Optics Communications 313 (2014) 94–98

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Multi-hole fiber based surface plasmon resonance sensor operated at near-infrared wavelengths

Di Gao [a], Chunying Guan [a,b,*], Yaowu Wen [a], Xing Zhong [a], Libo Yuan [a]

[a] Key laboratory of In-fiber Integrated Optics of Ministry of Education, College of Science, Harbin Engineering University, Harbin 150001, China
[b] Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

ARTICLE INFO

Article history:
Received 11 May 2013
Received in revised form
3 October 2013
Accepted 4 October 2013
Available online 17 October 2013

Keywords:
Surface plasmon resonance
Multi-hole fiber
Microstructured fiber
Refractive-index sensor

ABSTRACT

We propose a surface plasmon resonance (SPR) sensor based on a single mode optical fiber with six air holes. A thin gold film and a TiO_2 film are deposited on the walls of air holes. Due to high refractive index of TiO_2 the proposed sensor can operate at near-infrared (IR) wavelengths. The characteristics of the sensor were numerically investigated based on the finite-element method (FEM). The numerical results indicate that the optical loss spectrum of SPR sensor can be tuned easily by changing the thicknesses of gold and TiO_2 layers. The refractive-index resolution of 2.7×10^{-5} (sensitivity $S\approx370$/RIU) for aqueous analytes can be achieved.

1. Introduction

The metal surface charge density wave is defined as surface plasmon wave (SPW), which is actually an electromagnetic wave supported by the interface between a metal and a dielectric material. The physical process which SPW is excited by the electromagnetic wave is known as surface plasmon resonance (SPR). In the early 20th century, SPR phenomenon was firstly discovered by R. Wood through the abnormal diffraction light intensity distribution [1]. In 1993, R.C. Jorgenson proposed a novel SPR sensor with the advantages of high sensitivity, small size and real-time monitoring based on an optical fiber with a specially designed core, which is coated with a thin gold film [2]. Optical fiber SPR sensors are undoubtedly required for the coming development of miniaturized and compact SPR sensor systems. The optical fiber SPR sensors have been widely applied in biochemical detection as well as food and environmental testing [3]. For enhancing the evanescent field and the light–matter interaction, the fiber SPR sensors with various structures, including fiber tip [4], tapered fiber [5], fiber Bragg grating [6], U-bent fiber optic probe [7], and D-shape fiber [8], were proposed. In 2006, the high pressure microfluidic chemical deposition technique was presented to deposit homogeneous metallic films on the walls of air holes in microstructured fibers [9], which made it possible to realize on-line SPR microfluidic sensors in hollow fibers. Subsequently, more and more researchers began to focus on excitations of plasmon resonances in microstructured optical fibers (MOFs) and photonic crystal fibers (PCFs) with coated metal inclusions [10–13]. A three-hole fiber based SPR sensor operated at visible wavelengths was proposed [14]. The air holes of the fiber were deposited with a thin gold film and a thin dielectric layer. The refractive-index resolution of the sensor for aqueous analytes is up to 1×10^{-4}. A. Hassani proposed a PCF SPR sensor, in which phase matching between a surface plasmon mode and a core mode can be enforced by introducing air-filled microstructure into the fiber core [15]. A multi-core holey fiber based plasmonic sensor with a large detection range and high linearity was also reported [16]. However, the single mode operation in the visible wavelength range is inaccessible to achieve in the previous SPR sensors reported.

Optical fiber with a few air holes can compensate for the accumulated dispersion in single-mode fiber, and the low power fraction in the holes and structural simplicity help realize low loss [17,18]. In addition, the multi-hole optical fiber with a high refractive index core is easy to achieve single mode operation at near-IR wavelengths. In this paper, we propose a multi-hole fiber SPR sensor with a high sensitivity at the near-infrared wavelengths. The thin gold film and the TiO_2 layer are sequentially deposited on the walls of the air holes. The characteristics of the proposed sensor are numerically investigated. The effects of the thicknesses of the gold film and TiO_2 layer, the size and the doping level of the core, and the pitch between air holes on the transmission spectra are discussed to evaluate the sensor performance.

