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A Review of advancements (2007–2017) in plasmonics-based optical fiber sensors

Anuj K. Sharma[a,*], Ankit Kumar Pandey[b], Baljinder Kaur[a]

[a] Department of Applied Sciences (Physics Division), National Institute of Technology Delhi, Narela, Delhi 110040, India
[b] Department of Electronics and Communication Engineering, National Institute of Technology Delhi, Narela, Delhi 110040, India

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ABSTRACT

The present review summarizes the progress made in the area of plasmonics-based fiber optic sensors during the last decade (2007–2017). The review is in continuation with the previous review focused on the developments made in the above area during the timeframe of almost 25 years (*i.e.*, 1990–2006). In addition, other important reviews are also discussed in order to widen the scope of the work. This work is focused on review of four types of plasmonics-based optical fiber sensors *viz.*, single mode fiber, multimoded fiber, microstructured fiber, localized surface plasmon resonance (LSPR), and use of two-dimensional (2D) materials such as graphene, MoS_2 *etc.* The structures, performance parameters, and results related to some important works have been discussed. Based on the present state-of-the art, the future scope and related fields have been discussed.

1. Introduction

Surface plasmon resonance (SPR) is generally defined as the resonant excitation of electron density oscillations at the metal-dielectric interface and is realized with a glass prism-based Kretschmann configuration [1]. However, prism-based SPR sensor design is very bulky and is not suitable for remote sensing applications in hazardous areas. In this context, optical fibers made of glass materials can replace the glass prism for designing SPR sensors. The guidance of light through optical fibers is based on the phenomenon of total internal reflection (TIR) and optical fiber based SPR sensor design has certain advantages over prism based SPR sensor configuration such as:

I. Optical fiber SPR sensors are compact, low cost, and provide label free sensing.
II. Narrow resonance peaks with high sensitivity and stability.
III. Modification of holes' geometry in microstructured optical fibers (MOF) can be used to tune the sensor's performance.

The other advantages of optical fiber are its simple and flexible design, miniaturized sensor system, and capability of remote sensing. Fig. 1 shows the schematic of optic fiber SPR sensor. Generally, the cladding around the core of an optical fiber is removed and is coated with a thin metal layer. This metal layer may be further covered with buffer layer, which is finally covered with the sensing layer (analyte sample). The light signal is launched into one of the ends of the fiber and the modulated signal is detected at the other end. The modulated light carries the information regarding sensing layer properties.

The sensing application of optical fiber depends upon light wavelength, fiber parameters, fiber geometry, and metal layer properties. For instance, coupling mechanism will be different for single-moded and multi-moded optical fibers due to having different mode transmission properties depending upon a number of modes a fiber may support. Similarly, a straight fiber and a tapered fiber will show different strengths of light coupling because these fibers will show different penetration depths of the evanescent field due to having different geometrical configurations.

Further, a tapered fiber shows a substantial variation in evanescent field penetration along the tapered sensing region length whereas an un-tapered fiber exhibits a uniform penetration of the evanescent field along the sensing region. Furthermore, penetration of evanescent field and, therefore, the strength of light coupling with surface plasmons depends on an important fiber parameter known as numerical aperture, which is related to light acceptance limit of the fiber. The modulated spectrum of the light transmitted after passing through the SPR sensing region is detected at the other end of the optical fiber.

In 2007, a comprehensive review of SPR based fiber optic sensors was presented by Sharma et al. [1]. In that work, a systematic and chronological account of the evolution of fiber optic SPR sensors since the very beginning (*i.e.*, for a duration 1990–2006) of this extremely important research area was presented. Following the above review, a few other review articles on the related themes have been reported.

* Corresponding author.
E-mail address: anujsharma@nitdelhi.ac.in (A.K. Sharma).

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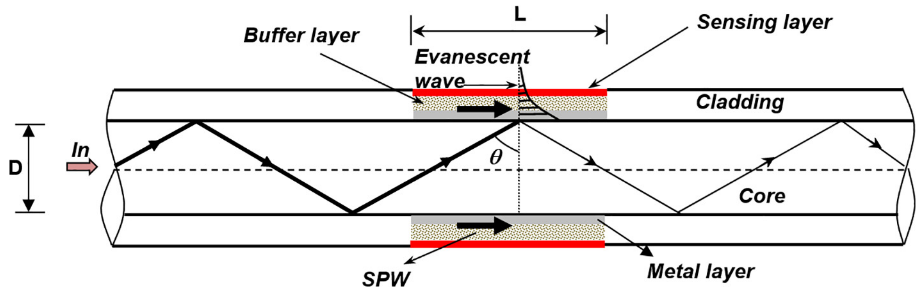

Fig. 1. Schematic of a typical fiber optic SPR sensor. L, represents the sensing length of fiber. SPW: surface plasmon wave.

Gupta and Verma reported the various designs of the fiber optic SPR probes [2]. The main emphasis of the above review was on the bimetallic coating, the effect of dopants in the fiber core, and selection of metals. Later on, Roh et al. [3] summarized the SPR sensors (Kretschmann prism configurations, fiber-optic sensors, nanoparticles based sensor, ring resonators *etc.*) with micro- or nano-structures. In continuation, Hernaez et al. gave emphasis to nanostructured fiber-optic sensors based on fluorescence, absorbance, interferometric nano-cavities, and SPR resonances [4].

