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Comparison of Tapered Optical Fiber Sensors Based on Gold, Silver, Copper and Aluminum Nanoparticles

Parisa Borjikhani[1], Mohammad Ismail Zibaii[2,*], and Nosrat Granpayeh[1]

[1]Center of Excellence in Electromagnetics, Optical Communication Laboratory, Faculty of Electrical Engineering, K. N. Toosi University of Technology, Tehran, Iran.

[2]Laser & Plasma Research Institute, Shahid Beheshti University, Tehran, Iran.

Abstract- Four tapered optical fiber sensors based on the localized surface plasmon resonance (LSPR) method with Au, Ag, Cu, and Al nanoparticles on the fiber waist area are simulated and investigated. The simulation method is a combination of the finite-difference time-domain (FDTD) and finite element method (FEM). The transmittance spectrum of the tapered optical fiber by variation of analyte refractive index is obtained for these four sensors and their amplitude and wavelength sensitivities are compared. It is shown that the Au sensor has the highest amplitude sensitivity of -4.5 per refractive index unit (1/RIU) and the Ag sensor has the highest wavelength sensitivity of 174.9 (nm/RIU) among these sensors. The results show that if the environmental conditions and the possibility of design for these sensors are provided, each sensor has its own advantages for diagnosing the diseases with the analyte refractive index range of 1.333-1.403.

Keywords: Sensor; Tapered Optical Fiber; Localized Surface Plasmon Resonance; Nanoparticles

* m_zibaye@sbu.ac.ir

1. Introduction

The tapered optical fiber has a good potential for diagnosing diseases through human blood samples. For example, this sensor can be useful in diagnosing diabetes mellitus, cardiovascular diseases, and gout by measuring glucose [1], cholesterol [2] and uric acid [3], respectively. In general, tapered optical fiber sensors can be used to measure various parameters such as refractive index [4], strain [5], and temperature [6]. Localized surface plasmon resonance (LSPR) is one of the optical properties of noble metal nanoparticles (NPs) such as Au, Ag, Cu, and Al [7] that is created by the collective oscillation of the free electrons in the metallic NPs [8]. Al and Cu are more abundant and cheaper than Au and Ag [9], [10], but Au and Ag are more biocompatible [7]. On the other hand, Au is more resistant to oxidation [11]. In this work, the sensitivities of the tapered optical fiber refractive index sensor based on NPs of these four metals are investigated and compared.

2. Theory and Simulation Method

The schematic view of tapered fiber is shown in Fig. 1, with NPs covering the waist. The fiber is a standard fiber with the core and cladding diameters of 8 µm and 125 µm, respectively, which is tapered in the middle area. The diameter and length of the waist are 9 µm and 1 mm, respectively. The fiber refractive index is obtained according to Sellmeier formula [12].

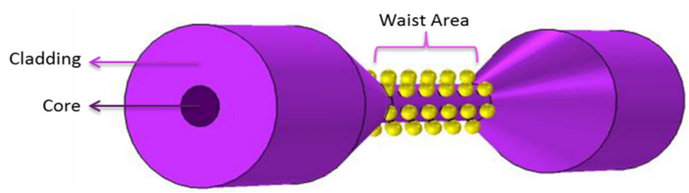

Fig. 1. Schematic view of tapered optical fiber with NPs on the waist area

This structure is used as a sensor of biological materials and the analyte (sensing material) around the fiber waist area has the refractive index range (n_a) of 1.333-1.403 [13]. This sensor is considered in four situations with Au, Ag, Cu, and Al NPs on the fiber waist area. The diameter of all NPs is 30 nm. The transmitted power of the tapered optical fiber based on NPs is obtained from the following equation [11]:

$$P_T = P_0 \exp\left(-2\pi R \frac{NC_{ext}}{A_{eff}} L\right) \quad (1)$$

where P_0, R, L, N, and C_{ext} are the input power, the waist radius and length, the number of NPs per unit area, and the extinction cross-section of one NP, respectively. So, the total number of NPs is $m = 2\pi RLN$. A_{eff} is the effective mode area on the waist which is associated with the Poynting vector distribution (S_z) of the mode under investigation [11]:

$$A_{eff} = \frac{\int_{A\to\infty} S_z dA}{S_z |_{r=R}} \quad (2)$$

The denominator of Eq. (2) shows how much the evanescent wave penetrates the fiber-analyte interface for the fiber waist with the radius of R. To find A_{eff} , the cross-section of the fiber waist in the analyte without the presence of NPs is simulated by the finite element method (FEM). In addition, to calculate C_{ext}, the absorption and scattering cross sections of a NP with the analyte background are obtained by the finite-difference time-domain (FDTD) method and added together. After calculating A_{eff} and C_{ext}, the transmittance spectrum of the tapered fiber based on NPs is obtained from Eq. (1).