---

* Corresponding author at: Harbin Engineering University, College of Science, Key laboratory of In-fiber Integrated Optics of Ministry of Education, 145-11 Nantong Street, Harbin 150001, China. Tel.: +86 45182519850.

E-mail address: cyguan@163.com (C. Guan).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.10.015

2. Multi-hole fiber SPR sensor and theoretical model

A schematic drawing of the proposed multi-hole fiber SPR sensor is shown in Fig. 1. The circular Ge-doped silica core with a radius of r_c is surrounded by six air holes coating with thin gold and TiO_2 films. The gold and TiO_2 films with a uniform thickness can be deposited on the walls of air holes by high pressure microfluidic chemical deposition technique [9]. In fact, TiO_2 layers are not only beneficial for spectral tuning but also can contribute to enhance evanescent fields. The thicknesses of gold and TiO_2 films are d_g and d_t, respectively. The diameter of the air holes is $d$and the pitch of air holes is Λ. n_{core} and n_{clad} represent the refractive indexes of the Ge-doped silica core and pure silica cladding, respectively. The refractive index of the analyte filled into air holes is n_a.

The transmission loss is one of the most important characteristics of the fiber SPR sensors. The fundamental mode loss spectrum of the fiber has an obvious peak when the phase matching condition between fundamental mode and plasmonic mode is satisfied. The transmission power exponentially decays with transmission distance L, which can be expressed as

$$P(z) = P(0)\exp(-2\gamma z) \tag{1}$$

Here, $P(0)$ and $P(z)$ represent the transmission power at $L = 0$ and z. The attenuation constantαcan be expressed as

$$\alpha = -\frac{10}{z}\lg[P(z)/P(0)] = 4.343(2\gamma) \tag{2}$$

The coefficient 2γ is proportional to the imaginary part of the mode effective index according to the following formula:

$$2\gamma = 2k_0 I_m(n_{eff}), \quad k_0 = 2\pi/\lambda \tag{3}$$

where $n_{eff}$is the effective refractive index of the guide mode and $k_0$is the vacuum wavenumber. The parameter $\alpha = 8.686 I_m(n_{eff})2\pi/\lambda$ is used to quantify the transmission loss of the optical fiber.

The finite element method (FEM) is available for researching the properties of the arbitrarily shaped optical fiber. We use the 2-D mode-analysis solver of commercial FEM software, COMSOL Multiphysics 4.3a, to investigate the proposed sensor's characteristics. Owing to the geometric symmetry, only a quarter of the fiber is modeled for reducing calculation time. The boundary conditions are perfect magnetic conductor (PMC) and perfect electric conductor (PEC) at symmetry boundaries (i.e. x and y directions in Fig. 1), respectively. The maximum mesh element sizes are set to their corresponding layer thicknesses in TiO_2 and gold layers. A circular perfectly matched layer (PML) boundary condition was applied to calculate complex propagation constant of the fundamental and plasmonic mode and analyze optical transmission characteristics.

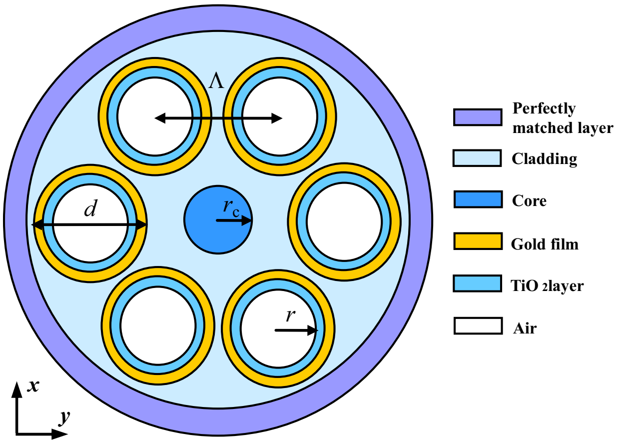

Fig. 1. Cross-section of the proposed SPR sensor.

