Sensors and Actuators A 244 (2016) 106–111

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

A reflective intensity modulated fiber tilt angle sensor based on an all-photonic crystal fiber interferometer

Yong Zhao [a,b,*], Xue-gang Li [a], Lu Cai [a]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] State Key Laboratory of Synthetical Automation for Process Industries, Shenyang 110819, China

ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form 9 April 2016
Accepted 11 April 2016
Available online 13 April 2016

Keywords:
Photonic crystal fiber
Interferometer
Tilt angle sensor

ABSTRACT

A highly sensitive tilt angle sensor based on an all-photonic crystal fiber interferometer (All-PCFI) was proposed and demonstrated in this paper. The All-PCFI was formed by a PCF with two collapse regions that were fabricated by fusion discharge technique. Then a device formed by cantilever beams and iron ball was designed to transform the tilt angle to the strain, which would be detected by measuring the spectral responses of the All-PCFI. Experimental results showed that the spectrum would be red-shifted when the tilt angle changed from 0° to 90°. And in the measurement range of 0°–45°, the linear measurement sensitivity could be up to 55.67 pm/°. In addition, the sensor could measure the tilt angle in all directions by demodulating signals of the four cantilever beams.

1. Introduction

Tilt sensing is an important process in many engineering, military fields and aerospace. Therefore, the tilt sensor has been widely studied. All-fiber sensing merits are well known to be small, to transmit over long distance, to be immune to Electro Magnetic Interference (EMI), which are also especially suitable for tilt sensing applications. The previously proposed optical fiber tilt sensors were almost based on fiber Bragg grating [1–6]. In those references, the tilt angle were determined by demodulating shifts of the fiber Bragg grating (FBG) center wavelength when the tilt angle changed. However, the methods used FBG were not perfect because the temperature cross sensitivity issue and the complex production process of the FBG. Therefore, In 2014, Lee et al. proposed a new in-line Mach-Zehnder (M-Z) interferometer which was fabricated by a SMF with two tapers to measure the directional tilt and the sensitivity could reach to 335 pm/° [7]. But the temperature cross sensitivity issue still existed. In addition, the proposed sensor was fragile and could only measure the directional tilt angle, which usually could not meet the needs of the project. Therefore, a kind of low-sensitive temperature, strong and all directional tilt angle sensor was badly needed. As everyone known, photonic crystal fiber (PCF) had been widely studied because its unique properties especially low temperature sensitivity, which was caused by a very low thermal expansion coefficient (TEC) and low thermo-optics coefficient [8]. And the investigators have been illustrated a series of in-line PCFIs formed by splicing two single mode fibers (SMFs) in the PCF and applied to the measurement of various parameters [9–12]. Meanwhile, the All-PCFI was proposed and applied to sensing field [13,14].

In this paper, a strong, low-sensitive temperature and highly sensitive tilt angle sensor based on a reflective intensity modulated All-PCFI was proposed and demonstrated. The proposed All-PCFI was formed by fabricating two collapse regions in the PCF through fusion discharge technique. And then the end of the second collapse region was plated with the silver film to increase the reflective intensity. The sensor had a smaller size due to the reflection type structure. Meanwhile, the proposed sensor was strong, low-sensitive to temperature and easy to fabricate.

2. Operating principle

2.1. Operating principle of the all-PCFI

Fig. 1(a) shows the schematic diagram of the proposed reflected All-PCFI, which was formed by a PCF with two collapse regions fabricated by fusion discharge technique, as shown in Fig. 1(b) and (c).

The PCF with two collapse regions forms an M-Z interferometer. The input optical signal launches into the PCF and propagates in the core of the PCF with the fundamental mode and the effec-

* Corresponding author.
E-mail addresses: zhaoyong@ise.neu.edu.cn, zhaoyong@tsinghua.org.cn (Y. Zhao).

http://dx.doi.org/10.1016/j.sna.2016.04.030

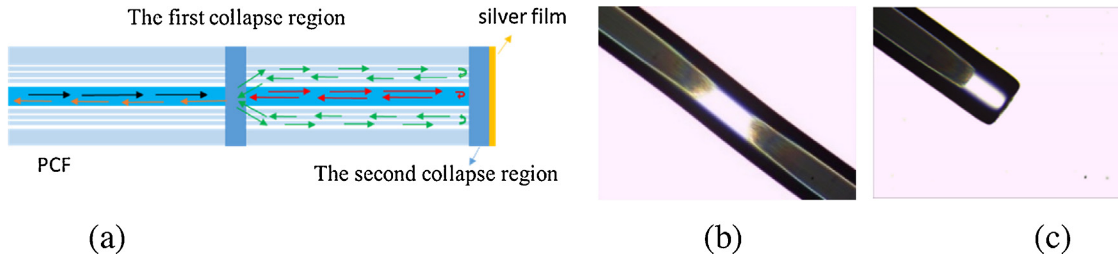

Fig. 1. (a) schematic diagram of All-PCFI (b) the first collapse region of the PCF under the microscope (c) the second collapse region of the PCF under the microscope.

