Optical Fiber Technology 46 (2018) 1–4

Contents lists available at ScienceDirect

Optical Fiber Technology

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

Strain sensor based on two concatenated abrupt-tapers in twin-core fiber

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ABSTRACT

In this paper, a novel and high sensitivity optical fiber sensor based on Mach-Zehnder interferometer (MZI) with two concatenated abrupt-tapers in twin-core fiber (TCF) is proposed and experimentally demonstrated. The setup includes two abrupt-tapers with different size in TCF and then spliced with two segment of normal single mode fibers (SMFs). The multiple cladding mode will be excited within the TCF, partly coupled with the core mode while in the first taper. After propagation of these coupled modes, they will be recouped in the second tapers. Through the two abrupt-tapers, we realized twice MZI. It is because of the two abrupt-tapers structure that the interference between modes is strengthened. Maximum interference resonance dips exceeds 19 dB. The interference fringe of this device would shift with the variation of strain. Therefore, we can desire the parameters through monitoring the wavelength shift of the transmission spectrum. The experimental results show that the sensitivity of the strain sensor is 6.39 pm/με when the resonance wavelength is 1466.2 nm. Especially, a higher sensitivity has achieved in this paper compared with other strain sensor, which sensitivity is up to 7.6 pm/με at 1716.5 nm with interferometer extinction ratio of 11 dB. The proposed sensor is easy-fabricated, low-cost and high sensitivity, which is very suitable for physical application of strain measurement.

1. Introduction

In recent years, the research of optical fiber sensing in China has covered many fields such as large scale structural engineering, electric power, petroleum, chemical industry and military owing to its many unique advantages, such as high sensitivity, anti-electromagnetic interference, electrical insulation, good corrosion resistance, fast measuring speed compared with traditional sensors [1]. Measurements of strain have become one of the hot topics in many fields [2]. In previous work, various optical fiber devices have been proposed to implement the measurements of the strain, such as long period fiber gratings (LPGs) [3–6], fiber Bragg gratings (FBGs) [7–9] have been widely employed in the sensor. Because FBG and LPG need CO_2 laser pulses, this process is tedious and expensive. In addition, FBG is sensitive to temperature, which will cause interference to strain measurement. Other types of sensor [10] such as a single mode-multimode-single mode fiber structure [11], photonic crystal fiber [12,13], holely optical fiber [14] etc. These sensors are usually integrated complex and high cost. Techniques based on abrupt tapered structure can excite multimode interference, which can form an in-fiber MZI. So this structure can be served as a reliable candidate device. In 2016, asymmetrically infiltrated twin core photonic crystal fiber based on a water filled MZI was proposed to measurement strain and temperature simultaneously [15]. In the same year, Chao Li proposed an all-fiber multipath MZI based on four-core fiber [16]. In 2017, a compact in-fiber MZI based on TCF with a novel T-shaped taper was proposed [17]. In 2018, a cascade structure made of a CO_2-laser-notched long-period fiber grating and a modular LPFG was proposed [18]. In order to increase sensing sensitivity, we introduce several abrupt-tapers in fiber with different size.

In this paper, we proposed a fiber optic sensor to measurement strain with high sensitivity. We fabricated two abrupt-tapers to form twice MZI with twin-core fiber. The proposed sensor is quite simply fabricated. The abrupt-tapered twin-core fiber is spliced to a single mode fiber and concatenate with a lateral-shifted junction. Compared with previously proposed strain sensor, high sensitivity can be obtained owing to the abrupt-taper, which result in the multiple modal interference in TCF. By studying and analyzing the experimental data, it is verified that the structure can achieve measurements stain with high sensitivity. Its easy fabrication and low cost will bring great potential in many fields.

2. Fabrication setup and principle

The proposed sensor structure, as shown in Fig. 1. And Fig. 2 shows the cross-section of the TCF by using an optical microscope. The TCF has a cladding diameter of 125 μm, while the core diameter was 10 μm and the core distance was 30 μm. The schematic diagram includes input SMF, two abrupt-tapers in TCF and an output SMF. And it is noted that modal interference is formed by two cascading abrupt-tapers, which was shaped by using taper program with a discharging current of 2 mA.