3. Numerical results and discussion

The loss spectrum of fundamental mode is exhibited in Fig. 2. Here, the refractive index of silica and Ge-doped silica is calculated by the Sellmeier dispersion formula [19] that is expressed as

$$n^2 - 1 = \sum_{i=1}^{3} \frac{[SA_i + X(GA_i - SA_i)]\lambda^2}{\lambda^2 - [Sl_i + X(Gl_i - Sl_i)]^2} \tag{4}$$

Here, SA, SL, GA, GL represent the Sellmeier constants, and X is the Ge-doped level. Suppose that X is 4%, which ensures that the proposed fiber operates in single mode at near-IR wavelengths. Furthermore, the refractive index of the cladding can be obtained by assuming $X = 0$. The gold dielectric constant in the visible and near-IR region is defined by the values in Ref. [20] The other parameters are $r_c = 3.5\ \mu m$, $d_g = 30$ nm, $d_t = 75$ nm, $\Lambda = 13\ \mu m$, $r = 6\ \mu m$, $n_a = 1.33$, and the refractive index of the TiO_2 layer is 2.65 [21]. Several resonance peaks occur in the near-IR wavelength range, which results from the coupling of the fundamental mode with higher order plasmonic modes as given in Ref. [16] The high-index TiO_2 dielectric layer permits tuning the resonant peak from visible to near-IR wavelengths. The resonance peak near 1.38 μm is selected for discussion because the bandwidth of this resonance peak is pretty narrow and so a high resolution can be achieved. The real parts of the effective refractive indices of the core and plasmonic modes in the proposed sensor are shown in Fig. 3 where the parameters of the sensor are defined as in Fig. 2. The loss spectrum of fundamental mode is also shown in Fig. 3. The insets (a) and (b) are the electric field distributions of the core and

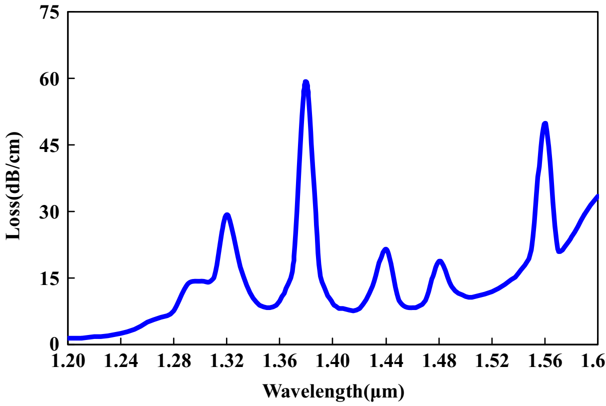

Fig. 2. The loss spectrum of the fundamental mode. ($r_c = 3.5\ \mu m$, $d_g = 30$ nm,$d_t = 75$ nm, $\Lambda = 13\ \mu m$, $r = 6\ \mu m$, $n_a = 1.33$)

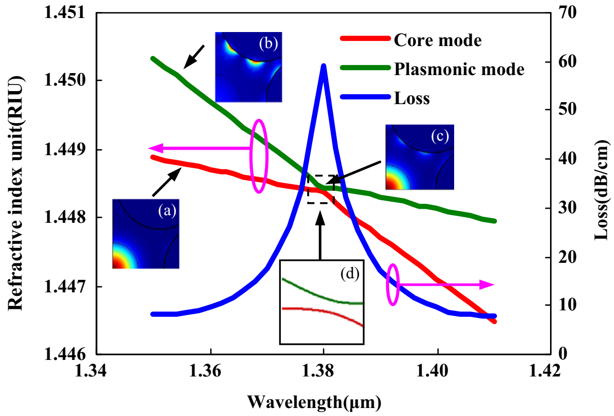

Fig. 3. Real parts of the effective refractive indices of the fundamental and plasmonic modes, and the fundamental mode loss. The insets (a) – (c) are the electric field distributions of the core and plasmonic modes, and the inset (d) is a zoomed view of the curves in the dashed box.