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Theoretical study of surface plasmon resonance based fiber optic sensor utilizing an additional layer of zinc oxide

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ABSTRACT

Surface plasmon resonance (SPR) based fiber optic sensor with bi layers of Pt-ZnO is theoretically studied. Sensitivity and figure of merit of sensor enhance with increase in thickness of Pt layer for all thicknesses of ZnO layers. Also, for a fixed thickness of Pt layer, sensitivity and figure of merit rise as the thickness of ZnO layer is raised from 0 nm to 20 nm 40 nm Pt–20 nm ZnO based SPR sensor demonstrates the highest sensitivity of 3161 nm/RIU.

1. Introduction

There has been growing effort committed to research and development of surface plasmon resonance based sensors during last three decades. Surface plasmon resonance (SPR) has been extensively used in sensing of various physical, chemical and biochemical parameters [1–4]. Surface plasmons are the charge density oscillations of free electrons in a metal resulting in generation of surface plasmon waves. Surface plasmon waves propagate along the interface between metal-dielectric medium and are transverse in nature with their electric field decaying exponentially in both metal and dielectric medium. Being transverse in nature, surface plasmon waves can be excited by exponentially decaying evanescent field of incident p-polarized light. When the wave vector and frequency of the exciting light become equal to that of surface plasmon wave, the energy is transferred from the incident light to the surface plasmon wave. SPR can be excited in a number of ways such as prism coupling, grating coupling and optical fiber coupling. In prism coupling, Kretschmann configuration based on attenuated total internal reflection (ATR) is generally used [5–7]. In Kretschmann configuration, a high refractive index prism is coated with a thin metal layer. The metal layer is in contact with the sample. Surface plasmon waves are excited by evanescent wave from prism at the total reflection condition. The prism coupler causes many drawbacks such as bulky size of sensor and unsuitability for remote sensing. In optical fiber coupling, the prism is replaced by the core of the optical fiber. Optical fiber based SPR devices allow several advantages over the prism and grating based SPR devices such as simplified and flexible optical design, possibility of remote sensing, continuous analysis and in situ monitoring [8–10]. To exploit these advantages, numerous experimental and theoretical research studies on optical fiber based SPR sensors have been performed [11–15].

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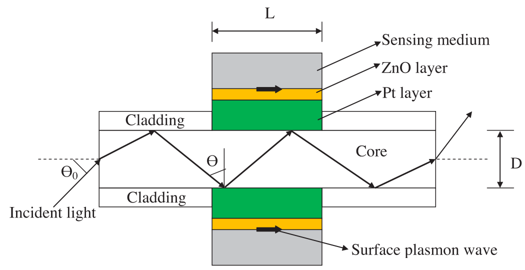

Fig. 1. Schematic diagram of SPR based fiber optic sensor.

Gold and silver are widely used as plasmonic metals because of having considerable amount of charge carriers. However, both of these metals have many significant demerits like their thin films are not continuous but agglomerate as islands and occurrence of band to band transitions in the visible region for gold films. Also, silver is not chemically much stable due to being prone to oxidation. In addition, because of good performance and prolonged stability, platinum (Pt) metal has attracted enormous research interest. Besides, Pt has extensive applications in optoelectronic devices, solar absorbers, jewellery industry and other decorative arts [16]. Pt is strongly reflecting, inert and chemically stable with high melting point. Pt based nanomaterials are used in sensors, fuel cells, automotive industry, petroleum refining, hydrogen production and anticancer drugs [17–19]. Moreover, the performance of SPR based devices has been shown to enhance by using conducting metal oxides along with plasmonic metals [20–23]. Among various conducting metal oxides, zinc oxide (ZnO) is widely used in many applications such as gas sensors, bio sensors, light emitting diodes, solar cells, lasers, transparent conducting films, photonic crystals, photo electrochemical cells and electrodes [24–28]. ZnO is a wide band gap semiconductor (band gap ∼3.37 eV at 300 K) and has high chemical stability, thermal stability and large mechanical strength. Apart from this, ZnO does not get easily oxidized when comes in contact with surrounding environment.

Pt based fiber optic SPR sensor is reported to possess good sensing performance [14]. Recently, SPR based fiber optic sensor utilizing bi layer combination of Au/Ag/Cu-ZnO reveals high sensitivity [15]. In this paper, a novel SPR based fiber optic sensor with bi layers of Pt-ZnO is theoretically studied. The influences of thicknesses of Pt and ZnO layers on the sensitivity and figure of merit (FOM) of sensor have been discussed in detail. The thicknesses of ZnO and Pt layers have also been optimized to achieve the best performance of the sensor. Sensitivity and FOM rise with increase in thickness of Pt layer for all thicknesses of ZnO layers. Also, for a fixed thickness of Pt layer, the sensitivity and FOM are elevated as the thickness of ZnO layer is raised from 0 nm to 20 nm. Optimized thicknesses of Pt and ZnO layers are obtained to be 40 nm and 20 nm respectively. 40 nm Pt-20 nm ZnO based SPR sensor achieves the maximum sensitivity of 3161 nm/RIU.

2. Theory

SPR sensing is based on the principle of ATR with Kretschmann configuration. In proposed SPR based fiber optic sensor, the SPR probe is a four layer system consisting of fiber core-Pt layer-ZnO layer-sensing medium as shown in Fig. 1.

The plastic cladding around the core from the middle portion of a step index multimode plastic clad silica (PCS) fiber (numerical aperture = 0.24 and fiber core diameter = 600 μm) is removed and is then coated with a thin Pt layer, which is then further coated with ZnO layer. Bi layers of Pt-ZnO are finally surrounded by sensing medium. Wavelength interrogation method is used to analyze the SPR sensor. In this method, the light from a broadband source is launched into one of the ends of the optical fiber with suitable optics and the transmitted light is detected at the other end of the optical fiber. At resonance wavelength, a sharp dip in the transmitted power appears. The resonance wavelength is dependent on the refractive index of sensing medium.

2.1. Fiber core

Core of optical fiber is assumed to be made of fused silica. The refractive index of fused silica varies with wavelength according to Sellmeier dispersion relation as,

$$n_1(\lambda) = \sqrt{1 + \frac{a_1\lambda^2}{\lambda^2 - b_1^2} + \frac{a_2\lambda^2}{\lambda^2 - b_2^2} + \frac{a_3\lambda^2}{\lambda^2 - b_3^2}} \quad (1)$$

where λ is the wavelength in μm and a_1, a_2, a_3, b_1, b_2 and b_3 are Sellmeier coefficients. The values of these coefficients are given as, $a_1 = 0.6961663$, $a_2 = 0.4079426$, $a_3 = 0.8974794$, $b_1 = 0.0684043$ μm, $b_2 = 0.1162414$ μm and $b_3 = 9.896161$ μm [29].