Optics Communications 359 (2016) 279–284

Contents lists available at ScienceDirect

Optics Communications

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

A photonic crystal fiber glucose sensor filled with silver nanowires

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ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form
28 September 2015
Accepted 29 September 2015

Keywords:
Photonic crystal fiber
Glucose sensor
Silver nanowires

ABSTRACT

We report a photonic crystal fiber glucose sensor filled with silver nanowires in this paper. The proposed sensor is both analyzed by COMSOL multiphysics software and demonstrated by experiments. The extremely high average spectral sensitivity 19009.17 nm/RIU for experimental measurement is obtained, equivalent to 44.25 mg/dL of glucose in water, which is lower than 70 mg/dL for efficient detection of hypoglycemia episodes. The silver nanowires diameter which may affect the sensor's spectral sensitivity is also discussed and an optimal range of silver nanowires diameter 90–120 nm is obtained. We expect that the sensor can provide an effective platform for glucose sensing and potentially leading to a further development towards minimal-invasive glucose measurement.

1. Introduction

In recent years, glucose sensors have become attractive due to the increase of diabetes. To get a good treatment, patients have to measure the blood glucose concentration frequently. Then a minimal-invasive, compact, and straightforward with high measurement accuracy glucose sensor is necessary. Several methods for measuring the concentration of a glucose solution have been proposed, such as sensors based on surface plasmon resonances (SPRs) [1], interferometers [2], [3], resonant cavities [4], and mid-infrared photoacoustics [5], [6]. However, these traditional methods present a number of disadvantages such as complicated structures, costly integration, lack of accuracy, low reliability, and difficulties in mass production. In [1], Lam et al. proposed a SPR system based on the gold coated prism for the measurement of glucose in aqueous solution with an extremely high detection resolution of 8.67×10^{-6} RIU, equivalent to 6.23 mg/dL of glucose in water. But the bulky structure makes it limited of mechanical reliability and impossible for highly integrate. In [6], Liakat et al. implemented a non-invasive setup to realize glucose sensing in biological fluids using mid-infrared light. Clinically accurate measurements as low as 30 mg/dL were obtained. However, water has strong capability to absorb mid-infrared light, then it can only penetrates up to 100 μm into human skin where blood capillaries are not reached. This would limit its widespread application. Optic fiber based SPR sensors have attracted much attention recently due to their high sensitivity, compact structure, easy to operate, and low cost [7]. Moreover, only a small quantity of test solution is required, potentially leading to its further development towards a minimal-invasive glucose measurement of interstitial fluid [1].

Compared with traditional optical fibers, photonic crystal fibers (PCFs) have many other advantages. They are made of single material and have several geometric parameters that can be manipulated for larger flexibility of design [8]. The cladding air holes can be used as channels either optical transmission or analyte, which can realize the interaction of light and matter [9]. The sensing mechanism of PCF–SPR sensors is through coupling the leaky core mode to the plasmon to achieve resonance sensing. The PCFs' flexible design makes it easy to equate the effective index of the core mode to that of the material under test. Thus phase matching condition between the core mode and the plasmon can be easily achieved at the required wavelength and then resonance occurs [10]. As analyte is inside the cladding air holes of the PCF, the sensor can have high reliability and the package can be very compact. Moreover, PCF based sensors can realize high sensitivity. In [11], Wu et al. presented a microfluidic refractive index (RI) sensor based on a directional coupler architecture using solid-core PCFs. It works for analytes having refractive indices slightly higher than the PCF background RI and the sensitivity of 30,100 nm/RIU has been derived from measurements.

In this paper, a PCF–SPR glucose sensor filled with silver nanowires has been analyzed through numerical simulations and demonstrated by experiments. We take a 8 cm LMA-10 PCF filled with analyte and silver nanowires as the active region. The proposed sensor is analyzed through the finite element method (FEM) using COMSOL multiphysics software. The simulated results show that a red-shift is obtained with the increasing of filling analyte RI

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http://dx.doi.org/10.1016/j.optcom.2015.09.102
0030-4018/

and that 90–120 nm should be an optimal range of silver nanowires diameter for the proposed sensor. To demonstrate its feasibility, a setup has been built and the average spectral sensitivity 19009.17 nm/RIU for experimental measurement is obtained, equivalent to 44.25 mg/dL of glucose in water. The detection resolution of such a sensor is lower than 70 mg/dL for efficient detection of hypoglycemia episodes, which can provide a reference for the implementation and application of glucose sensors or other biochemical sensing.

2. Theoretical analysis

The numerically simulated PCF is commercially available LMA-10 produced by NKT Photonics. The diameter of the core is $d_c = 10$ μm. The diameters of the cladding air hole and the pitch are approximately $d = 3$ μm and $\Lambda = 6.5$ μm, respectively. The outer cladding diameter is $D = 125$ μm. The whole cladding consists of seven layer air holes of hexagonal lattices. The RI of fused silica fiber is determined by Sellmeier equation and the RI of silver nanowires is referred to the Handbook of Optics. The simulated cross section of the LMA-10 PCF is shown in Fig. 1(a).

