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Photonic crystal fiber based plasmonic sensors

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ABSTRACT

The development of highly-sensitive miniaturized sensors that allow real-time quantification of analytes is highly desirable in medical diagnostics, veterinary testing, food safety, and environmental monitoring. Photonic Crystal Fiber Surface Plasmon Resonance (PCF SPR) has emerged as a highly-sensitive portable sensing technology for testing chemical and biological analytes. PCF SPR sensing combines the advantages of PCF technology and plasmonics to accurately control the evanescent field and light propagation properties in single or multimode configurations. This review discusses fundamentals and fabrication of fiber optic technologies incorporating plasmonic coatings to rationally design, optimize and construct PCF SPR sensors as compared to conventional SPR sensing. PCF SPR sensors with selective metal coatings of fibers, silver nanowires, slotted patterns, and D-shaped structures for internal and external microfluidic flows are reviewed. This review also includes potential applications of PCF SPR sensors, identifies perceived limitations, challenges to scaling up, and provides future directions for their commercial realization.

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1. Introduction

Surface plasmon resonance (SPR) sensors have attracted lots of interests due to their unique capabilities such as high sensitivity and wide range of applications in environment monitoring [1], food safety [2,3], water testing [4], liquid detection [5,6], gas detection [7,8], biosensing [9,10], and medical diagnostics [11], including drug detection [12,13], bioimaging [14], biological analyte [15,16], and chemical detection [16–19] (Fig. 1). SPR effects are also utilized in optoelectronic devices such as optical tunable filters [20,21], modulators [22,23], SPR imaging [24,25], and thin-film thickness monitoring [26,27]. Besides the SPR techniques some other optical sensing techniques are also available such as microring resonators, waveguides, and resonant mirror [28,29]. In 1950s, surface plasmons (SPs) were theoretically introduced by Ritchie [30]. Based on SPs using the attenuated total reflection (ATR) method, prism coupled SPR Otto configuration was studied by Otto [31], where the prism and plasmonic metal layer were separated by a dielectric (sample) medium. The sensing technique in this study was quite sophisticated as it was required to maintain a finite gap between the prism and metallic layer. The Otto configuration was upgraded by Kretschmann setup, where the prism and metallic layer were in direct contact [32]. To date, Kretschmann and Otto configurations have been among top popular techniques for generating the surface plasmon waves (SPWs). By matching the frequency of incident photons and surface electrons, free electrons are resonating which results in generation and propagation of SPW along the metal-dielectric interface. [33,34]. The fundamental principle of conventional SPR sensors are also described (Supporting Information, Fig. S1). In the 1980s, a SPR sensor was experimentally demonstrated for chemical and biological detection [15]. SPR sensors require a metallic layer that enables transport of large amount of the free electrons. These free electrons are contributing in negative permittivity, which is essential for plasmonic materials. Conventional prism based Kretschmann setup is widely used for SPR sensors, where a prism coated with plasmonic materials is used [18]. As dielectric refractive index (RI) is altered, the propagation constant of the surface plasmon mode is altered which results in changing the coupling conditions or properties of light wave and SPW [16].

