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# Highly sensitive force sensor based on balloon-like interferometer

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ABSTRACT

An all-fiber highly sensitive force sensor based on modal interferometer has been presented and demonstrated. The single-mode fiber (SMF) with coating stripped is designed into a balloon-like shape to form a modal interferometer. Due to the bent SMF, the interference occurs between the core mode and cladding modes. With variation of the force applied to the balloon-like interferometer, the bending diameter changes, which caused the wavelength shift of the modal interference. Thus the measurement of the force variation can be achieved by monitoring the wavelength shift. The performances of the interferometer with different bending diameter are experimentally investigated, and the maximum force sensitivity of 24.9 pm/μN can be achieved with the bending diameter 14 mm ranging from 0 μN to 1464.12 μN. Furthermore, the proposed fiber sensor exhibits the advantages of easy fabrication and low cost, making it a suitable candidate in the optical fiber sensing field.



## 1. Introduction

Optical fiber sensors have been attracted great interest in manufacturing industries, railway, protection of ecosystems due to the specific advantages of flexibility, high sensitivity, compact size, low-cost, and immunity to electromagnetic interference over traditional sensors. In the last several decades, optical fiber sensors have been widely applied to monitor a wide range of parameters such as refractive index (RI), curvature, force, temperature and so on [1–9].

Optical fiber force sensors have drawn special attentions in the practical applications, such as the health monitoring of composite materials, civil engineering structures, micro-mechanical systems, medical applications and so on. They has been widely developed based on fiber Bragg grating (FBG) and fiber modal interferometer. Liu et al. and Guo et al. present force sensor based on FBG [10,11], but the proposed methods to measure force are complicated, and the demand of fabrication of FBG is high. In order to enhance the force sensitivity, various micromachining technologies, such as flame-brushing technique, $CO_2$ laser heating technique, have been used to fabricate the microfiber Bragg grating [12–15], but the precision of the micromachining technology is too high and the manufacturing process is complex. Dong et al. proposed a Mach-Zehnder interferometer based on core-offset structure to measure force [16], but the configuration is fragile and easy to break. Besides, Liu et al. proposed a force sensor based on Fabry-Perot (FP) micro-cavities [17,18], and the proposed structures suffer from the same problem of the micromachining technology.

In this paper, we propose and experimentally demonstrate a highly sensitive force sensor based on balloon-like modal interferometer, which is comprised of a bent standard uncoated-SMF. The interference takes place between core mode and cladding modes induced by the bending SMF. With the force change, the bending diameter of balloon-like structure changes, which lead to the change of the RI of the core mode and cladding modes, and the resonant wavelength of the transmission spectrum shifts. The relationship between the bending diameter and force sensitivity has been investigated, and experimental results show that the maximum force sensitivity is 24.9 pm/μN with the bending diameter 14 mm in the range from 0 μN to 1464.12 μN. In the meanwhile, the properties of temperature for the proposed optical fiber sensor with the bending diameter 14 mm has been investigated as well, and the temperature sensitivity of 91.8 pm/°C is achieved.

## 2. Principle

The schematic diagram of the fiber sensor structure is shown in Fig. 1. The balloon-shaped fiber sensor is composed of a segment of

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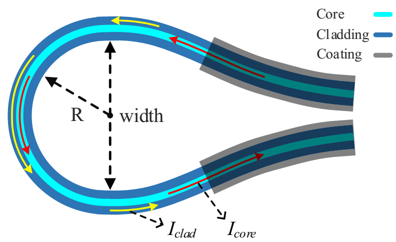


**Fig. 1.** Schematic diagram of the fiber sensor.

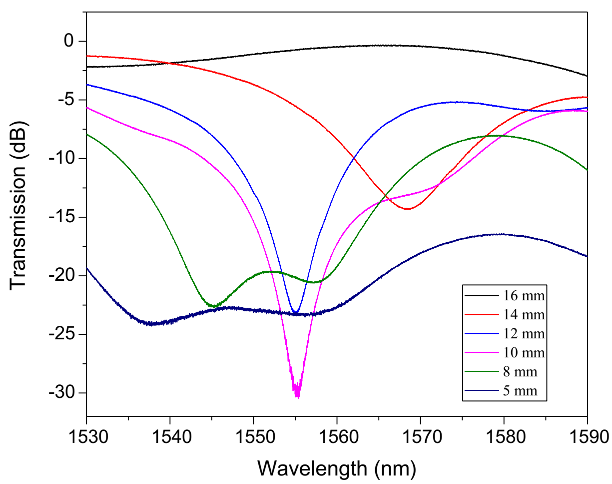


**Fig. 2.** Transmission spectrum of the balloon-shape structure with different bending diameters.

bending coating-stripped SMF. In Fig. 1, the bending diameter of the sensor structure is defined as width, and R is the bending radius. When the input light propagates to the bending section, a part of light will be free from the constrain of the core and penetrate into the cladding. After passing through the balloon-like bending section, the cladding modes will couple back to the core of the SMF. Due to the different effective RI of core mode and cladding modes, the optical path lengths are different. The interference is formed between the light of cladding modes and the remainder light in the core. The transmitted intensity of the balloon-like modal interferometer can be expressed as [19]

