Sensors and Actuators B 209 (2015) 602–605

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

An in-line optical fiber refractometer with porous thin film coating

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ARTICLE INFO

Article history:
Received 12 September 2014
Received in revised form
17 November 2014
Accepted 18 November 2014
Available online 12 December 2014

Keywords:
Fiber optic
Refractive-index sensor
Dielectric films
Fabry–Perot interference

ABSTRACT

An in-line refractive-index sensor is proposed and demonstrated. The sensor is based on Fresnel reflection modulated by Fabry–Perot interference, which consists of a section of multi-mode fiber (MMF) tip coated with porous dielectric multilayer. The measure is conducted by monitoring the shift of the interference fringe, which is correlated to different refractive indices. When the external refractive index (RI) changes from 1.333 to 1.443, the RI sensitivity is 135.5 nm/RIU with good linearity. The miniature size, simple physical structure, small temperature dependence, linear response and ability for batch fabrication make the device attractive for chemical and biological sensing.

1. Introduction

Refractive index (RI) sensing is very important for many fields, such as medical diagnostics, food quality testing, environmental monitoring, and biohazard detection. In recent years, optical fiber RI sensors have been attracted much research interest due to their advantages of miniature design, electromagnetic immunity, good performance and durability to harsh environments. Optical fiber RI sensors in general, can be divided into two categories. There are optical fiber RI sensors based on fiber coupled-mode theory and light-wave interference theory. The former includes fiber Bragg gratings (FBGs) [1–5], and long period gratings (LPGs) [6–8], in which the resonant wavelengths of gratings depend on RI of external environment due to the mode coupling. While the later includes interference structure such as Mach–Zehnder (M–Z) interferometer [9–11] and Fabry–Perot (F–P) interferometer [12–20].

For grating-based sensors, inherently cross-sensitivity problem, expensive fabrication equipments and fragile structure restrict their practical applications. RI sensors with M–Z interference structure also have some drawbacks that need to be overcome. For example, some sensors are complicated in manufacture process, unstable in structure, or not cost-effective.

In this paper, we present an in-line F–P sensor for RI measurement. The F–P structure located at the tip of multi-mode fiber, consists of three layers of porous dielectric film with Physical Vapor Deposition (PVD) method [21–23]. To evaluate its capability for refractive index measurement, the fiber FPI device was tested using glycerol/water solutions with different concentrations, and ethanol at room temperature. By tracking the phase shift of the interference signal, the RI of solution under tested can be extracted. Compared with other types of RI sensors, the F–P refractive index sensor with coating demonstrates the advantages of compact in configuration, small cross-sensitivity to temperature and ease of operation. Especially, a single coating process can easily fabricate a large number of sensors with almost identical performance, significantly reduce mass production cost.

2. Sensing probe and optical interrogation system

A section of commercial multi-mode fiber (MMF) with core and cladding diameters of 100 μm and 140 μm respectively was firstly stripped and cut with a fibre cleaver, then MMF was put into vacuum evaporation coating machine. Three layers of $TiO_2/SiO_2/TiO_2$ dielectric oxides were deposited on the cleaved end of MMF to generate an extrinsic FPI by Physical Vapor Deposition (PVD) technology. ZZS1100-8/G Box-type vacuum coating system (RANKUUM

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http://dx.doi.org/10.1016/j.snb.2014.11.131
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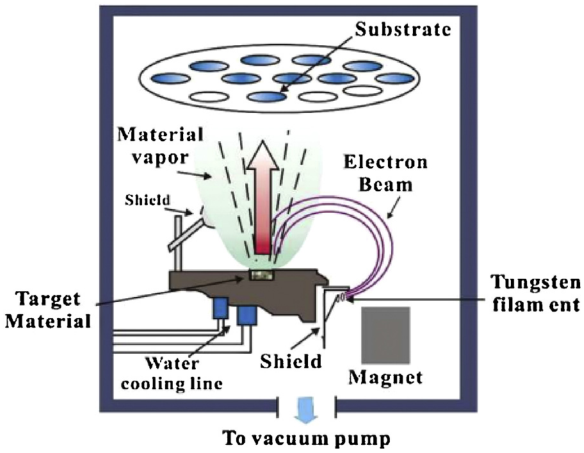


Fig. 1. Schematic diagram of PVD technology used for oxide thin film deposition on MMF fiber.

MACHINERY LTD CHN) was employed for the coating deposition. Fig. 1 shows the schematic diagram of PVD technology.

