Sensors and Actuators B 245 (2017) 423–427

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Spectrum ameliorative optical fiber temperature sensor based on hollow-core fiber and inner zinc oxide film

Hao Sun [a], Hao Luo [b,*], Xin Wu [a,*], Lei Liang [b], Yucheng Wang [a], Xiangchao Ma [a], Jianqi Zhang [a], Manli Hu [b], Xueguang Qiao [b]

[a] School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, China
[b] School of Physics, Northwest University, Xi'an 710069, China

ARTICLE INFO

Article history:
Received 24 October 2016
Received in revised form 15 January 2017
Accepted 24 January 2017
Available online 29 January 2017

Keywords:
Fiber optics
Optical fiber sensor
Temperature
Hollow-core fiber
Zinc oxide

ABSTRACT

The conventional optical fiber sensors based on hollow-core fiber (HCF) are suitable for high-temperature measurement. However, the limit effect of HCF's air core on transmission light is weak and thus result in a large transmission loss. Therefore, this paper proposed and demonstrated a spectrum ameliorative optical fiber temperature sensor based on HCF and inner zinc oxide (ZnO) film. The HCF's inwall is coated with a layer of thin ZnO film to enhance the limitation on the transmission light and improve the output spectrum. Experimental results show that the extinction ratio of transmission spectrum increase about 5 dB and the spectral pattern is more smooth and uniform. This method of coating film on the HCF's inwall to improve output spectrum is effective. The proposed sensor can realize high temperature measurement up to 460 °C.

1. Introduction

Optical fiber sensor is a type of optical sensing technology by detecting the transmission light within fiber changed with the external environment. It has many outstanding advantages over conventional electrical or chemical sensors, such as low cost, compact size, high sensitivity, high flexibility, corrosion resistance and good electromagnetic interference immunity [1]. These features make it can be used for measuring many kinds of parameters, such as temperature, humidity, refractive index, strain, curvature, acceleration, chemical gas, etc. Consequently, various types of optical fiber sensors got extensive research and development in recent decades [2–6].

Hollow-core fiber (HCF) is a type of cylindrical hollow waveguide with air fiber-core and it has low infrared transmission loss and high power threshold value [7,8]. The unique medium structure and transmission characteristics make it can be used widely and reveal extraordinary advantages in the sensing fields [9–11]. Especially, the HCF based on pure fused silica has large temperature measuring range, which make it very suitable for high-temperature sensing environments.

In 2008, Jung et al. reported an ultracompact inline Mach-Zehnder interferometer sensor, which consists of a composite leaky hollow fiber segment spliced between two SMFs [12]. This sensor obtains a temperature sensitivity of 52 pm/°C from 25 °C to 330 °C. In 2012, Ferreira et al. proposed a spatial optical filter sensor based on hollow-core silica tube and tested its sensing response to different physical parameters e.g. strain, temperature and refractive index [13]. Their experimental results show that this sensor can be used for high temperature measurement (up to 1000 °C) with a sensitivity of 27.5 pm/°C. Recently, Feng et al. reported a high temperature sensor based on resonant reflection in HCF [14]. In the temperature range of 200 °C–800 °C, this sensor attained a temperature sensitivity of 28.97 pm/°C. These sensors in Refs. [12–14] are the commonly used SMF-HCF-SMF (SHS) sensing structures, which have the advantages of simple structure and easy manufacture. However, the SHS structure usually suffers from some persistent drawbacks of large transmission loss, low extinction ratio or irregular spectral pattern. This is because the limit effect on transmission light of HCF's air core in the SHS structure is weak and most of light scattering out from HCF's cladding. This problem will limit the HCF-based sensors' widespread application.

Zinc oxide (ZnO) is a type of important photoelectric semiconductor material with wide band gap and large exciton binding energy. ZnO material can be used to build various nanostructures with different morphologies easily by controlled growth. So it has been used widely in photoelectric diode, sensors, pressure sensitive

* Corresponding authors.
E-mail addresses: luo@nwu.edu.cn (H. Luo), xwu@xidian.edu.cn (X. Wu).

http://dx.doi.org/10.1016/j.snb.2017.01.151
0925-4005/

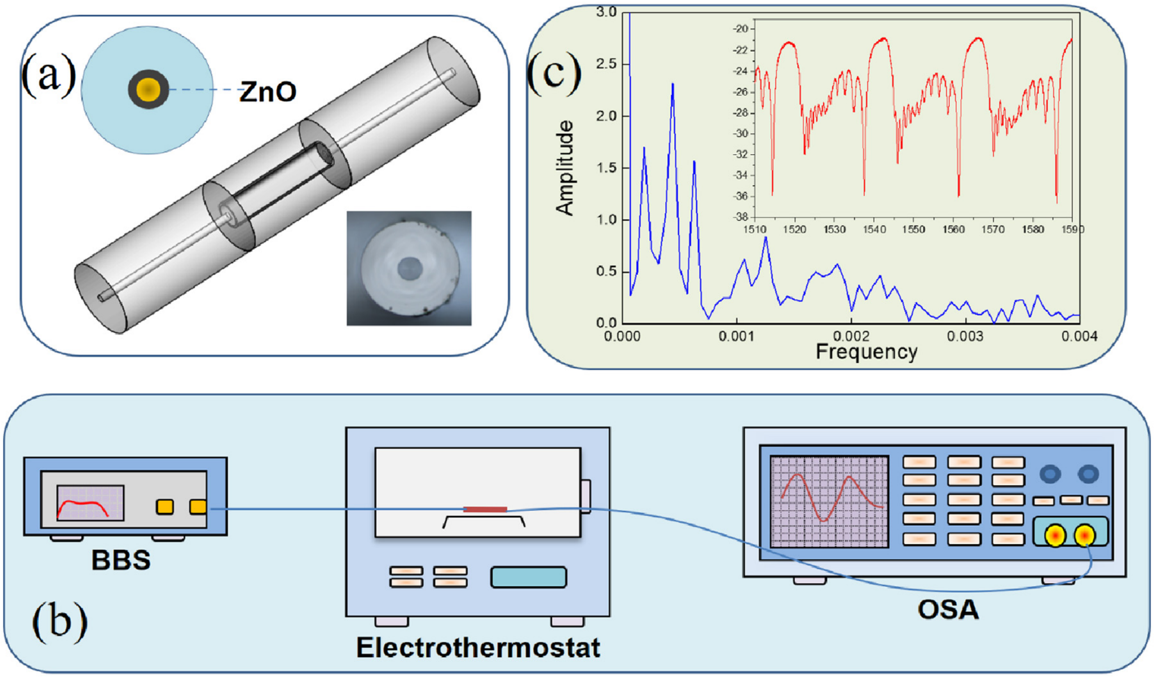

Fig. 1. (a, b) The schematics of the proposed sensor and experimental facilities; (c) The transmitted spectrum (red) and the corresponding spatial frequency spectrum (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resistance and photoelectric detector [15–18]. Due to the melting point up to 1975 °C, the high thermal stability make ZnO suitable for high-temperature environments.

In previous work, the effect of high temperature annealing and moving contact line on ZnO nanostructures were researched [19,20]. An improved sol-gel method for preparation of ZnO nanomaterial and coating ZnO film on the capillary tube's inwall was demonstrated. Consequently, in this paper, a spectrum ameliorative optical fiber high temperature sensor based on HCF and inner ZnO film is proposed and experimentally demonstrated. This sensor consists of a common SHS structure and a layer of thin ZnO film coated on the HCF's inwall. Here the ZnO film is used to enhance the limitation on the transmission light of HCF's cladding and improve the output spectrum. Experimental results show that the extinction ratio of transmission spectrum increases distinctly and the spectral pattern is more smooth and uniform. The proposed temperature sensor with the sensing length of 6 mm can realize high temperature measurement up to 460 °C.

2. Sensor design and fabrication

The schematic diagram of this proposed sensor is shown in Fig. 1(a). It consists of input SMF, 6 mm HCF and output SMF, of which the HCF's inwall is coated with a layer of ZnO thin film. The core/cladding diameters of the used SMF (YOFC FullBand® +) and HCF (Polymicro Tech. TSP030150) are 9/125 μm and 30/125 μm, respectively. Here the used HCF is one kind of fused silica capillary tubing. The coating process of ZnO film and the fabrication process of the sensor are described below.

The preparation of ZnO film layer was divided into two steps, i.e. coating and annealing, as shown in Fig. 2. Firstly, the coating solution was obtained by mixing zinc acetate dihydrate ($Zn(CH_3COO)_2{\cdot}2H_2O$, Alfa Aesar, 98%) and diethanolamine ($(HN(CH_2CH_2OH)_2$, Alfa Aesar, 99%) into ethanol under vigorous stirring at 60 °C for 20 min. The final molarities of zinc acetate dihydrate and diethanolamine in the mixed solution are both 0.1 mol/L. Here the diethanolamine was used to increase the stability of the sol. Then one of the HCF's end-face was inserted into the cooled coating solution vertically. Under the effect of capillary force, the coating solution was sucked into the HCF's air core and it could rise up about 10 mm. Whereafter, the vertical HCF was dried and the zinc acetate (ZnAC) film could be deposited on the HCF's inwall after evaporation. The thickness of ZnAC will influence the final thickness of ZnO film, it can be adjusted and controlled by changing the solution concentration and drying temperature. Finally, the completely dried HCF was annealed in a tubular furnace at 385 °C for 20 min. During the annealing process, the zinc acetate transformed to zinc oxygen through multi-step decomposition and thus formed a layer of ZnO film. The thickness of ZnO film is estimated less than 100 nm.

During the coating deposition process, the ZnO was also attached to the end-face of HCF. So before fabricating the sensing structure, the HCF's end-face need to be forced weld to an SMF under the manual control mode by an arc fusion splicer (Fujikura FMS-60), and then be cut by a cutting knife at the HCF-side of the weld plane to ensure the smooth of HCF's end-face. Usually the splice temperature exceeds the softening temperature of HCF when welding the HCF to SMF, this will result in the air core collapse near the welding plane. The collapse will cause larger transmission loss and messy interference spectrum. In order to avoid this issue and ensure the mechanical strength of welding plane simultaneously, the splicing time and discharge power were optimized for 3500 μs and −30 bit. After splicing the section of HCF between input SMF and output SMF, the final sensor was fabricated.

Because of the mismatch between fiber core's diameters of SMF and HCF, the light injected from in-put SMF into the downstream HCF will excite multiple high-order eigenmodes. Due to the different transmission coefficients, part of these modes will interfere with each other when recoupling into the output SMF. And the other part of light will escape out from the HCF's cladding, as shown in Fig. 3. According to Ref. [21], the refractive index (RI) of wurtzite ZnO is 2.0, which is greater than HCF's RI. The layer of ∼100 nm ZnO film coated on HCF's cladding can enhance the limitation on transmission light. The transmitted spectrum of this proposed sen-