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Photonic crystal fiber based surface plasmon resonance chemical sensors

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ABSTRACT

Research developments of the photonic crystal fiber based surface plasmon resonance (PCF-SPR) chemical sensors were intensively reviewed. Photonic crystal fibers, such as the microstructured optical fiber, the photonic bandgap fiber and the Bragg fiber with various structures were applied to the SPR sensors, including fuse-tapered fiber structure, D-type fiber structure and cladding-off fiber structure. Those sensors were classified as three kinds of configurations which were respectively based on the inner metal layer, the metallic nanowire and the outer metal film. What's more, the principles, superiorities and problems of the PCF-SPR sensors were also discussed in detail.

1. Introduction

The surface plasmon resonance optical fiber sensor was firstly proposed by Doctor Jorgenson from University of Washington in 1993 [1]. Based on this kind of sensor, the highest resolution of refractive index measurement was 7.5×10^{-4} RIU at the wavelength of 900 nm. Since then, fiber optic SPR sensor structures for chemical and biochemical sensing have been reported. In order to enhance sensitivity and narrow resonance peak, single mode fibers (SMF) were used as the sensing element instead of the multimode fibers (MMF) [2]. To improve the performance of the optical fiber sensors, side-polishing [3], tapering and changing the structure of the end of fiber [4] and other methods were proposed. D-shaped optical fiber [5], photonic crystal fiber [6], fiber grating SPR sensor [7] were presented to improve the reliability and flexibility. In 2014, Zhao et al. improved the manufacturing technique of coating optical fiber based SPR sensor utilizing silver mirror reaction [8], which made the process of fabrication more practical. According to the controllability of coupling between optical waveguide modes and surface plasmon waves, more and more attention is paid to the photonic crystal fiber based surface plasmon resonance sensor recent years.

While presenting this review, some important reviews in the related areas have been presented previously. One of them just concentrated on SPR sensors, and presented most important examples of SPR sensors and their applications [9]. Another review focused on the fiber optic SPR sensors, explained principles of SPR and fiber optic SPR sensors followed by their applications [10]. Another review highlighted the status of localized surface plasmon resonance sensing [11]. In 2009, Lee et al. reviewed the status of micro- and nanostructured optical fiber sensors [12]. However, Lee's review paid most attention to grating structure and holey structure of fiber optic SPR sensor. Few reviews about surface plasmon resonance sensor based on the photonic crystal fiber with one and two dimensional periodical structures could be seen in the literatures. Several years past, some new structures were proposed since then. In this review, we focused on the SPR sensors utilizing different structure of photonic crystal fiber (PCF), including photonic-bandgap fibers, Bragg fibers, holey fibers and hole-assisted fibers.

The organization of review is as follows. A brief but necessary history of fiber optic SPR sensor is given in Section 1. The basic principle of SPR and the fiber optic SPR sensor is described in the following section. In the subsequent section, different structures of PCF based SPR sensors are classified into three kinds. The characteristics of them are discussed in details respectively. Finally, the advantages and disadvantages of PCF based SPR sensors are

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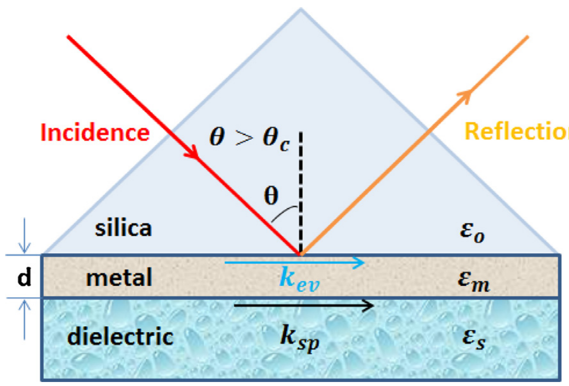

Fig. 1. Schematic diagram of Kretschmann configuration.

concluded. We also provide the future scope of further research of PCF based SPR sensors.

2. Principle of the fiber optic SPR sensor

2.1. Principle of surface plasmon resonance

Surface plasmon resonance (SPR) generally refers to the coupling between the electromagnetic wave and the surface plasmon wave (SPW), also known as the surface plasmon polariton (SPP), on the surface between a metal and a dielectric medium. The SPW is a transverse magnetic (TM) polarized electromagnetic wave decaying evanescently into the media, which magnetic vector is perpendicular to the direction of propagation of the SPW and parallel to the plane of interface. The SPR could occur when the frequencies and parallel components are both matched between the incident TM polarized electromagnetic wave and SPW. In the case of attenuated total reflection in a prism coupling configuration, surface plasmon resonance results in the transfer of energy from incident photons to surface plasmons, which reduces the energy of the reflected light. The surface plasmon resonance was firstly realized on the Otto configuration with silver film by Otto [13], and improved by Kretschmann [14]. Then, we will take the Kretschmann configuration as an example to explain the principle of surface plasmon resonance.

