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Fiber curvature sensor based on spherical-shape structures and long-period grating

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ABSTRACT

A novel curvature sensor based on optical fiber Mach–Zehnder interferometer (MZI) is demonstrated. It consists of two spherical-shape structures and a long-period grating (LPG) in between. The experimental results show that the shift of the dip wavelength is almost linearly proportional to the change of curvature, and the curvature sensitivity are $-22.144\ \text{nm/m}^{-1}$ in the measurement range of $5.33–6.93\ \text{m}^{-1}$, $-28.225\ \text{nm/m}^{-1}$ in the range of $6.93–8.43\ \text{m}^{-}$ and $-15.68\ \text{nm/m}^{-1}$ in the range of $8.43–9.43\ \text{m}^{-1}$, respectively. And the maximum curvature error caused by temperature is only $-0.003\ \text{m}^{-1}/°\text{C}$. The sensor exhibits the advantages of all-fiber structure, high mechanical strength, high curvature sensitivity and large measurement scales.

1. Introduction

Fiber curvature sensors based on inline Mach–Zehnder interferometers (MZIs) have attracted considerable interest due to the advantages of high sensitivity, anti-electromagnetic interference and small size. Most in-line MZIs curvature sensors are fabricated by specialty optical fiber, such as multimode fiber (MMF) [1], photonic crystal fiber (PCF) [2,3] and polarization maintaining fiber (PMF) [4]. However, those fibers are expensive, which limited the applications. There are various MZI structures based on single mode fiber (SMF) to realize curvature measurement. Such as two peanut-shape structures [5], the sensor based on lateral-offset and up-taper [6], and the sensor cascading two abrupt-tapers [7]. Besides, a number of optical fiber curvature sensors have been proposed based on long period fiber grating (LPG). LPG was first reported in 1996 by A. M. Vengsarkar et al. [8], and then gets great developments in curvature sensing field. Such as a pair of LPGs [9], the temperature and strain insensitive long period grating [10]. There are also some structures based on fiber grating cascading with other structures. For instance, Frazão proposed a Mach–Zehnder interferometer combined with a multimode fiber and a long-period grating [11].

In this paper, we proposed a highly sensitive curvature sensor based on a long period fiber grating and two spherical-shape fiber structures. As a LPG is embedded into the two spherical-shape structures, three different interferometers are formed and the interference could be enforced correspondingly. And then interference fringe with high visibility is expected to be observed. In addition, the proposed sensor has the advantages of high mechanical strength, high curvature sensitivity and large measurement scale.

2. Sensor fabrication and principle

The schematic diagram of the proposed sensor head is shown in Fig. 1(a). It consists of two spherical-shaped fiber structures and a LPG in between. We fabricated two MZIs with different positions of the LPG. And the length between the two spherical-shape structures are keep at 35 mm. For sensor 1, the LPG stands in the middle of the two spherical-shape structures, whereas the position of the LPG for sensor 2 is as follows: L1 = 3 mm, L2 = 8 mm. LPG is inscribed by the high frequency CO_2 laser (CO_2-H10, Han's Laser), and the period and length of the LPG are 600 μm and 24 mm, respectively. The spherical-shape structures are fabricated by commercial fusion splicer (Fujikura FSM 60S) with manual splicing, the discharge duration is 1200 ms and the discharge intensity is 135 bit. Firstly, applying arc discharge twice at one end of a single mode fiber (SMF), the end of SMF will be soften and become a sphere, as shown in Fig. 1(b). The diameter of the spherical-shape structure is 186 μm. Then, this spherical-shape end is spliced to the end of a LPG, which center wavelength is about 1578 nm. The fabricate method of the second spherical-shape structure is the same as that of the first one. Finally a MZI is fabricated.

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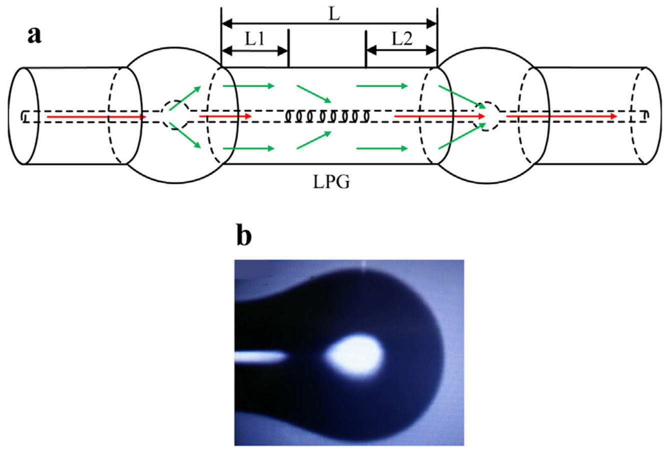

Fig. 1. (a) The schematic diagram of the MZI; (b) the photo of the spherical-shape structure.

The first spherical-shape structure works as a coupler which can excite part of light into the cladding, as a LPG is embedded between the two spherical-shape structures, the light transmitting in the cladding can be coupled back into the core at the LPG and the second spherical-shape structure, respectively. Moreover, LPG can also excite the light in the core into the cladding, and after propagating a certain distance in the cladding, the light can be coupled back into the core at the second spherical-shape structure. Thus three different interferometers are formed and the interference fringes are overlapped correspondingly.