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https://doi.org/10.1016/j.yofte.2018.09.013
Received 16 July 2018; Received in revised form 28 August 2018; Accepted 10 September 2018

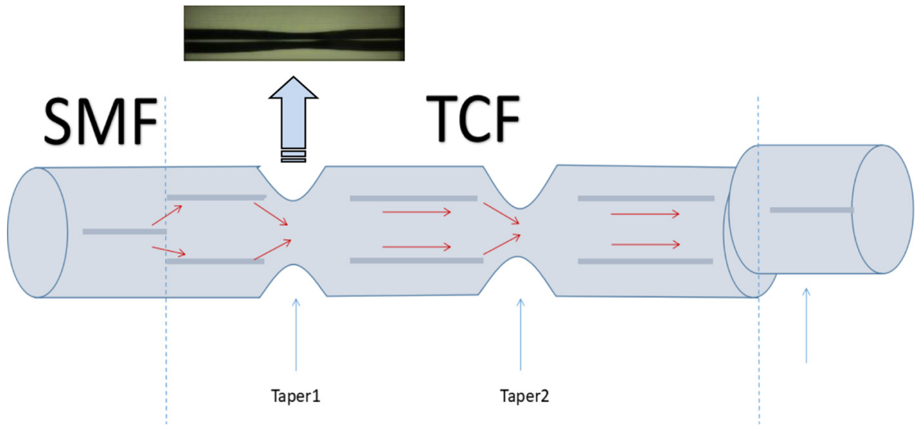

Fig. 1. Schematic diagram of the strain sensor.

Fig. 2. Microscope image of the cross section of TCF.

The length of TCF was measured about 7.2 cm, while the SMF was 1 cm. When the light transmits into the TCF, the fundamental mode in the core into the first abrupt-taper, several cladding modes will be excited. After propagation, they will produce a phase difference. The taper waist with the different size, they are 91 μm and 81 μm, respectively.

As we all know, the interference is based on the core mode and cladding modes caused by the two abrupt-tapers. And the inference intensity can be expressed as:

$$I = I_{core} + I_{clad} + 2\sqrt{I_{core} + I_{clad}}\cos\varphi \tag{1}$$

where I, I_{core} and I_{clad} are the intensity of the interference signal, the light intensity of the core mode and several cladding modes, respectively. The phase difference φ between the core and the cladding mode can be expressed by:

$$\varphi = \frac{2\pi\Delta_{neff}L}{\lambda} \tag{2}$$

where Δ_{neff} is the effective refractive indices difference between the two interference modes, and L is the length of the TCF, λ is the wavelength of the propagating light. The wavelength reaches the attenuation peak when the phase difference is satisfied φ = (2 m + 1) π, and the attenuation peak wavelength can be written as:

$$\lambda_m \frac{2\Delta_{neff}L}{(2m+1)} \tag{3}$$

in here, the m is the integer. λ_m is the wavelength of the interference dip.

As we can see from Eq. (2), the wavelength and effective refractive index difference will influence the wavelength shift. According to the sensing theory, the change of refractive index of fiber is caused by an optical effect. When we exert strain, the refractive index of the axial direction of the fiber changes, and the corresponding photoelastic effect of the medium causes phase change. When added strain, a wavelength dip will shift. Therefore, we can measure strain by monitoring the wavelength shift. And the interference attenuation peak shift induced by strain change can be shown as:

$$\frac{\Delta\lambda_m}{\Delta\varepsilon} = \left(1 + \frac{p_{e1}n_{eff1}p_{e2}n_{eff2}}{\Delta n_{eff}}\right)\lambda_m = (1 + p_e)\lambda_m \tag{4}$$

where p_{e1}, p_{e2} are the photoelastic constants of two modes. Δε is the variation of strain, which can be expressed as:

$$\Delta\varepsilon = \frac{\Delta L}{L_{all}} \tag{5}$$

where ΔL is the accuracy of strain, L is the total length between the fiber.

3. Experiment and discussion

In order to further prove the feasibility of the structure mentioned in this paper, we design the experimental setup as shown in Fig. 3(a).

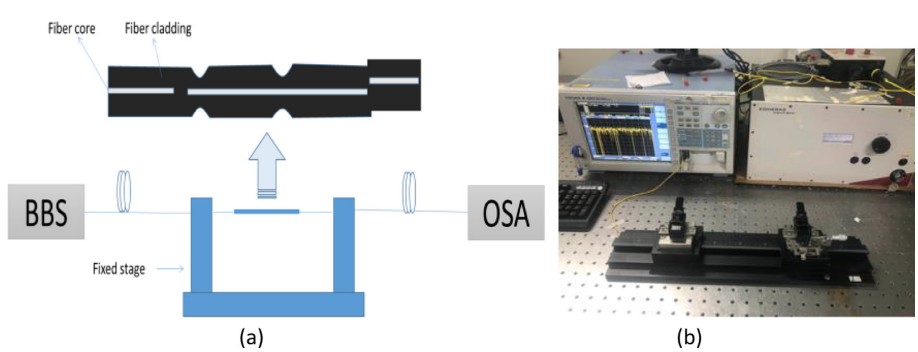

Fig. 3. (a) Schematic diagram of the experiment setup. (b) Experimental device in the laboratory.