According to the Maxwell's equations and the corresponding boundary conditions, the propagation constant k_{sp} of surface plasmon wave propagating along the interface of metal and a semi-infinite dielectric can be described as [15]:

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_s}{\varepsilon_m + \varepsilon_s}} \tag{1}$$

where ε_m denotes the dielectric constant of the metal, ε_s is the dielectric constant of the dielectric, ω is the frequency of incident light and c is the speed of light. This equation is specific to the semi-infinite dielectric-metal layers, but it can be applied to the case of prism coupling approximately, such as Kretschmann configuration.

In the case of Kretschmann configuration, the propagation constant of the evanescent wave in the direction parallel to the metal surface k_{ev} is given by the following expression:

$$k_{ev} = \frac{\omega}{c}\sqrt{\varepsilon_0}\sin\theta \tag{2}$$

where ε_0 refers to the dielectric constant of the silica in the incidence region, as shown in Fig. 1. θ is the angle of the incident light. Only TM polarized waves can excite the SPW.

The surface plasmon resonance occurs when the wave vector of the evanescent wave matches with that of the surface plasmon wave at a specific angle of incidence. The resonance condition for SPR is given by:

$$\frac{\omega}{c}\sin\theta_{res} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_s}{\varepsilon_0(\varepsilon_m + \varepsilon_s)}} \tag{3}$$

where θ_{res} is named as the resonance angle. This resonance condition also demonstrates the sensing principle of SPR sensors. The refractive index of analytes (i.e. $\varepsilon_s{}^{1/2}$) can be measured by detecting the resonance angle with a certain incident wavelength (angle interrogation), or detecting the resonance wavelength with a certain incident angle (wavelength interrogation).

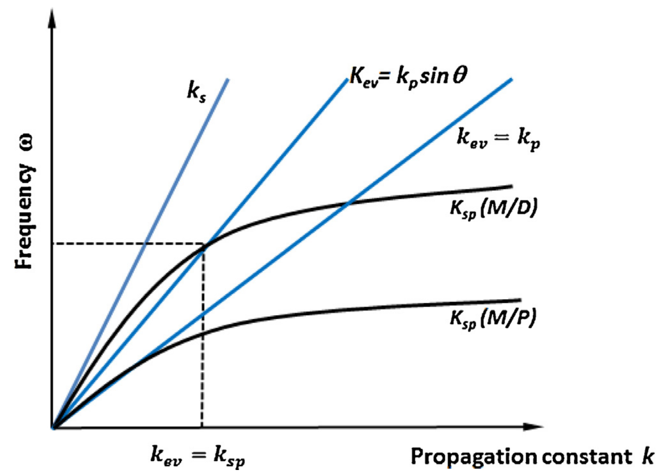

Fig. 2. Incident light wave in dielectric medium (K_S), evanescent wave (K_{ev}), the dispersion curve of surface plasma wave of metal-dielectric medium interface (M/D) and metal-prism interface (M/P).

Fig. 2 illustrates the conditions of resonance clearly. The propagation constant curves of surface plasmon wave and evanescent wave cross at many position between $k_{ev} = k_p \sin\theta$ and $k_{ev} = k_p$ (such as, for various sets of incident angle and frequency (θ, ω)). This indicates that the match of evanescent wave (k_{ev}) and surface plasma wave (metal–dielectric medium (M/D) interface) depends on the incident angle and frequency of light source. Another noticeable feature is that the surface plasmon wave on metal–prism interface (M/P) locates on the right of the maximum propagation constant of evanescent wave ($k_{ev} = k_p$) so that the two curves will never cross. This implies that the surface plasma resonance will never be excited on the metal–prism interface (M/P).

2.2. Principle of SPR based on optical fiber

The SPR principle of prism coupling remains valid in the case of SPR based on optical fiber, since guidance of light in optical fibers is also based on total internal reflection (TIR). The fiber core used to create TIR can replace the coupling prism in the SPR sensing system. Two kinds of typical fiber optic SPR sensors are illustrated in Fig. 3.

The transmission-based fiber optic SPR sensor was formed by removing the cladding in the sensing section and then coating a metal layer on the exposed fiber core, as showed in Fig. 3(a). The principle of the reflection-based fiber optic SPR sensor illustrated in Fig. 3(b) is basically the same as the transmission-based one. The reflection-based sensor utilizes a reflection mirror at the end of the probe to reflect the signal back to the fiber. Generally, we use wavelength interrogation method with a polychromatic light source in the case of the fiber optic SPR sensor. Different from the prism-coupling SPR sensor, the incident angle in the optical fiber is hard to control, since its range varies from the critical angle to approximately 90°. The TIR takes place at the interface between fiber core and metal layer, and the evanescent wave permeating