Optical Fiber Technology 22 (2015) 42–45

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Theoretical analysis of tapered fiber optic surface plasmon resonance sensor for voltage sensitivity

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ARTICLE INFO

Article history:
Received 30 May 2014
Revised 27 October 2014
Available online 24 January 2015

Keywords:
Fiber optic sensors
Surface plasmon resonance
Fiber tip
Sensitivity

ABSTRACT

The geometry dependent reflecting spectrum, resonance wavelength and sensitivity of surface plasmon resonance (SPR)-based tapered fiber optic sensor have been investigated. It is observed that as the tip end diameter decreases, the refractive index sensitivity of proposed sensor monotonically increases. However, the voltage sensitivity increases with the tip end diameter decreasing to a certain value. The relationship between the tip end diameter and refractive index sensitivity, voltage sensitivity present here gives a guideline to use tapered fiber optic SPR sensor targeting specific applications.

1. Introduction

Surface plasmon resonance (SPR) sensors have been important and indispensable tools in chemical and biological analysis and environment control for several decades due to their advantages in high sensitivity, label-free, non-destructive and real-time detection [1–5]. Owing to the additional unique advantages, such as miniaturization, integration and remote sensing, the fiber optic sensor based on surface plasmon resonance has drawn much attention. Numerous fiber optic SPR sensor structures for chemical and biochemical sensing have been reported to investigate the sensitivity, which is the most important factor of sensor [6–11]. Several types of noble metal have been proposed to coat on fiber to improve the SPR sensitivity [7,8,10].

The high sensitive nature of surface plasmon resonance is governed by the evanescent field generated at the metal-dielectric interface [12,13]. Therefore, fiber tapering, *U*-shaping and side-polishing techniques etc. have been adapted to enhance the amplitude of evanescent field, and make this evanescent field penetrate further into the surrounding environment and probe its optical properties [6–10,14,15]. Because the penetration depth and the number of reflections of incident light in the sensing region is dependent on the taper angle, the optical sensitivity of tapered fiber optic sensor is frequently investigated by controlling the taper profile and angle [16]. In a traditional fiber-based SPR sensor system, light with a wide range of angles determined by the numerical aperture (*NA*) of the fiber is launched into the core of fiber to excite the surface plasmon wave. Compared to the traditional one, the tapered-end SPR fiber optic sensor provides the accessibility to tune the coupling wavelength by modifying the geometry of cylindrical probe tip, which makes the amplitude of the evanescent field be tunable and controllable.

It has been demonstrated that the electrical signal is able to be extracted by using fiber optic SPR sensor [17]. The parameters, including gold film thickness, numerical aperture of optical fiber, fiber core diameter and sensing length, related to the voltage sensitivity have been thoroughly investigated in order to optimize the traditional fiber optic SPR sensor structure. The tapered fiber optic sensor exhibits enhanced sensitivity as mentioned above. In this present study, a detailed theoretical investigation of the surface plasmon resonance-based tapered fiber optic sensor has been carried out. The dependence of tip end diameter on the SPR refractive index sensitivity was investigated. Moreover, the effect of tip end diameter on its voltage sensitivity was emphasized.

2. Models and method

The theoretical modeling of tapered fiber optic surface plasmon resonance sensor is based on the principle of attenuated total reflection. The proposed tapered profiles, where the conical surface is coated with Au film and the end face is coated with a totally

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http://dx.doi.org/10.1016/j.yofte.2015.01.004

reflected film is shown in Fig. 1(a). The proposed cell structure and optical measurement setup are shown in Fig. 1(b). The cell has a gold-coated fiber sensor probe, an Ag/AgCl wire and a platinum (Pt) wire. The gold-coated fiber sensor probe is used to detect the presence of voltage. The Ag/AgCl wire and the platinum (Pt) wire are reference and auxiliary electrodes respectively, which are used to control the voltage applied on the gold-coated fiber sensor with the help of potentiostat. The fiber coupler has the function of delivering light into probe and spectrometer sequentially. The spectrometer collects the light reflected from fiber sensor for analysis.

The wavelength dependent dielectric constant of core in the fiber is given by [17,18].

$$n_1(\lambda) = \sqrt{1 + \frac{A_1\lambda^2}{\lambda^2 - B_1^2} + \frac{A_2\lambda^2}{\lambda^2 - B_2^2} + \frac{A_3\lambda^2}{\lambda^2 - B_3^2}} \qquad (1)$$

where Sellmeier coefficients $A_1 = 0.6961663$, $A_2 = 0.6961663$, $A_3 = 0.8774794$, $B_1 = 0.4079426$, $B_2 = 0.0684043$, $B_3 = 9.896161$ and λ is the wavelength of incident light.

The relative permittivity of gold in the sensing region is well described by Drude–Lorentz model [18].

$$\varepsilon_{DL}(\omega) = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega + i\gamma_D)} - \frac{\Delta\varepsilon\Omega_L^2}{(\omega^2 - \Omega_L^2) + i\Gamma_L\omega} \qquad (2)$$

where ω is the angular frequency of light, ε_∞ is the dimensionless high frequency limit contributed from interband transition of electrons, γ_D is the damping coefficient due to the dispersion of the electrons, Ω_L and Γ_L are respectively the strength and spectral width of the Lorentz oscillator and $\Delta\varepsilon$ is a weight factor. The plasmon frequency ω_D is potential dependent [19,20], so that the change of potential will alter the plasmon frequency and ultimately result in the change of the relative permittivity of gold.