The electromagnetic mode of the glucose sensor is solved by the FEM using COMSOL multiphysics software. In the numerical simulation, some silver nanowires are embedded in the air holes of the first layer as the sensing region. In [12], Lu et al. demonstrated that when the number of silver nanowires embedded in each air hole of the first layer is three, the sensor will get saturated spectral and intensity sensitivities. The sensitivities will remain relatively stable with the continuously increasing of the silver nanowires numbers. Moreover, the irregularity of the filled nanowires has no effect on sensitivity. In [13], Luan et al. reported that the silver nanowires are unlikely to suspended in the liquid (leave from the holes surface) because of the gravity effect, then they testified that the resonance wavelength will not change as long as the nanowires are still on the surfaces of the holes and that sensitivity of the sensor is relatively stable with the randomly filled nanowires. The cross section of the channels filled with analyte and silver nanowires is shown in Fig. 1(b). The purpose of the design is to enhance the coupling between a core-guided mode and a plasmon mode, and simultaneously to reduce the plasmon to plasmon mode coupling [14,15]. The electric field distributions of the fundamental mode of LMA-10 is shown in Fig. 1(c). Obviously, we can see that the fundamental mode is confined well within the core, and the arrows indicate the electric field direction.

As a PCF–SPR sensor, the most crucial requirement is phase matching of a core-guided mode and a plasmon mode. Fig. 2 shows the changes of effective refractive indices of the two modes in the vicinity of the phase matching point of the proposed sensor when glucose solution is 10 g/L. Theoretically, phase matching requires equating the propagation constants of the two modes, implying that the effective refractive indices of the two modes have to be close. The effective RI of a core-guided mode is close to that of a core material. The effective RI of a plasmon mode is determined by the background silica, the adjacent analyte, and the metallic coating, usually at a value not significantly larger than the filling analyte [16]. When the phase matching is satisfied at a certain wavelength, the energy of a core-guided mode is transferred to the plasmon mode and a resonant loss peak will be observed at this wavelength.

To investigate the relationship between the loss spectra and the glucose concentration, samples ranging from 10 g/L to 60 g/L are used in the simulation. The RI of glucose solution can be calculated by [2]:

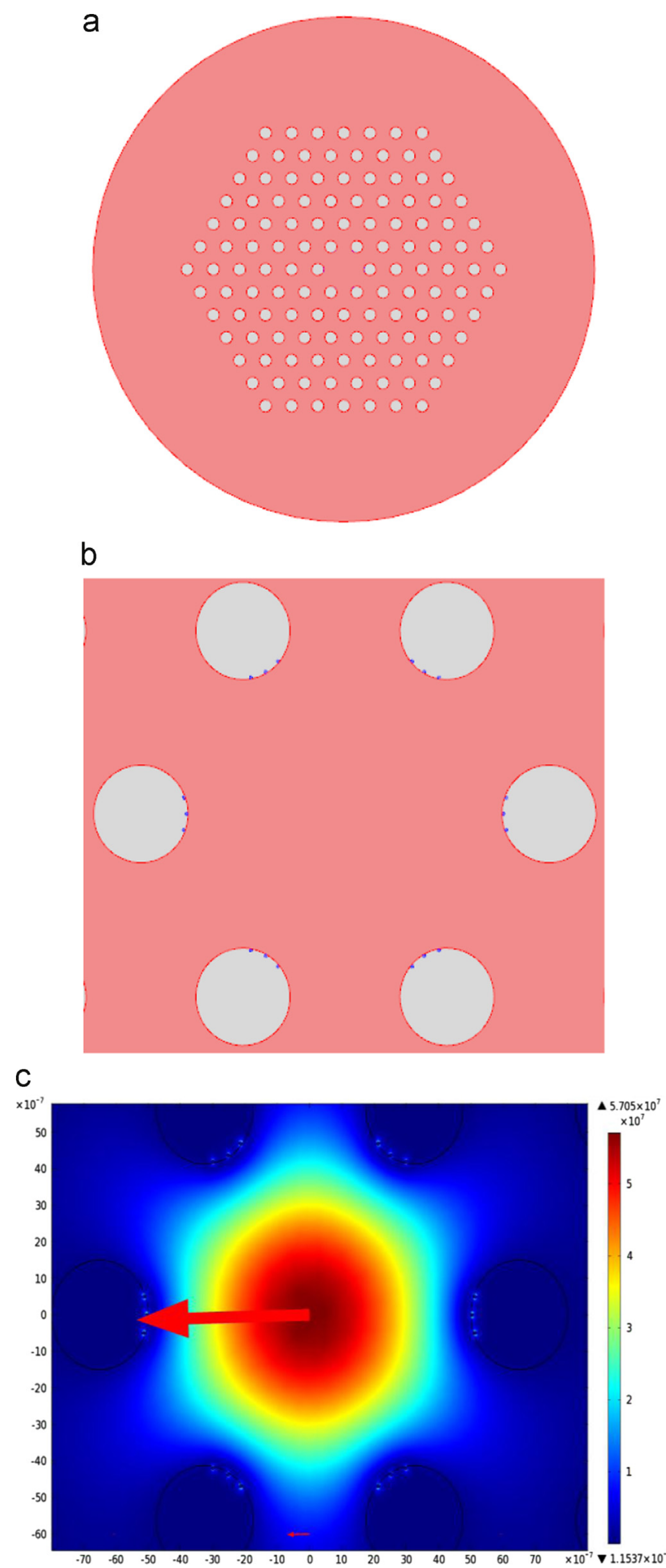

Fig.1. (a) The simulated cross section of LMA-10. (b) Cross-section of the channels filled with analyte and silver nanowires. (c) The electric field distributions of the fundamental mode.

$$n = 0.00011889c + 1.33230545 \tag{1}$$

where c is the glucose concentration (g/L) and n is the glucose solution RI.

Confinement loss is the light confinement ability within the core region, and the corresponding expression is defined as: