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Intensity modulation type fiber-optic strain sensor based on a Mach–Zehnder interferometer constructed by an up-taper with a LPG

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ABSTRACT

A highly sensitive and compact fiber-optic strain sensor was presented and experimentally demonstrated. The sensor is based on an in-line fiber Mach–Zehnder interferometer (MZI), which is constructed by connecting a long-period fiber grating (LPG) with an up-taper. With the increasing of the axial strain on the sensor, both of the up-taper's diameter and the light coupling efficiency decreased. By measuring the transmission intensity changes of the resonant dips at wavelength ~1553.4 nm under the fiber axial strain ranging from 0 to 590 με, the sensitivity of 0.026 dB/με was obtained, which is almost 2 times of the existing similar strain sensor. And the results were also confirmed by simulations.

1. Introduction

Fiber-optic strain sensors have been widely used for the health monitoring of the building, bridge, dam and so on. Fiber Bragg grating (FBG)-based sensor is widely applied to measure strain and temperature simultaneously [1,2]. A single mode–multimode–single mode (SMS) fiber structure had also been proposed for strain measurement [3,4]. Long-period fiber grating (LPG) has been demonstrated in a wide range of sensing areas since first reported in 1996 by Vengsakar et al. [5]. The large applications of LPG are mainly for its low insertion loss, compactness, sensitiveness to surrounding environment and etc. It can also resolve the problem of the relative large bandwidth of resonant dips, so the transmission capacity and measurement precision for sensing can be greatly improved. Typical fiber-grating-based modal Mach–Zehnder interferometers (MZIs) are LPG pair [6], the fiber fundamental core mode can be coupled into the cladding by the first LPG to excite the high-order cladding modes, and then be re-coupled into the core by the second LPG, the interference between the fiber fundamental core mode and different cladding modes can be seen in the OSA. The coupling efficiency mainly depends on the distance between two LPGs.

In this paper, a detailed experimental demonstration along with theoretical analysis of a fiber-optic strain sensor based on MZI exploiting up-taper and LPG is presented and discussed. By measuring the transmission intensity changes of the resonant dips at wavelength ~1553.4 nm under the fiber axial strain ranging from 0 to 590 με, the sensitivity of 0.026 dB/με was obtained, which is almost 2 times of the existing similar strain sensor.

2. Sensor fabrication and principle

Schematic diagram of the proposed fiber-optic MZI is shown in Fig. 1(a). It consists of an up-taper and a LPG. The space between the up-taper and LPG is ~15 mm [7]. When the light is launched into the fiber (black arrow), massive light energy is coupled from the core to excite a large number of high-order modes that guided by the cladding of the fiber (blue arrow), and the remaining light still propagates in the core as the fundamental core mode (red arrow). Then, the cladding modes are re-coupled into the fiber core by the LPG to interfere with the fundamental core mode. Lengths of this kind MZI's two arms are exactly same, but the optical lengths are different because of the different effective indices of each optical length [8]. The transmission spectra of the proposed structure are shown in Fig. 2 (black line).

LPG was fabricated in a single mode fiber (SMF-28) by high-frequency CO_2 laser pulses (Han's Laser CO_2). The grating period and length of the LPG are 600 μm and 24 mm, respectively. Its center wavelength is ~1535 nm, as shown in Fig. 2 (red line).

Fig. 1(b) is the microscopic image of the up-taper. It was made

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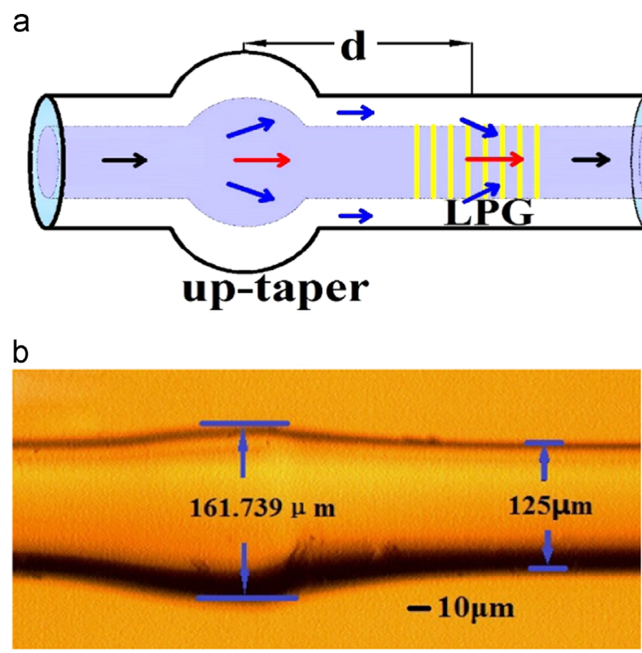

Fig. 1. (a) Schematic configuration of the structure, (b) microscopic image of the up-taper. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

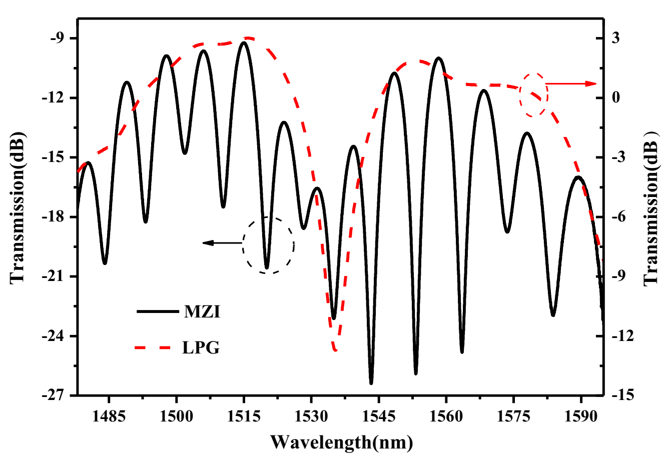

Fig. 2. Transmission spectra of the proposed MZI sensor and the LPG. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

