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Optical fiber sensor based on capillary wall for highly-sensitive refractive index measurement

Yun Liu, Wei Peng*, Xinpu Zhang, Siyu Qian

College of Physics and Optoelectronic Engineering, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

This paper reports a temperature-compensated fiber-optic refractive index (RI) sensor for high sensitivity measurement. The sensor includes a piece of fused-silica capillary (FSC) and a fiber Bragg grating (FBG), both of which are sandwiched by single-mode fibers (SMFs). When light from the lead-in SMF enters into the wall of the FSC that acts as a RI sensing element, multiple modes are excited and interfere to form fringes collected by the lead-out SMF. The FBG is fabricated adjunct to the FSC to compensate its temperature sensitivity. The FSC based sensor prototype is fabricated and sealed in a flow cell to test its performance. Experimental results show that the sensor is highly sensitive to RI, and the sensitivity in the tested RI range from 1.33 to 1.35 is 698.52 nm/RIU and from 1.35 to 1.37 is 1061.78 nm/RIU. The temperature sensitivity of the FSC is -0.173 nm/°C, which is compensated by the FBG. This capillary wall based sensor can be further developed as a miniaturized fiber optic biosensor for biochemical application.

1. Introduction

Fiber optic sensors have been extensively investigated in the past three decades because of their distinctive advantages over traditional sensors. Specifically, a fiber optic refractive index (RI) sensor has attracted considerable interest by offering outstanding advantages that include but not limited to high sensitivity, simple fabrication, corrosion resistance and low cost [1–4]. Many types of fiber optic RI sensors have been developed and practically applied based on different optical mechanisms or components such as fiber Bragg gratings (FBGs) [5], long period gratings [6], photonic crystal fibers [7], multimode fibers [8], tapered fibers [9], polarimetric optical fiber [10], Mach–Zehnder interferometers [11], and a single mode–multimode–single mode (SMS) structure [12]. All of them are based on the interaction between the evanescent field and the analytes. Sensitivity is an important parameter to characterize an RI sensor. There are several general solutions to improve sensitivity, all toward increasing the evanescent field intensity that can interact with the analytes or increasing the length of the sensing region, such as fiber splicing between different optical fibers [13,14], chemical etching [15], laser micromachining [16], and fiber tapering [17]. However, some of these techniques need complicated fabrication process or expensive devices. Many processes that reduce the fiber thickness render low mechanical strength of the sensors, which significantly compromises their potential for practical applications.

In this paper, a novel fiber optic RI sensor based on the model interference in a capillary wall is demonstrated theoretically and experimentally. Although micro-capillaries have been used to fabricate microcavity or capillary cell for chemical sensing [18,19], to form a ring resonator or using whispering-gallery modes resonances for RI measurements [20,21], or to configure a microfluidic structure [22], we use the capillary wall as optical waveguide for RI sensing which is different from all other works. By cleaving and splicing a short piece of capillary between two SMFs one of which includes an FBG, we achieve a high-sensitivity temperature-compensated refractometer. Compared with the most current fiber RI sensor, this sensor is highly sensitive, compact, of low cost, easy to fabricate, and robust, which is suitable for biochemical detection.

2. Operating principle

Fig. 1 illustrates the schematic of the temperature-compensated FSC-wall based fiber optic RI sensor system. As shown in Fig. 1(a), a piece of FSC is spliced between two single mode fibers (Corning, SMF-28) using a commercial fusion splicer (FSM-50s, Fujikura) in manual operation mode by carefully controlling the splicing parameters including the motor movement steps and distances, the current for the electric arc (35 mA) and the arc duration time (700 ms). Using a BraggStar ArF excimer laser (Tuilaser) some FBGs are fabricated in SMFs that can be spliced with any optical fiber

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* Corresponding author. Tel./fax: +86 411 84706693.
E-mail address: wpeng@dlut.edu.cn (W. Peng).

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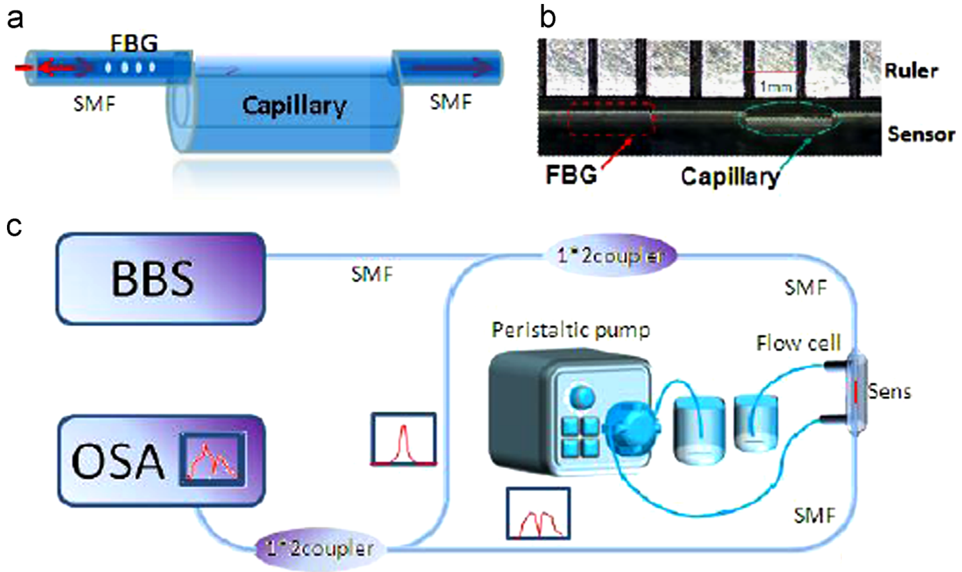