Consider the propagation of a guided ray launched in the fiber through tapered region as shown in Fig. 1, D_1 and D_2 are the diameter of the fiber core and tip end respectively. L is the length of the tapered region. The tip radius varied with the z coordination is [18].

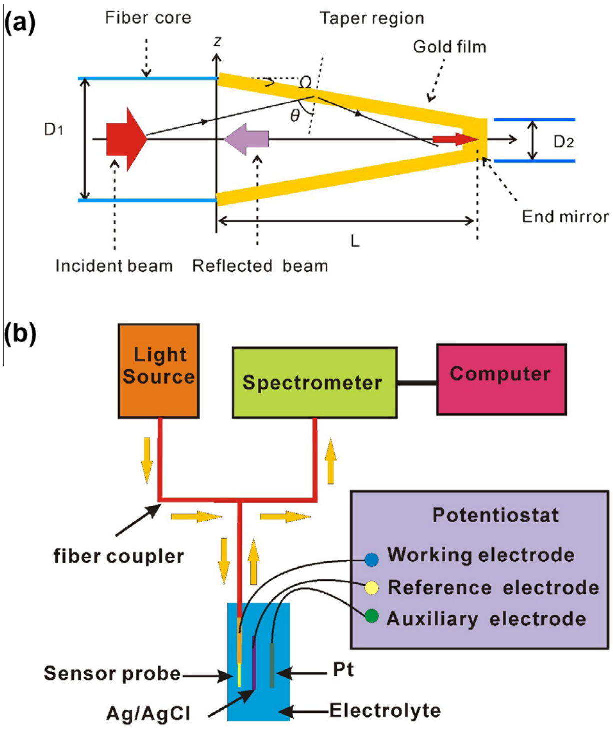

Fig. 1. Schematic diagram of the tapered fiber optic SPR sensor structure (a) and the measurement setup (b).

$$r(z) = \frac{D_1}{2} - \frac{z}{L} \times \left(\frac{D_1}{2} - \frac{D_2}{2}\right) \qquad (3)$$

The beam launched into the tapered region results in a range of angles $[\phi_1, \phi_2]$ that it is traveling through this region. Thus the transformed angle at a distance z from the input end of the taper can be expressed as [9,18].

$$\phi_1(z) = \cos^{-1}\left[\frac{\frac{D_1}{2}\cos\theta_{cr}}{r(z)}\right] - \Omega \qquad (4)$$

$$\phi_2(z) = \frac{\pi}{2} - \Omega \qquad (5)$$

where $\theta_{cr} = 90 - \sin^{-1}\left(\frac{NA}{n_1}\right)$ is the critical angle and $\Omega = \tan^{-1}\left[\left(\frac{D_1}{2} - \frac{D_2}{2}\right)/L\right]$ is the taper angle respectively.

Corresponding to the angular range $[\phi_1, \phi_2]$, the power of light transmitted in the core and reflected by the gold mirror can be expressed by [9,18].

$$P = \frac{\int_0^L dz \int_{\theta=\phi_1(z)}^{\theta=\phi_2} R_p^{2Nref(\theta,z)} \left(n_1^2 \sin\theta\cos\theta/(1 - n_1^2\cos^2\theta)^2\right) d\theta}{\int_0^L dz \int_{\theta=\phi_1(z)}^{\theta=\phi_2} \left(n_1^2 \sin\theta\cos\theta/(1 - n_1^2\cos^2\theta)^2\right) d\theta} \qquad (6)$$

where

$$Nref(\theta, z) = \frac{L}{2r(z)\tan(\theta + \Omega)} \qquad (7)$$

$Nref(\theta, z)$ is the total number of reflections performed by a ray making an angle θ and distant z from the input end of taper. R_p is the reflection intensity for p-polarized incident light and is calculated with the help of N-layer matrix method [14,17]. Because the sensitive area is generally far from the input end of the optical fiber, so that the polarization effect of different launched rays is neglected here [18].

In this paper, the gold film is directly in contact with the electrolyte of NaCl, whose refractive index is assumed as 1.33. The step index fiber of core diameter 600 μm, numerical aperture 0.22 are used with different tip end diameters of tapered sensing region with 10 mm length and coated by 50 nm Au film.

3. Results and discussion

The plasmon resonance wavelength of tapered fiber optic SPR sensor depends on several factors, ranging from the refractive index of surrounding environment to the dielectric constant of gold. As the profiles of sensing region is tapered, the effects of tip end diameter on the reflection spectrum is investigated firstly. In general, the resonance condition can be expressed as [9,18]

$$\frac{2\pi}{\lambda} n_1 \sin\theta = \mathrm{Re}\left[\frac{2\pi}{\lambda}\left(\frac{\varepsilon_{DL} n_s^2}{\varepsilon_{DL} + n_s^2}\right)^{1/2}\right] \qquad (8)$$

As the wavevector of incident light at an angle θ matches with the real part of surface plasmon propagation constant depending on the sample refractive index n_s and the dielectric constant of gold ε_{DL}, a strong surface plasmon wave is generated at the gold-dielectric interface.

Increasing the degree of taper leads to an increase in the angular range of guided ray launched in fiber core, so that the broader range of angles results in the resonance condition to be satisfied at a longer wavelength region according to the Eq. (8) [9]. Fig. 2 shows the reflecting powers of fiber optic SPR sensor with different diameters of tip end, and the applied voltage = 0 V is chosen. It is shown that the resonance wavelength is red-shifted and the