated with bilayers (Au:SiC) based on micro-bend to sense the deformation induced from applied pressure at the sensing part. The gold nanoparticles (Au) is used to enhance the sensitivity of the fabricated sensor and SiC thin film is used as a layer to reinforce the sensor toward the applied pressure. The convenient Optical Time Domain Reflectometry (OTDR) is used as analyser to locate the light loss measurements according to local applied pressure along the fiber.

2. Experimental Section

2.1. Optical Fiber Sensor Preparation

Multimode optical fiber with parameters (refractive index of 1.456 and a length of 100 m) was proposed as the pressure sensors in this work. The diameters of core and a clad of fabricated sensor used in this study are 50μm and 125μm respectively. it should note that a large amount can be carried using this type of fiber compared to the single-mode optical fiber, which leads to an increase in the amount of reflected light to the detector in the OTDR device. The sensing part is proposed by 1 cm etching of its clad via the chemical etching method. Additionally, acetone, alcohol, and distilled water were used respectively to remove the impurities from the sensing part of the fiber before the etching process. Then optical fiber is dipped in the hydrofluoric acid bath (49% HF) to start the etching process. Because of the reaction between the HF acid and the silica, the clad of optical fiber has been completely removed within 20 minutes. Figure 1 illustrated the images from an electron microscope sensing part before and after etching.

![Image of SEM images of sensing part before and after etching](image-url)
After removing the clad of the optical fiber sensor using the chemical etching method, the gold (Au) thin film was deposited on the sensing part (1cm length) of multi-mode optical fiber with a distribution thickness of 35 nm by sputter coater to enhance the sensitivity of the system. The gold layer deposition was carried out via a Sputter Coater (Quorum Q150R ES, UK) which is working with a gold target bombarded using ions of argon gas. The sputter coater is fitted with a quick-change target of 57 mm and the sample chamber of 165 mm in diameter as illustrated in Figure 2. Additionally, the distance between the optical fiber and the gold target was 10 cm, the coating process was achieved inside the chamber at a pressure of $3 \times 10^{-3}$ Torr and a current of 40 mA. The optical fiber sensor was placed inside the sputter-coated chamber and it fixed in a parallel position to the gold target. This way, the sample was oriented almost facing the flow of gold atoms, which is increasing the atoms of gold on the sample, so all surfaces of optical fiber will be coated.

![Figure 2. setup of sputter-coater diagram](image)

Then, the silicon carbide thin film (SiC) was deposited over the Au thin film to reinforce the optical fiber sensor for wide range of applied pressure as illustrated in Figure 3. The deposited SiC thin film on the sensing part of the sensor was carried out by the HOME-MADE Instruments 150 MHz VHF-PECVD system with typical parameters of 20 W, $9 \times 10^{-2}$ Torr and 20 °C. The selected mixture precursor of silane gas (SiH4 99.999%) and methane gas (CH4 99.999%) were used to depositing the SiC with 540 nm of thickness, while the Ar gas has been used as the carrier gas. All of the gasses were entered the reaction chamber through a conventional showerhead electrode.
2.2. Set up of Microbending Sensor System

The Scrambler Mode used in this work is shown in Figure 4a. It produces a periodic microbending on the sensing part of the fiber which leads to an increase the applied pressure. The two plates with stainless steel teeth of scramble mode are responsible for generating the pressure on the fiber. In addition, the knob (divided from $\theta = 0^\circ$ to $\theta = 360^\circ$) is used to move the plates forward or backward which leads to an increase or decreases the applied pressure on the sensing part placed between two plates. Moreover, when the angle $\theta$ (angular displacement) of the control knob increase, the distance (linear displacement) between the plats is increased. Where the conversion between the angular displacement and the linear displacement was calculated using the traveling microscope as shown in Figure 4b. The relationship between the angular displacement and linear displacement is shown in Table 1.

![Figure 3. Schematic diagram of sensing part of optical fiber coated with SiC thin film over the Au layer](image)

![Figure 4. a) Scramble Mode tool, b) the traveling optical microscope](image)
Table 1. Illustrate relationship values between the angular displacement and the linear displacement

| Angular displacement $\theta^\circ$ | Linear displacement $d$ (µm) |
|-------------------------------------|------------------------------|
| 0                                   | 0                            |
| 30                                  | 21                           |
| 60                                  | 42                           |
| 90                                  | 60                           |
| 120                                 | 84                           |
| 150                                 | 105                          |
| 180                                 | 126                          |
| 210                                 | 147                          |
| 240                                 | 166                          |

Figure 5 illustrates the optical fiber sensing system for pressure measurement. It consists of the multimode optical fiber coated with bilayers Au:SiC as a sensor and optical time-domain reflectometer (OTDR) as an analyzer. Once the optical fiber placed between the plates, the deform in the optical fiber can be observed as shown in the inset image from Figure 4. Moreover, the disturbance in the intensity at the sensing part will be produced due to the pressure generated from the teeth of two plates which leads to an increase the losses measured from the OTDR trace.

![Figure 5. Optical fiber micro-bending sensor for pressure measurement](image-url)
3. Results and Discussion

3.1. The Response of Optical Fiber pressure Sensor with Au thin film Coating

Figure 6 a. shows the absorption spectra of Au deposited on the optical fiber sensor for pressure measurement. It can be seen that the maximum absorption peak is located at 530, this indicates that the Au thin film successfully synthesized on the optical fiber. In addition, the Au elemental was proved by EDX analysis at the sensing part of the optical fiber sensor as shown in Figure 6b which is confirmed the presence of Au thin film is clearly detected, where the appearance of Au peaks verifies the existence of the Au layer on the sensor. The scanning electron microscopy (SEM) micrograph analysis shows the surface and cross-section images of the optical fiber sensor coated with gold thin film in Figure 6 c. It notices that the optical fiber become shinier after deposited Au thin film, where the Au thickness is found to be 35 nm.

![UV-Vis spectra of the Au thin film deposited on the sensing part of optical fiber, EDX spectrum of the sensing part coated with Au thin film, SEM images of the deposited Au thin film on the sensing part of optical fiber.](image-url)
In order to corroborate the enhancement in the sensitivity of the optical fiber pressure sensor, different pressure was applied on the sensing part using the Mode Scrambler tool. Here the sensitivity of the optical fiber sensor represented the change in the return losses measured from the OTDR trace due to the applied pressure at a sensing part. The initial value of the angular displacement is chosen to be $\theta = 30^\circ$ which is equal to the linear displacement of 21 $\mu$m (see Table 1). Figure 7 illustrates the losses in the OTDR trace as a function of the applied pressure of the optical fiber sensor. As can be seen from Figure 7, the return losses represent the step drop in the OTDR trace.

![Figure 7. The return losses measurements from the OTDR trace](image)

To more clearly compare the response of the sensors before and after Au coating, the return losses from OTDR trace have been plotted as a function of the applied pressure by mode scramble tool before and after Au coating as shown Figure 8. The vertical axis is the return losses measured from the OTDR trace and the x-axis is the values of the applied pressure. Different pressure of ranging from 20 um to 126um was applied over the proposed optical fiber (see the linear displacement in Table 1).

![Figure 8. The return losses obtained from the OTDR trace vs. the linear displacement (applied pressure)](image)
It can be seen that the return losses of the sensors before and after Au coating increased when the applied pressure is increased on the sensing part. Additionally, the values of the return losses of the sensor coated with Au increased clearly and it found to be larger than sensor without Au coating. The maximum sensitivity of the sensor coated with Au was higher and it found to be 30 % dB/um whereas the lower sensitivity was for the sensor without Au coating which is equal to 9 % dB/um. It can be noted that the improvement in the sensitivity of the sensor is due to located the Au nanoparticles in the sensing section of the sensor which is mostly lead to light perturbation at the sensing section; thus, the return loss (light scattering) increases and consequently, increases the sensitivity of the sensing system. It is; however, the fiber that has been distorted and damaged at the maximum linear displacement of 126 um (see Table 1). It is impractical to work optical fiber when is subjected to a large pressure since optical fibers at the sensing part are extremely fragile. To solving this problem, the silicon carbide (SiC) was used as layer to reinforce the optical fiber at sensing part.