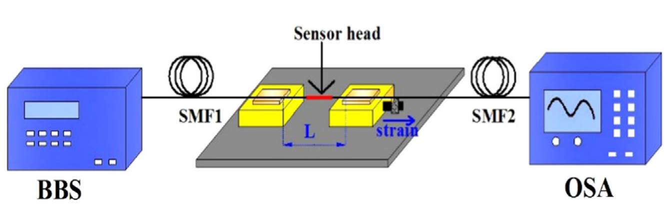

Fig. 3. Schematic of experimental setup.

easily by using a fusion splicer (Fujikura FSM-60s) under the manual splicing mode, where we used a much larger overlap distance of 130 μm to replace the common setting of 10 μm. Diameters of the fiber core and the cladding for the up-taper are ~15 and 161.74 μm, respectively.

Additionally, the light energy which is coupled into the fiber cladding is depended on the up-taper's diameter [9,10]. Accordingly, changes of interference intensity of the proposed MZI can be given by [11,12,15],

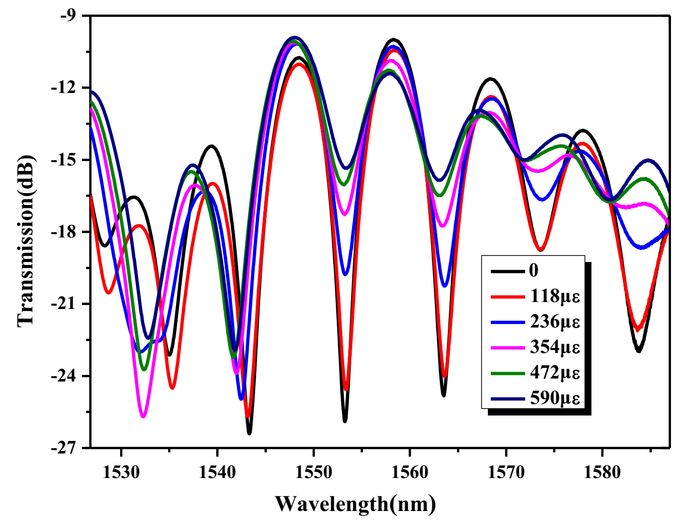

Fig. 4. Transmission spectra variation against the different axial strains.

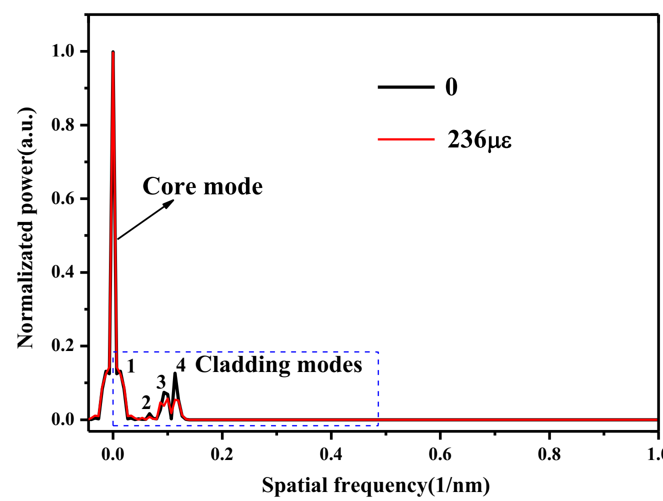

Fig. 5. Spatial frequency spectra of the proposed sensor.

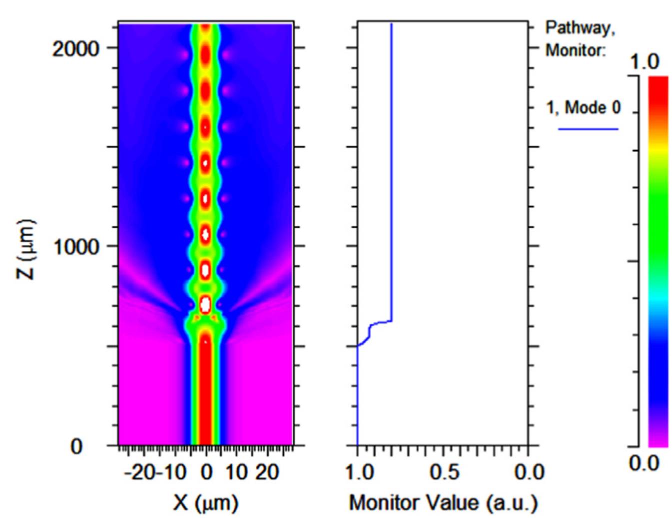

Fig. 6. Simulation of the light propagating through the up-taper ($D_t = 15$ μm).

$$K = \frac{2\sqrt{I_{core}/I_{clad}}}{1 + I_{core}/I_{clad}} \tag{1}$$

where K is the fringes visibility. I_{core} and I_{clad} are the light intensity