In 2013, Mescia and Prudenzano reviewed the recent advances in optical fiber sensors based on fiber Bragg grating (FBG), long period gratings (LPGs), and evanescent field [5]. Among more recent reviews (*i.e.*, in 2016), the article from Jin and Granville discussed the progress of polymer optical fibers (POFs) focusing on novel techniques for POF sensor fabrication, monolayer graphene, evanescent wave absorption, localized surface plasmon resonance (LSPR) and fiber Bragg grating [6]. In another 2016 review article, Klantsataya et al. reviewed the different designs of the optical fiber, metallic coatings, excitation methods of SPR, interrogation methods, and sensing based applications, as well as a comparison, was made for recent experimental observations of various SPR-based fiber optic sensors [7]. In the same year, Gupta et al. explored the molecularly imprinting technology (MIT) with SPR\LSPR phenomena and the synthesis methods of molecularly imprinted polymers (MIPs) for chemical and biological applications was discussed in detail [8].

In continuation of the above-mentioned review articles, the present review summarizes, in an orderly manner, the developments and advancements that took place in the last decade (2007–2017) in the area of SPR based fiber optic sensors. Keeping track with the latest topics such as microstructured fibers, application of 2D materials (e.g., graphene, MoS_2 *etc.*), and localized SPR, the present review aims at emphasizing on the above topics, which may be taken up by the upcoming generation of researchers. The organization of the review has been broadly done on the basis of types of fibers (single mode, multi-moded, and microstructured optical fiber) used in SPR-based sensors. Another categorization of the works is done in terms of the popular sub-techniques (*e.g.*, LSPR) used in fiber optic sensors.

2. SPR sensors based on single mode fibers (SMF)

A single mode fiber (SMF) has core diameter in the range of 1–10 µm and supports only fundamental mode consisting of two orthogonal polarizations. Moreover, field of the fundamental mode is Gaussian shaped distributed across the core and clad. SMF is used in sensing applications to meet the requirement of extreme sensitivity and well-defined polarization of light [9]. SMF based sensor is of intrinsic type as measured action on light took place in fiber itself, and allows small phase changes in modulated light [10]. This section presents the advancements in applications of SMF in SPR based sensors.

Chiu and Shih reported the simulation and experimental results for a single-mode D-type SPR based fiber-optic sensor using the phase measurement method. Results confirmed the dependence of both sensitivity and measurement range on the angle of incidence and the gold (Au) film thickness. The study concluded that smaller incident angle and higher refractive index (RI) of specimen lead to a higher sensitivity but with a smaller measurement range [11]. Allsop et al. reported SPR-based fiber optic sensor device based on ultraviolet inscription of a grating-type structure into both single-layered (germanium) and multilayered thin films (layers of Ge, Si, and Ag) deposited on the flat side of a lapped D-shaped fiber. They studied polarization dependence of Ge-SiO_2-coated and Ge-SiO_2-Ag-coated fiber and found the largest polarization in the latter case when surrounded by air. Ge-SiO_2-Ag-coated device possessed spectral sensitivity of 90 nm/RIU (for RI range of 1–1.15), while with a single layer of Ge, a sensitivity of 6790 nm/RIU was achieved (RI: 1.33–1.36) [12]. Ahn et al. described a waveguide coupled surface plasmon resonance (WCSPR) sensor with sandwiched dielectric layer between two metals that allowed to tune the resonance wavelength in a broad range from visible to IR spectral region and multi-mode generation [13]. In another work, the detection of trinitrotoluene (TNT) was reported by Cennamo et al. based on POF with molecularly imprinted polymer (MIP) film deposited on top of thin Au film. The basic design of the proposed sensor is almost same as shown in Fig. 1 with a modification that metal layer was sandwiched between photoresist buffer layer and MIP layer as shown in Fig. 2. Thus, MIP layer was in direct contact with sensing medium (analyte). Proposed sensor scheme is suitable for remote\online monitoring exploiting fiber optic link [14].

In a study reported by Santos et al., the results of two simulation methods, *i.e.*, (*i*) Fresnel's equations, and (*ii*) finite-difference time domain (FDTD) method were compared in case of D-type fiber spliced between two single mode fibers [15]. The proposed simulation technique produced results with greater accuracy and robustness. Moreover, the analyses of parameters such as the intensity of magnetic and electric field across the structure were added advantages. An electrochemical SPR based fiber optic sensor was proposed and experimentally demonstrated by Yuan et al. for *in-situ* monitoring of electroactive biofilms (EABs). Proposed sensor consisted of tilted fiber Bragg grating (TFBG) coated with Au layer, imprinted on a single mode fiber core. Both the optical (plasmon) and electrochemical information can be simultaneously detected with the proposed sensor probe [16]. Simultaneous measurement of temperature and RI was reported by Weng et al.

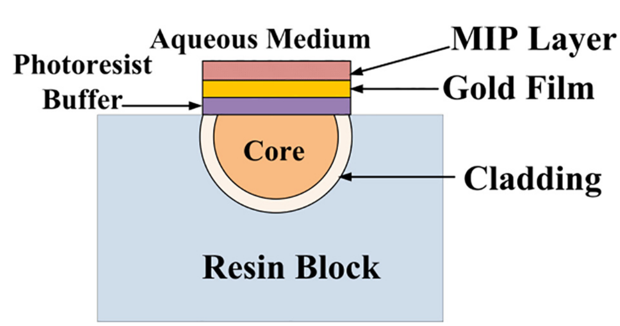

Fig. 2. Schematic of the optical chemical sensor with metal layer sandwiched between photoresist buffer layer and MIP layer (adapted from [14]).