Although the performance of prism based SPR sensors (Kretschmann setup) is robust, they are suffering from bulky configuration due to the required optical and mechanical components. These requirements limit the optimization and practical application of these devices at point-of-care settings [18]. The bulky optomechanical components required for the angular interrogation in these devices are also at high costs. Commercial SPR systems such as Biacore, GE Healthcare are also not competitive compared to other devices for industrial application. The conventional SPR sensors are not suitable for field-based applications as a results of moving optical and mechanical parts [18]. The limitations of conventional SPR sensors led to emerging the conventional optical fiber based SPR sensor for chemical sensing applications in the 1990s [17]. There have been various configurations proposed for optical fiber based SPR sensors to provide wider operating range and higher resolution [35–38]. However, optical fiber based SPR sensors are required to direct the incident light at a narrow angle. A planar photonic crystal waveguide-based SPR biosensor was reported where the low refractive index analyte was used for matching the phases [39]. In late 20s, the microstructured optical fiber (MOF) based SPR was proposed [40]. To date, numerous PCF SPR sensors have been demonstrated with different configuration of PCF structures which altering the prism [41–60]. PCF based SPR sensing are capable to be miniaturized. Harnessing its advantages such as small size, ease in light launching, single-mode propagation and ability in controlling evanescent field penetration have made PCF as a promising candidate for SPR sensing [46,47]. However, the reported PCF based SPR sensor structures are not practical from fabrication point of view. As a result, reported PCF SPR sensors were mainly investigated either numerically or analytically. Finite Element Method (FEM) is widely used to numerically investigate the sensing performance. Moreover, analytical approaches such as wavelength and amplitude interrogation method are often used to analyze the sensing performance of these sensors.

The purpose of this review is to (i) discuss conventional prism and fiber based SPR sensing, and describe their drawbacks, (ii) demonstrate how SPR technology fits into the existing PCF sensing, (iii) illustrate various proposed structures and development in layers engineering for improving the sensing performance and also reducing fabrication complexity, and (iv) highlight the current gaps in this field and provide potential solutions. The scope of this review consists of state-of-the-art techniques for the PCF SPR sensors, and their potential applications in public health and industrial setting. It also discusses optical properties of plasmonic materials (gold, silver, copper, graphene and aluminum), metal coating techniques, and their limitations in high sensing performance achievement. Moreover, the sensing performance (RI range, amplitude and wavelength interrogation sensitivity, resolution) of the reported technologies are reviewed.

2. Optical fiber based surface plasmon resonance sensors

2.1. Conventional optical fiber based SPR sensors

Conventional optical fibers are widely used instead of prism in SPR sensors. Transmission and reflection based fiber optic probes have been reported for various sensing applications [55]. Fiber optics based sensors utilize the total internal reflection (TIR) to guide the light for sensing through SPR method. For the transmission based probe, cladding consists of a metal layer and immobilized ligands to detect the unknown concentration of an analyte. In the reflection based method, the end of fiber probe has a mirror to reflect the signal back to the fiber. Transmission method is widely used for fiber based SPR sensors, where the plasmonic metal layer or nanoparticles is placed in an etched cladding region [35–38,61–64]. Various types of fiber optic based SPR sensors including tapered fibers [65,66], D-type fibers [67], Single mode Fibers (SMFs) [68], Multi-mode Fibers (MMFs) [69], Bragg-grating fibers [70], Wagol wheel fibers [71], and H-shaped fibers [72] have been studied. However, the performance of the sensors can be enhanced by modifying the structural parameters/properties of an optical fiber [55]. Recently, Liu et al., utilize the fiber optic based SPR sensors combined with smartphone technologies for imaging and health monitoring applications (Fig. 2a(i)) [73] by using sodium chloride solution with varying RIs ranging from 1.328–1.351 (Fig. 2a(ii)). Abbe refractometer was used to calibrate the sodium chloride solution along with a mini pump to characterize the sensitivity and solution compounds. A low-cost portable smartphone-based fiber optic glycerol SPR sensor was demonstrated by Bremer (Fig. 2b) [74]. Glycerol solution was used to examine the sensor performance resulting in a sensitivity of 5.96×10^{-4} refractive index unit (RIU)/pixel in the range of 1.33–1.36. Fiber optic based label-free biosensors at low-costs were reported for DNA–protein interactions and DNA hybridization measurement by Pollet (Fig. 2c) [75].

Fiber optic based localized SPRs (LSPR) were demonstrated for the purpose of analyzing the antibody-antigen reaction of interferon-gamma (Fig. 2d) [76]. Fiber end was concentrated with the gold NPs and the sensor sensitivity was increased by controlling the density of nanoparticles. The performance comparisons of