3. Results and Discussion

Figures 2(a-d) show the transmittance spectra of the tapered optical fiber based on Au, Ag, Cu, and Al NPs, respectively. As shown, the variation of analyte refractive index with a step of 0.01 have been detected by these sensors and among these four sensors, the resonance of the Al sensor is in lower wavelength and the resonance of the Cu sensor is in higher wavelength. In addition, Fig. 2(e) shows the amplitude of the transmission dip versus analyte refractive index for these four sensors. The results show that the Ag sensor has the deepest resonance. After Ag sensor, the Au sensor resonance is deeper, but Au NPs are more resistant to oxidation than Ag NPs. The slope of these lines is considered as amplitude sensitivity. The amplitude and wavelength sensitivities of these four sensors are compared in Fig. 2(f). It can be seen that the amplitude sensitivity of the Au sensor and the wavelength sensitivity of the Ag sensor are higher than the others. The Au sensor has the lowest wavelength sensitivity of 58.1 (nm/RIU), which is close to the experimental structure reported in [13] with the wavelength sensitivity of 51 (nm/RIU). In general, according to the environmental conditions and the possibility of sensor design, the suitable refractive index sensor can be selected for analyte detection.

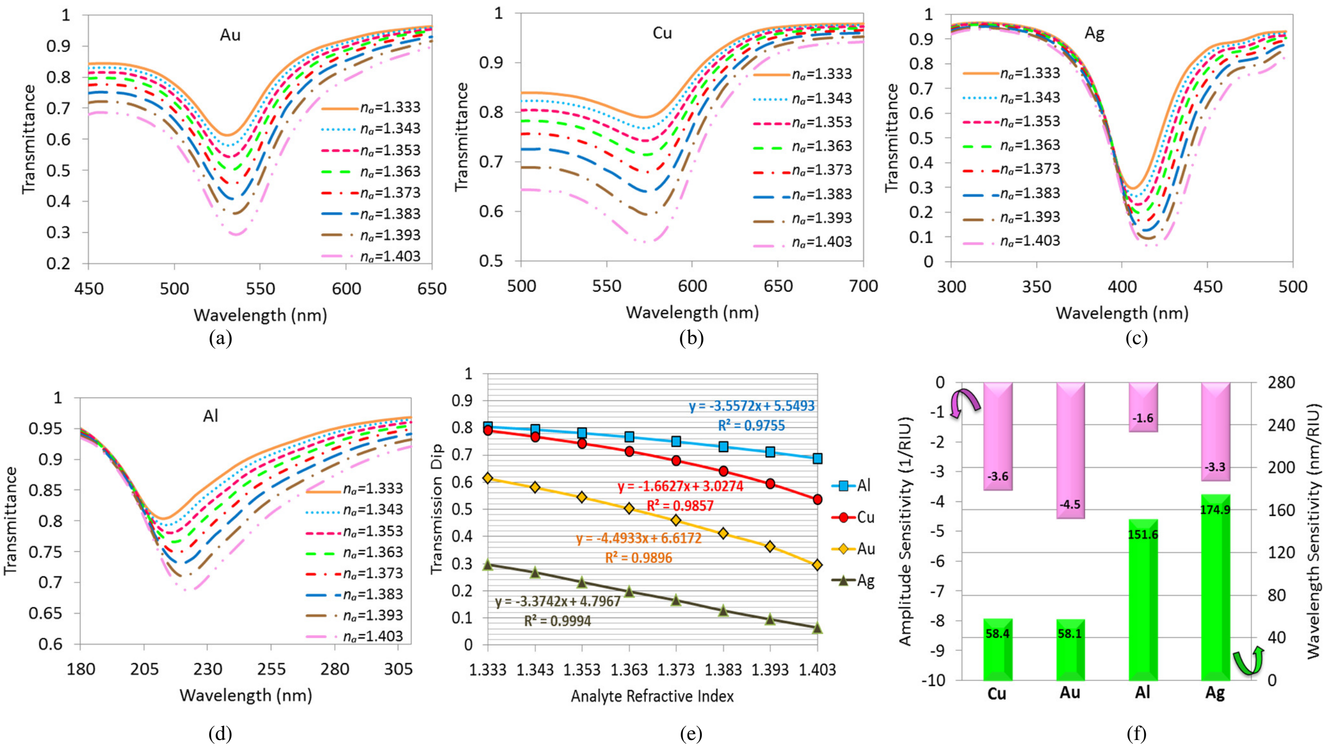

Fig. 2. The transmittance spectra for different analyte refractive indices for tapered optical fiber based on (a) Au NPs, (b) Ag NPs, (c) Cu NPs, (d) Al NPs, (e) the amplitude of the transmission dip vs. analyte refractive index and the percentage of linearity as $R^2 \times 100$, and (f) amplitude and wavelength sensitivities for these four sensors, for number of m =4000000 NPs on the fiber waist area

4. Conclusion

Four tapered fiber refractive index sensors based on Au, Ag, Cu, and Al nanoparticles were compared. The results showed that the Au sensor had the highest amplitude sensitivity of -4.5 (1/RIU) and the Ag sensor had the highest wavelength sensitivity of 174.9 (nm/RIU) for diagnosing diseases with the analyte refractive indices in the range of 1.333-1.403.

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