3.2. Optical Fiber Response with bilayers Au:SiC Coating

In this section, the performance of the optical fiber sensor coated with the bilayer Au and SiC layer was experimentally investigated. The SiC thin film was used as a reinforced layer for the optical fiber to enhance the sensitivity of the sensor when the applied pressure increases the most. Figure 9 depicted the typical SEM images cross-sectional view of the sensor coated with Au and SiC thin films. As can be seen from Figure 9, the SiC is formed as an outer layer with thickness of 540nm, and Au thin film with thickness of 35 nm is formed underneath the SiC layer. In addition, the Au and SiC layer was confirmed by EDX analysis. Figure 10 displays the typical EDX spectra scanned on the optical fiber sensor coated with the Au:SiC. As can be seen, the elements of Au, Si and C is clearly detected, and the corresponding atomic percentage (at.%) is 4.2%, 50.2%, and 21.1%, respectively, which proves the existence of Au and SiC layer on the optical fiber.

![Figure 9. SEM image of the optical fiber pressure sensor coated with bilayer Au:SiC](image_url)
In order to improve the ability of the sensor, different pressures were applied over the proposed optical fiber sensor and the return losses from OTDR trace were measured. Figure 1 shows the return losses versus the applied pressure on the optical fiber sensor coated with Au and coated with bilayer Au:SiC. The black line represents the sensor coated with Au thin film while the red line belongs to sensor coated with bilayers SiC: Au thin film. It is observed that the return losses are directly proportional to the applied pressure on the optical fiber sensor. As can see from Figure 1, the applied pressure on the optical fiber coated with Au thin film is limited to 104 μm (linear displacement), where the pressure behind this point leads to break the optical fiber. Once the SiC coating over the Au layer, the ranges of applied pressure on the optical fiber sensor clearly increased to 210 μm (red line) and approximately it exhibits a linear response over the considered pressure range with a maximum sensitivity of 35 dB/μm. We can infer that using the SiC coating as reinforcing layer over the Au layer, the optical fiber can be improved and developed to measure a wide range of applied pressure without deforming the sensing part.

![Figure 10. EDX spectrum of the optical fiber sensor coated with bilayer Au: SiC](image)

Figure 10. EDX spectrum of the optical fiber sensor coated with bilayer Au: SiC

![Figure 11. the comparative of return losses vs. linear displacement of the optical fiber sensor coated with Au (black line) and coated with bilayer Au:SiC (red line)](image)

Figure 11. the comparative of return losses vs. linear displacement of the optical fiber sensor coated with Au (black line) and coated with bilayer Au:SiC (red line)
4. Conclusion

The fabrication and characterization of multimode optical fiber sensors based bilayers Au:SiC coating for pressure measurement was presented in this work. The prepared sensor was coated with bilayer Au:SiC thin film to enhance the sensitivity of the sensing system for applied pressure. The use of SiC thin film over the Au thin film as the reinforce layer showed significant sensitivity of the sensor in a broad dynamic range of pressure that applied on the sensing part compare to that observed in sensor coated with Au which operation with a limited range. The maximum sensitivity of the sensor coated Au:SiC found to be 35%. The results proved that the fabricated sensor coated with Au: SiC revealed that the tested fiber sensor is capable to measure a wide range of applied pressure on the sensing part without produce any deform. In the concludes, the properties of the deposited optical fiber sensor can be controlled significantly by the selection of the material thin film deposition.

References

[1] Zhao, Pengcheng, et al. "Mode-phase-difference photothermal spectroscopy for gas detection with an anti-resonant hollow-core optical fiber." Nature communications 11.1 (2020): 1-8.

[2] Shanavas, Shajahan, et al. "Development of high-performance fiber optic gas sensor based rice-like CeO2/MWCNT nanocomposite synthesized by facile hydrothermal route." Optics & Laser Technology 123 (2020): 105902.

[3] Minkovich, Vladimir P., et al. "Microstructured optical fiber coated with thin films for gas and chemical sensing." Optics Express 14.18 (2006): 8413-8418.

[4] Abdelghani, A., et al. "Optical fibre sensor coated with porous silica layers for gas and chemical vapour detection." Sensors and Actuators B: Chemical 44.1-3 (1997): 495-498.

[5] Duong, Hong Dinh, Younsook Shin, and Jong Il Rhee. "Development of novel optical pH sensors based on coumarin 6 and nile blue A encapsulated in resin particles and specific support materials." Materials Science and Engineering: C 107 (2020): 110323.

[6] Lin, Jie. "Recent development and applications of optical and fiber-optic pH sensors." TrAC Trends in Analytical Chemistry 19.9 (2000): 541-552.

[7] Zhong, Yongchun, et al. "Ultrafast freestanding microfiber humidity sensor based on three-dimensional graphene network cladding." Optics Express 28.4 (2020): 4362-4373.

[8] Sharma, Anuj K., Baljinder Kaur, and Vasile A. Popescu. "On the role of different 2D materials/heterostructures in fiber-optic SPR humidity sensor in visible spectral region." Optical Materials 102 (2020): 109824.

[9] Alwahib, Ali Abdulkhaleq, et al. "Surface plasmon resonance sensor based on D-shaped optical fiber using fiberbench rotating wave plate for sensing pb ions." Optik 202 (2020): 163724.

[10] He, Ying, et al. "Wet-spinning of fluorescent fibers based on gold nanoclusters-loaded alginate for sensing of heavy metal ions and anti-counterfeiting." Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy (2020): 118031.

[11] Yap, Stephanie Hui Kit, et al. "Carbon Allotrope-Based Optical Fibers for Environmental and Biological Sensing: A Review." Sensors 20.7 (2020): 2046.

[12] Zhang, Wenhao, and Tiechao Jiang. "Design of biomolecule interaction detection system based on fiber biosensor." IEEE Sensors Journal (2020).

[13] El-Sherif, Mahmoud, Lalitkumar Bansal, and Jianming Yuan. "Fiber optic sensors for detection of toxic and biological threats." Sensors 7.12 (2007): 3100-3118.

[14] Lee, Thomas, et al. "Chemical sensing with microbent optical fiber." Optics Letters 26.20 (2001): 1541-1543.

[15] Luo, Fei, et al. "A fiber optic microbend sensor for distributed sensing application in the structural strain monitoring." Sensors and Actuators A: Physical 75.1 (1999): 41-44.

[16] Yang, Xiufeng, et al. "Textile fiber optic microbend sensor used for heartbeat and respiration monitoring." IEEE Sensors Journal 15.2 (2014): 757-761.
[17] Spillman, W. B. "Multimode fiber-optic pressure sensor based on the photoelastic effect." Optics letters 7.8 (1982): 388-390.
[18] Luo, Fei, et al. "A fiber optic microbend sensor for distributed sensing application in the structural strain monitoring." Sensors and Actuators A: Physical 75.1 (1999): 41-44.
[19] Zhang, Y., et al. "Sensitivity amplification of bubble-based all-silica fiber liquid-pressure sensor by using femtosecond laser exposure." Optics Communications (2020): 125291.
[20] Nath, Pabitra. "Non-intrusive refractometer sensor." Pramana 74.4 (2010): 661-668.
[21] Annamdas, Kiran Kishore Kumar, and Venu Gopal Madhav Annamdas. "Review on developments in fiber optical sensors and applications." Fiber Optic Sensors and Applications VII. Vol. 7677. International Society for Optics and Photonics, 2010.
[22] Lagakos, Nicholas, J. H. Cole, and Joseph A. Bucaro. "Microbend fiber-optic sensor." Applied optics 26.11 (1987): 2171-2180.
[23] Berthold, John W. "Historical review of microbend fiber-optic sensors." Journal of lightwave technology 13.7 (1995): 1193-1199.
[24] Kamarulzaman, Amirul Hazim, and Wan Maisarah Mukhtar. "Hybrid U-Shaped-Microbend SMF Evanescent Wave Sensor for River Water Quality Assessment: A Preliminary Study." Science Letters 14 (2020): 1.
[25] Miliutina, Elena, et al. "Enhancement of Surface Plasmon Fiber Sensor Sensitivity Through the Grafting of Gold Nanoparticles." Photonic Sensors (2019): 1-8.
[26] Tseng, Yuan-Tai, et al. "A gold-nanoparticle-enhanced immune sensor based on fiber optic interferometry." Nanotechnology 19.34 (2008): 345501.
[27] Kong, Juan, Nikolas Provatas, and David S. Wilkinson. "Anelastic Behavior Modeling of SiC Whisker-Reinforced Al2O3." Journal of the American Ceramic Society 93.3 (2010): 857-864.