LSPR-Based Fibre Optic Sensor Fabricated by Laser Annealing of Thin Gold Films

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ABSTRACT

A fibre optic sensor based on localized surface plasmon resonance (LSPR) is fabricated by transforming a thin gold film deposited on the sensor tip into gold nanoparticles (AuNPs) using the laser annealing technique. The reflected spectra of the sensor exhibit a strong LSPR peak between 600 and 650 nm. The sensor is capable of detecting refractive index (RI) changes within the tested range of 1.3 to 1.395. As the RI increases, clear wavelength shifts in the peak wavelength are observed. The sensor responds linearly to RI variations, achieving a sensitivity of -215.8 nm/RIU. SEM analysis confirms the successful formation of AuNPs, which are essential for the sensor's high sensitivity and consistent performance. The fabricated sensor is cost-effective, easy to fabricate, and suitable for biochemical applications.

Keywords: Fibre optic sensor, Localized surface plasmon resonance, Laser annealing, Refractive index sensing.

1. INTRODUCTION

Fibre optic sensors (FOS) have been extensively researched for a wide range of applications, including measuring the concentrations of chemicals, and biomolecules. Their appeal lies in several key advantages, such as low cost, flexibility, availability, high sensitivity, and rapid response.[1] Most of these sensors operate by detecting changes in the refractive index (RI) of the surrounding environment, caused by variations in the concentration of the target analyte, through analysing changes in the wavelength, intensity, polarization, and phase of the light traveling through the sensor.[2] To achieve high-sensitive RI measurement, researchers have developed various FOS structures, such as Mach-Zehnder interferometers,[3] surface plasmon resonance (SPR), localized surface plasmon resonance (LSPR),[4,] and evanescent wave sensors.[5] Each of these structures offers distinct advantages for sensing applications. Among these structures, FOS based on SPR and LSPR using metal nanoparticles (NPs) are renowned for their exceptional sensitivity to changes in the RI near surfaces.[4] In particular, LSPR-based sensors are highly attractive in this category due to their ability to confine plasmonic oscillations at the nanoscale, making them particularly effective for detecting extremely low concentrations of molecules of chemical and biological agents.[6]

The fabrication techniques of LSPR-based FOS are pivotal in defining their performance attributes, such as sensitivity, repeatability, reproducibility, durability, and suitability for specific chemical and biological applications. Achieving high performance requires protocols that prioritize precise nanoparticle production, ensuring consistent size and shape, along with reliable nanoparticle coating to prevent detachment and maintain sensor stability.[7]

The attachment of NPs to fibre optics is generally categorized into chemical and physical bonding techniques, each offering specific advantages and limitations. Chemical bonding, being the most widely used approach, is associated with challenges such as inconsistent nanoparticle distribution and variable coating densities, which compromise reproducibility. Moreover, its weak chemical bonds can lead to nanoparticle detachment. Surface tension during measurements may also lead to nanoparticle aggregation on the fibre surface, further impacting the sensor's performance.[8,9] In contrast, physical bonding methods, such as focused ion beam (FIB) milling,[10] and electron beam-induced deposition (EBID),[11] address the limitations associated with chemical bonding. However, these techniques are often costly, complex, and require a significant time investment which can hinder their widespread adoption.[12]

Kalfagiannis et al. introduced a novel technique known as Laser-Induced Self-Assembly (LISA) to produce controllable and reproducible NPs through laser annealing (LA).[13] This method involves the use of precisely calibrated laser energy density (i.e. fluence) to locally heat and melt thin films of noble metals, enabling the formation of NPs without the need for complex and expensive patterning processes.

To the best of our knowledge, the use of the LA method to develop LSPR-based optical fibre sensors remains unexplored. This study introduces a new approach that bridges this gap by employing LA to fabricate controllable and robust nanostructures directly on the tip of the optical fibre, facilitating highly sensitive detection of RIs, in a facile, quick, and cost-effective manner.