In the experiments, the basic vacuum pressure of coating chamber is set at 0.01 Pa, oxygen (O_2) with a velocity of 80 sccm is supplied as procedure gas. Under 150 °C baking temperature, the deposition rate for SiO_2 and TiO_2 was 2.5 Å/s and 5 Å/s respectively. The dielectric coatings are realized without ion-source assistance, which enables the porous structure [24,25]. The schematic diagram of the thin film-coated RI sensor is shown in Fig. 2(a). The first and the third layers of 228 nm TiO_2 are employed as mirror layers while 1600 nm SiO_2 coating is used as cavity layer in the F–P structure. Fig. 2(b) shows a 20k× Scanning Electron Microscope (SEM) image of the sensing coating. Three-layer structure can be seen clearly from Fig. 2(b). The total thickness of the sensing element—the film is about 2.05 μm. Instead of a single layer, three-layer structure is employed in this work to improve visibility of interference fringe and to adjust the center wavelength of the reflection in the range of 500–800 nm as shown in Fig. 3.

The RI measurement and characterization system are schematically shown in Fig. 4. A miniature broadband halogen tungsten lamp, miniature fiber optic spectrometer (S3000 from Seeman Technology, wavelength resolution: 0.3 nm), a 3-dB multi-mode optical fiber coupler (OC) are employed to interrogate the thin film RI sensor. And the sensing tip is placed into the liquid of which RI is to be measured. Light from halogen tungsten lamp illuminates the multilayer sensor through the OC, the reflected lights from the $TiO_2/SiO_2/TiO_2$ multilayer structure generate interference fringes in the spectrometer. The reflected light is coupled to another arm of the OC, and then is recorded with the miniature fiber spectrometer. Finally the sensing data were collected to a computer for further data treatment and evaluation.

The sensing principle is based on the shift of reflected interference spectrum due to the absorption of the molecules of aqueous

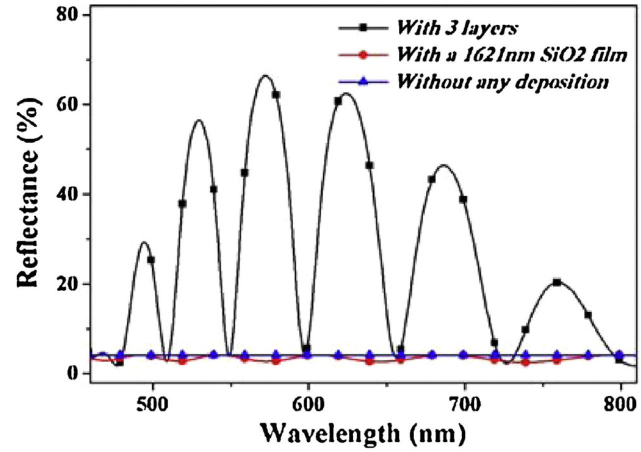


Fig. 3. Theoretical reflections of the sensor with 3 layers, pure SiO_2 film and without any deposition.

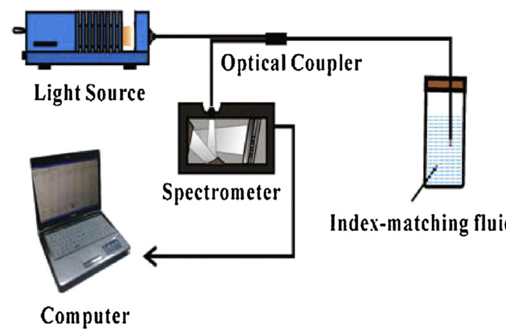
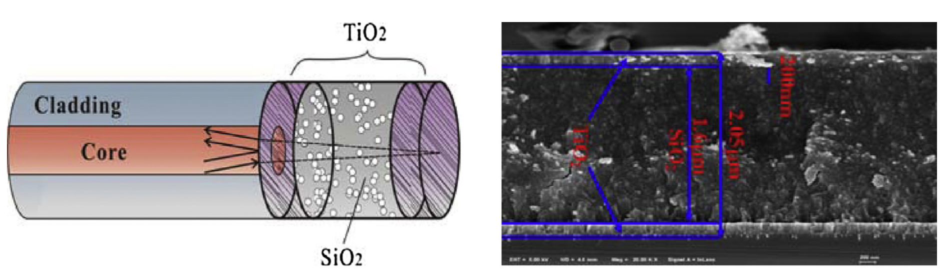


Fig. 4. Optical inspection system for the thin film temperature sensors.

solution in the porous structure as the influence of capillary condensation [26]. This absorption of aqueous solution will change the effective refractive index of the multilayer F–P cavity, and therefore results in the shift of interference fringe. The higher refractor of aqueous solution means the greater shift of the reflected spectrum. In this way the correlation between the refractive index of the aqueous solution under tested and the shift interference fringe are maintained.

3. Experiment and results

Preliminary results of using the sensor to measure the refractive index of glycerol/water and sucrose/water solutions were successfully demonstrated. The variable refractive index liquid was prepared by mixed deionized (DI) water with different mass concentrations of glycerol from 0 to 80% in increments of 10%, and their



(a) (b)

Fig. 2. (a) Schematic diagram of the $TiO_2/SiO_2/TiO_2$ multilayer sensor and (b) scanning electron microscope (SEM) image of the sensing probe.