$$I = I_{core} + I_{clad} + 2\sqrt{I_{core}I_{clad}}\cos(\Delta\varphi) \quad (1)$$

where $I_{core}$ and $I_{clad}$ are the intensity of the core mode and cladding modes, respectively. $\Delta\varphi$ is the phase difference between core mode and cladding modes, which is expressed as

$$\Delta\varphi = \frac{2\pi L(n_{core} - n_{clad})}{\lambda} = \frac{2\pi \Delta n L}{\lambda} \quad (2)$$

Here $\lambda$ is the vacuum wavelength. L is the effective length of the balloon-like bending region. $n_{core}$ and $n_{clad}$ are the effective RI of the fundamental core mode and cladding mode, respectively. $\Delta n$ is the effective RI difference between them. When $\Delta n = (2\text{ m} + 1)\pi$, where m is an integer, the interference pattern reaches dips. And the resonant wavelength $\lambda_{dip}$ can be presented as

$$\lambda_{dip} = \frac{2\Delta n L}{2m + 1} \quad (3)$$

Therefore, by monitoring the resonant wavelength variation the balloon-like interferometer can measure physical parameters, which change the effective RI of the core mode and the cladding modes and the effective length of the balloon-like interferometer.

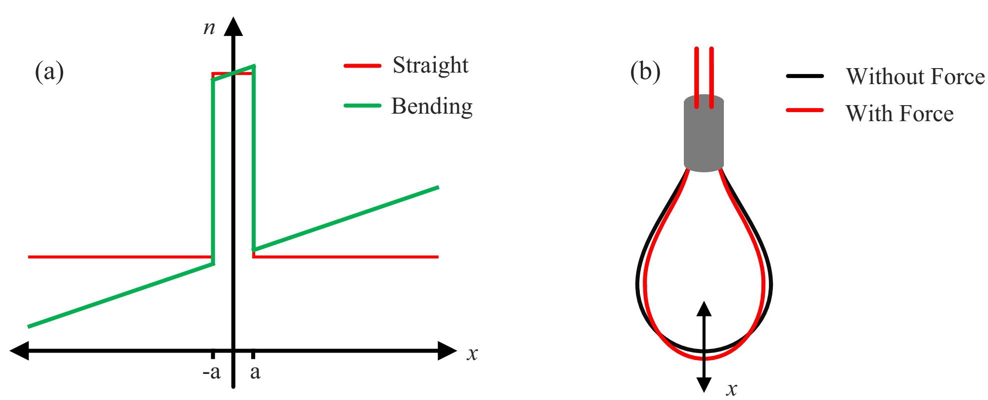


**Fig. 3.** (a) Refractive index profile of the straight/bending SMF; (b) schematic diagram of the balloon-like structure with force.

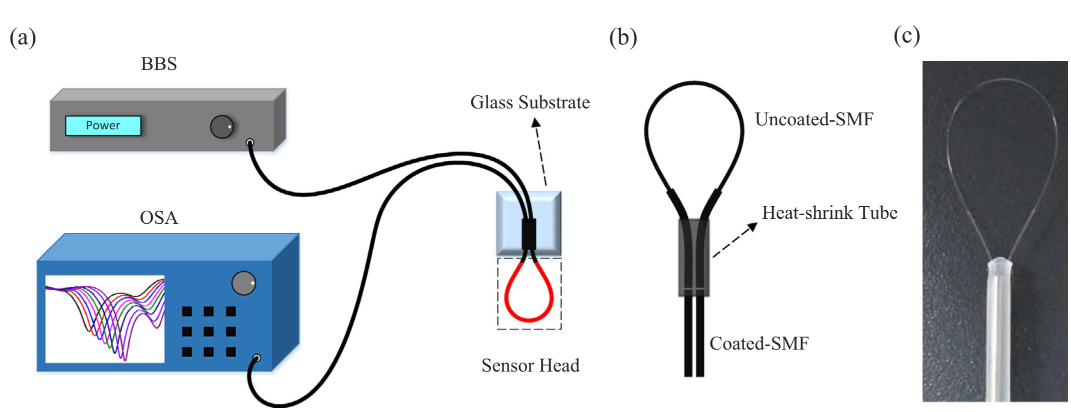


**Fig. 4.** (a) Experimental setup for force measurement; (b) structural diagram of the sensor fabricated in the experiment; (c) the picture of the fabricated sensor.