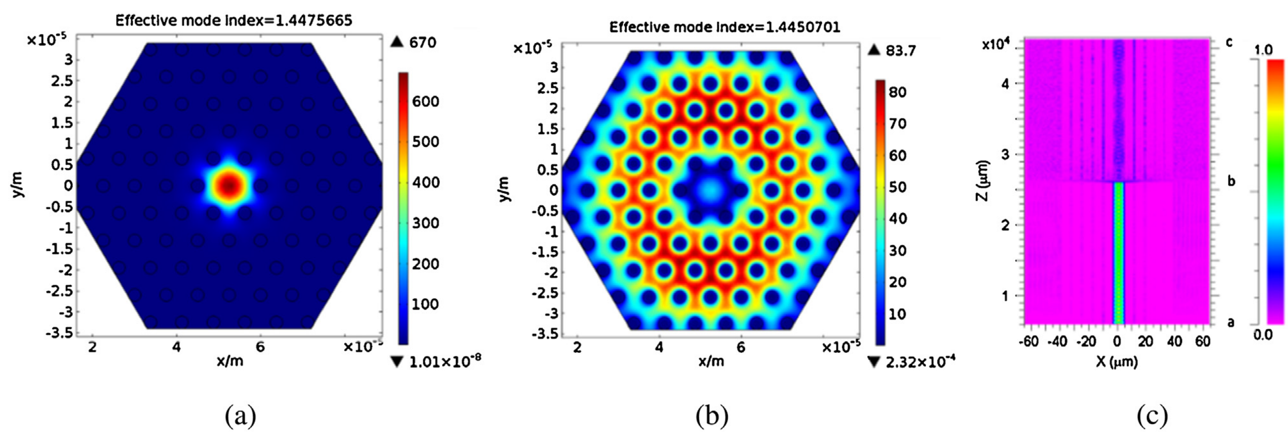

Fig. 2. (a) the fundamental mode of the PCF (b) one of the cladding modes (c) the electric field distribution when the light through the first collapse region.

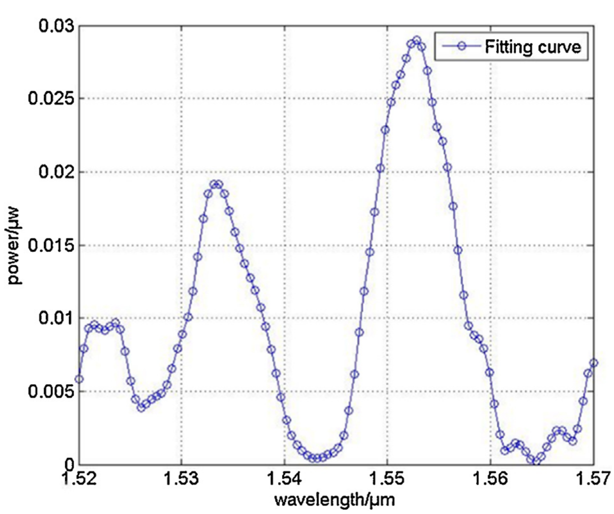

Fig. 3. the simulation spectrum of the All-PCFI.

tive refractive index was 1.4475665, as shown in Fig. 2 (a). When the light propagate through the first collapse region, a part of lights excite the cladding modes, as shown in Fig. 2(b) and the others continue to propagate forward along the core of PCF with the fundamental mode. Fig. 2(c) wis the optical field distribution when the lights through the first collapse region, which proved that the cladding modes have been excited.

When the lights (core mode and cladding modes) arrive to the second collapse region and silver film, the lights were reflected and returned back. Then the reflected cladding modes would re-coupling back to the core of the PCF and interfere with the reflected core mode light in the first collapse region. Because of the phase difference between the core mode and the cladding modes, an interference output could be observed, as shown in Fig. 3. Fig. 3 is the spectrum simulated by Rsoft, which proved the existence of M-Z interference. It is noted that the interference spectrum was uneven, which may be caused by stacking multiple cladding modes.

The interference spectrum could be analyzed by using a simple two-mode interference model, which had been widely used in this field to qualitatively analyze the fiber mode interference:

$$I_{out} = I_{core} + I_{cladding} + 2\sqrt{I_{core} I_{cladding}} \cos\delta \quad (1)$$

where I_{core} and $I_{cladding}$ were light intensities of the core and cladding modes, and δ was the phase difference between cladding modes and core mode, which could be expressed as

$$\delta = \frac{2\pi L}{\lambda} \times \Delta n_{neff} \quad (2)$$

where λ was the centre wavelength of the light and the Δn_{neff} was the effective index difference, which could be defined as:

$$\Delta n_{neff} = n_{core}^{neff} - n_{clad}^{neff} (n_{core}^{neff} > n_{clad}^{neff}) \quad (3)$$

when the PCF was bent or stretched, photo-elastic effect would happen and cause the refractive index profile of the fiber changed. Thus the RI difference, i.e. Δn_{neff} was changed.

It could be seen from the Eq. (1) that the interference light intensity got the minimum when the phase difference δ was an odd multiple of π and it could be expressed as

$$(2K+1)\pi = \frac{2\pi L}{\lambda} \times \Delta n_{neff} \quad (4)$$

where the K was the natural number. And the dip wavelength of the interference spectrum could be expressed as

$$\lambda_{\min} = \frac{2L \times \Delta n_{neff}}{2K+1} \quad (5)$$

Therefore, when the Δn_{neff} changed, the dip wavelength of the interference spectrum would change. Above analysis showed that the strain could be measured by recording the wavelength shift of the interference spectrum recorded by optical spectrum analyser (OSA).