Fig. 1. Schematics of the sensor principle and experimental setup. (a) The structure of the fused-silica capillary wall based fiber-optic refractometer. (b) The photograph of the sensor. (c) Schematic of the RI measurement setup.

material. The TSP250350 FSC used in this work is made by Polymicro Technologies (a subsidiary of Molex), which has inner and outside diameters of 250 and 350 μm, respectively. The 50-m-thick wall of FSC is used as the RI sensing element for light mode modulation, while the FBG is introduced in the lead-in SMF for temperature compensation to increase the RI sensitivity of the FSC. Some sensor prototypes are developed by using above optical fiber materials and procedures. Fig. 1(b) shows a photograph of a prototyped sensor which includes a piece of 1.5 mm-long FSC and a 4 mm-long FBG which has a Bragg wavelength at 1543 nm and the reflection at the Bragg wavelength is more than 90%. Since the bend loss and the volatility of sample will influence the measurement result, the sensor is packaged in a flow cell made by a glass tube.

Fig. 1(c) shows the experimental setup for RI measurement. The light source used in the experiment is a broadband light source (BBS) centered at 1550 nm. An AQ6370 optical spectrum analyzer (OSA) (Yokogawa) is used to measure the spectrum. The sensing head is kept straight and sealed in a flow cell, and the liquid (NaCl solution) is pumped into the flow cell by a peristaltic pump. To ensure that the NaCl solution in flow cell can outflow adequately, the inlet is placed at the bottom of flow cell while outlet at the top. This can reduce the measurement error caused by the possible residual solution when different NaCl solutions are pumped successively into the flow cell. The sensor is connected with an OSA and a BBS by two 1 × 2 broadband 50/50 couplers to monitor the reflection spectrum and the transmission spectrum of the FBG simultaneously. When light emitted from the BBS reaches the FBG, it is partly reflected by the FBG at its central wavelength, and the remaining light propagates through the FSC where multiple modes are excited and interfere with each other. Then the interference signal is partially coupled into the lead-out SMF and its spectrum is measured by the OSA.

A three-dimensional simulation based on the beam propagation method was performed using an *Rsoft* commercial photonic analysis software. The simulation model and the electric fields distribution of the longitudinal section (on the *X–Z* plane) and the cross section (on the *Y–Z* plane) are calculated and presented in Fig. 2(a)–(c). It is assumed that the capillary length is 1.5 mm, the RIs of the SMF cladding and core are 1.444 and 1.45, respectively, and the RI of the capillary is 1.45. Fig. 2(b) and (c) presents the light intensity distribution in the model, which indicates that light from the lead-in SMF spreads into the capillary wall of the FSC and partly converges in the lead-out SMF. From media1, we can clearly see that when light propagates from the lead-in SMF into the FSC, multiple modes are excited in the capillary wall. These modes interfere with each other in the capillary wall. When they reach

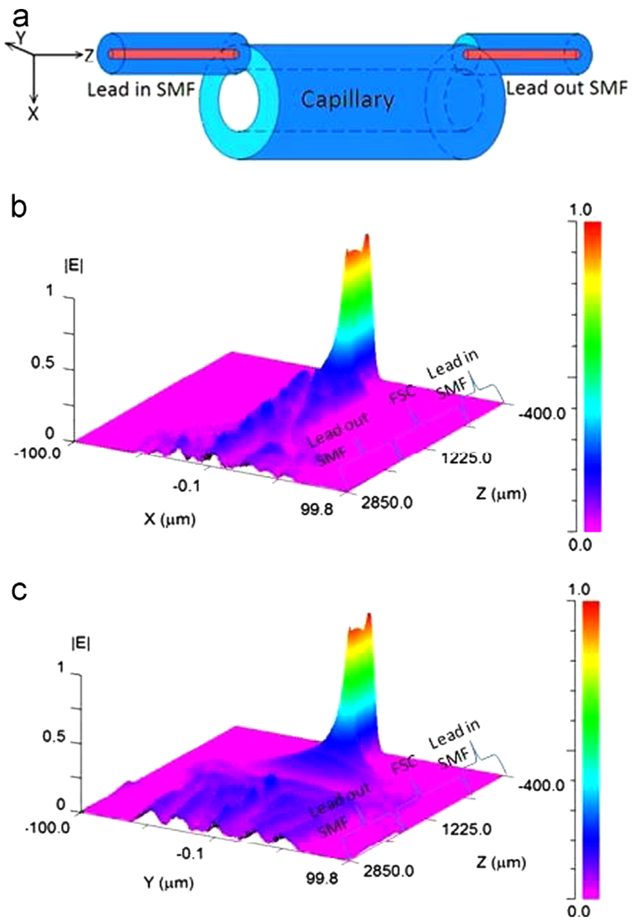

Fig. 2. Simulation modeling of FSC based RI sensing element (a) and optical field distribution of capillary wall based sensor in *X–Z* plane (b) and *Y–Z* plane (c) (operating wavelength is 1550 nm).