2. METHODOLOGY

The fabrication of AuNPs on the optical fibre tip begins with securely mounting a bundle of ten cleaved multimode optical fibres with a core diameter of 105 µm (FG105LCA, Thorlabs, United Kingdom) in a custom-designed holder to maintain a vertical orientation, with the tips pointing upward. The mounted fibres are then placed in a sputtering chamber (Q150R ES, Quorum, United Kingdom) to deposit a uniform gold layer on the tips of the fibres, which is crucial for the subsequent generation of NPs. To form AuNPs, the coated tips of the fibres are subjected to laser annealing, with the setup detailed by Kalfagiannis.[14] Briefly, the process utilizes an excimer laser (LAMBDA PHYSIK LPX 305i, United States) that generates unpolarized light pulses with pulse duration of 25 ns, and energy up to 1200 mJ per pulse at a wavelength of 248 nm (KrF). A beam delivery system comprising a variable attenuator, a beam homogenizer, and a mask-projection system was utilized to deliver the laser beam to the samples. The attenuator regulated the beam intensity, while the homogenizer ensured a uniform energy density distribution across the laser spot (top-hat profile). The homogenized beam was then directed through a mask and projected onto the sample (bundle of fibres).

As depicted in Figure 1, the experimental setup to test the fabricated sensor consists of a light source (HL-2000-FHSA, Ocean Optics, United States), a spectrometer (Maya2000Pro, Ocean Optics, United States), and a 1×2 fibre coupler (TM105R5S1B, Thorlabs, United Kingdom). On one side, the sensor is fusion spliced to the end of the coupler using a fusion splicer (FSM-100P, Fujikura, Japan). On the opposite side, the coupler is connected to the spectrometer and the light source. The light source delivers the input light to the coupler, and the spectrometer interfaced with a PC monitors the reflected spectra from the sensor tip as it interacts with solutions of different RI.

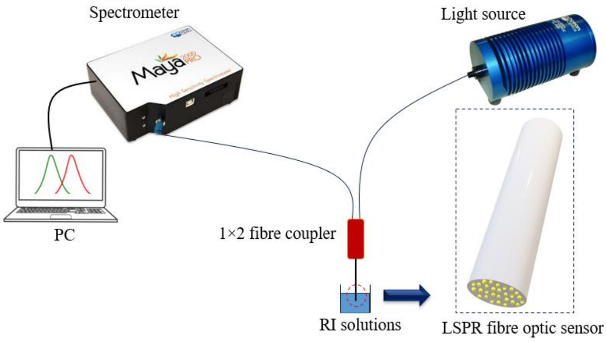


Figure 1. Schematic diagram of the experimental setup.

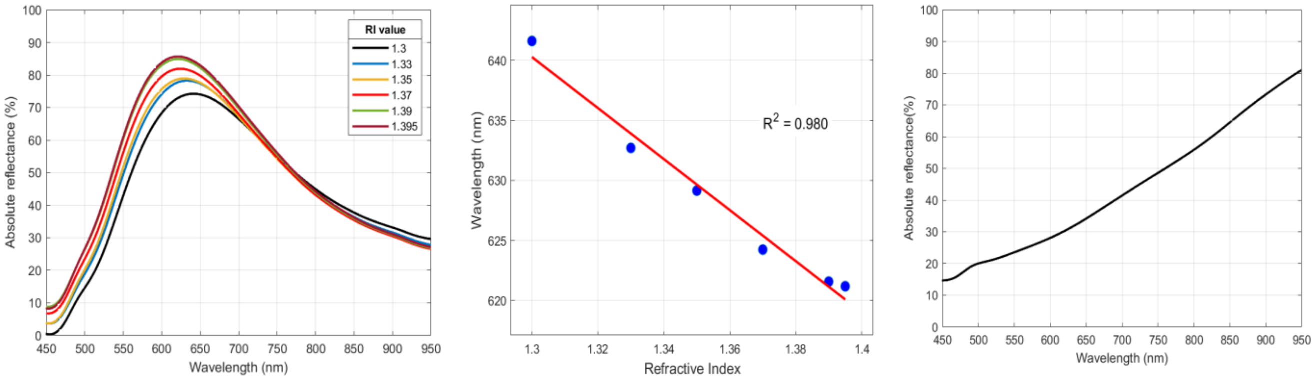
3. RESULTS AND DISCUSSION

3.1. Sensor response to varying RI levels

The fabrication of the sensors involved depositing 10 nm of gold film on the fibre tip, followed by laser annealing at a fluence of 400 mJ/cm² with 2000 laser pulses (delivered at 5 Hz). Strong LSPR peaks between 600 and 650 nm were observed in the fabricated LSPR sensors, with the bare fibre (without AuNPs on the tip) reflection spectrum serving as the baseline for measurements. This peak is attributed to the LSPR effect, which arises from the resonant interaction of incident light with the conduction electrons in the AuNPs, enhancing the localized electromagnetic field.

The sensor's response to different RIs ranging from 1.3 to 1.395 is illustrated in Figure 2(a). An increase in RI has resulted in a wavelength shift of the reflectance peak to the left. It should be noted that the blue wavelength shift observed is contrary to theoretical expectations in literature,[15] and the investigation of this phenomenon is still a work in progress. Figure 2(b) shows the sensor's linear behaviour of the peak wavelength in response to the RI changes, with a linear fit yielding an R^2 value of 0.98. The sensor demonstrates a wavelength sensitivity of -215.8 nm/RIU. Also, as shown in Figure

2(c), the as-deposited fibre (after gold thin film deposition and prior to laser annealing) shows a reflection spectrum with no peaks and therefore cannot be used as a wavelength-based sensor.

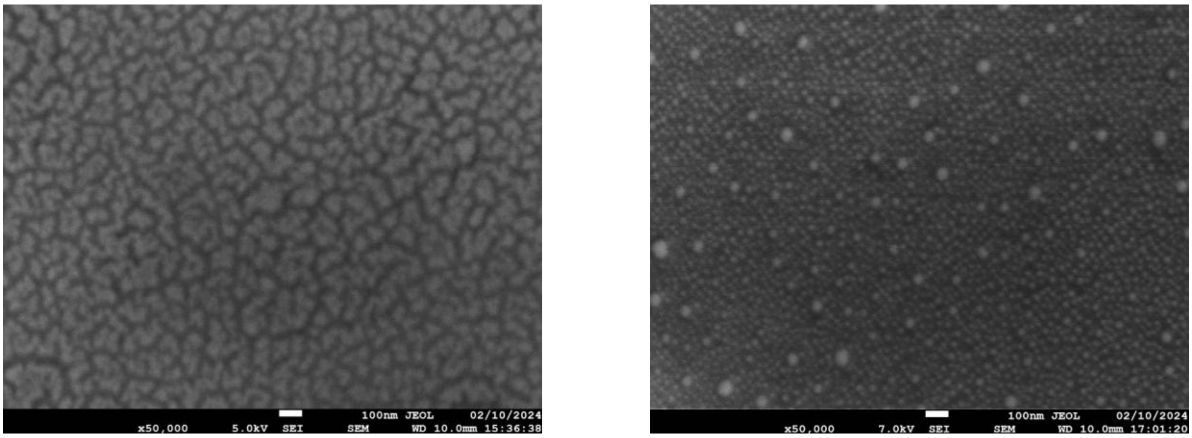


(a) (b) (c)

Figure 2. (a) Spectra of the fabricated sensor in response to solutions with different RI, (b) linear response plot of the sensor with R^2= 0.98, (c) as-deposited fibre reflection spectrum with no LSPR peak.

3.2. Scanning electron microscopy (SEM) analysis

Figure 3 presents the field emission SEM (FE-SEM) images of the fibre end face captured using FE-SEM machine (JSM-7100F, JEOL, Japan). The images were captured at magnification of ×50,000. Figure 3(a) depicts the as-deposited fibre tip with no visible AuNPs but with the characteristic discontinuous character of an ultra-thin film (10 nm nominal thickness). Figure 3(b) shows the fibre tip after laser annealing with a fluence of 400 mJ/cm² and 2000 pulses, where formed AuNPs are observed with a well-distributed arrangement.



(a) (b)

Figure 3. FE-SEM images of 10 nm gold coated fibre tip (a) before laser annealing (as-deposited) at a magnification of ×50,000, (b) after annealing with a laser fluence of 400 mJ/cm² and 2000 pulses at a magnification of ×50,000.

4. CONCLUSIONS

This study demonstrates successful fabrication of an LSPR-based FOS by transforming a 10 nm gold thin film deposited on the fibre tip into AuNPs using LA at a fluence of 400 mJ/cm² with 2000 laser pulses. The fabricated sensor exhibits high sensitivity to RI changes within the measured range of 1.3 to 1.395, with a strong LSPR peak between 600 and 650 nm. The sensor responds linearly to RI variations, achieving a sensitivity of -215.8 nm/RIU. SEM analysis confirmed the formation of AuNPs. This cost-effective and facile fabrication approach makes the sensor a promising candidate for biochemical applications. Future studies will explore optimizing fabrication parameters to enhance performance and improve selectivity and sensitivity through appropriate coatings.

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