And the interference occurs because of the refractive index difference between fiber core and cladding [12]. The interference caused by three interferometers can be simplified as the theory of two-beam interference, and thus the transmission can be given as [7]:

$$I_{total} = I_1 + I_2 + 2\sqrt{I_1 I_2}\ \mathrm{COS}\ \Phi \tag{1}$$

where I_1 and I_2 are the transmission intensities of two interfering modes, and the phase difference Φ between the core mode and the cladding mode after propagating through the length L of the sensor can be expressed by:

$$\Phi^m = \frac{2\pi}{\lambda}\Delta n_{eff} L \tag{2}$$

where Δn_{eff} is the change of the effective index difference of two interference modes, L is the length of the proposed MZI and λ is the input wavelength.

As a fiber is bent, a strain is induced in the fiber core and cladding, and then the refractive index of fiber core and cladding is varied. The effective refractive index difference Δn_{eff} in our curvature experiment can be defined as:

$$\Delta n_{eff} = \Delta n_{eff0} + k\Delta\epsilon \tag{3}$$

where Δn_{eff0} is the effective index difference of the core and cladding mode when the fiber is kept straight at first, $\Delta\epsilon$ is the strain between the fiber core and cladding caused by bending, and k is the strain refractive index coefficient, which can be seen as a constant.

The different strain between the cladding and core caused by the fiber bending can be given by [13]:

$$\Delta\epsilon = d/R \tag{4}$$

where d is the distance between core and cladding, R is bending radius. Considering to the interference condition, the interference wavelength can satisfies the equation of:

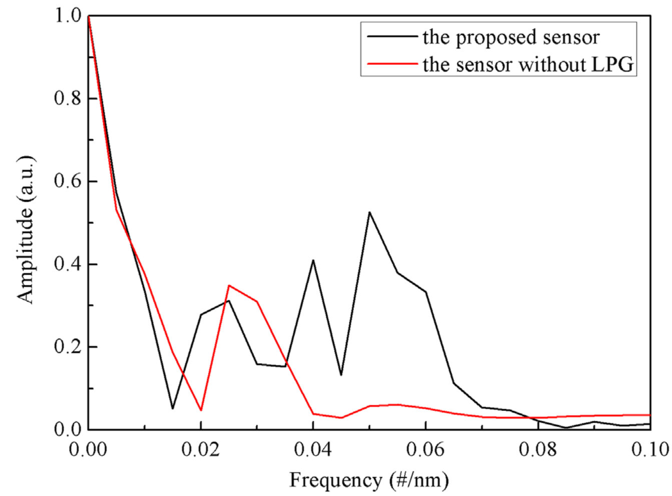

Fig. 2. The spatial frequency spectra of the proposed sensor and the sensor without LPG.

$$\Phi^m = (2m + 1)\pi \tag{5}$$

where m is an integer. According to those equations above, the resonant dip wavelength is given by:

$$\lambda_m = \frac{\Delta n_{eff0} L}{2\,\mathrm{m}+1} + \frac{KLd}{2\,\mathrm{m}+1} \times \frac{1}{R} \tag{6}$$

It can be seen according to Eq. (6) that the dip wavelength is linear to the curvature of the fiber. Thus the wavelength shift of the interference dip can be expected to observe in curvature sensing.

In order to get further information about the propagating modes involved in the interference, we also fabricated the sensor without LPG, and the length between the two spherical structures is also kept at 35 mm. The transmission spectra are analyzed by fast Fourier transform (FFT) and the corresponding spatial frequency spectra are shown in Fig. 2. It can be observed that there is only one peak for the sensor without LPG, while there are three peaks for the proposed sensor. More peaks means more cladding modes. That is to say, the sensor with LPG excites more cladding modes, and the sensitivity is expected to be improved correspondingly.

3. Experimental results and discussion

The experimental setup for curvature measurement is shown in Fig. 3. The light from a broadband source (BBS) with the wavelength range from 1440 nm to 1640 nm is injected into the MZI and the transmission spectrum is recorded by an optical spectrum analyzer (OSA) with a resolution of 0.02 nm. The two ends of the MZI are clamped on two stages, one of the stages is fixed and the other stage is movable inward 0.25 mm each time.

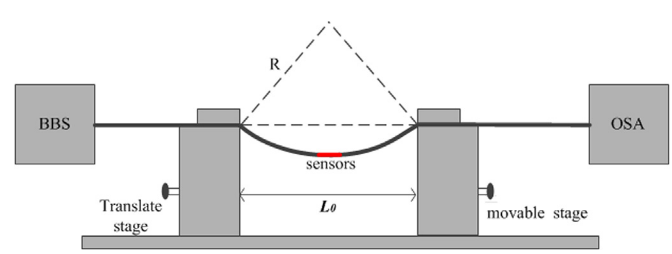

Fig. 3. The experimental setup for curvature measurement.