A novel all-fiber micro-displacement sensor based on long period grating and tip structure*

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A novel high sensitivity all-fiber micro-displacement sensor is proposed and experimentally demonstrated. This sensor consists of a long period fiber gating and a fiber tip, which is achieved only by a commercial arc discharge fusion splicer, and thus possesses a lower cost. The wavelength sensitivity of the proposed sensor could be up to 934 pm/μm, which is four times higher than that of the long period fiber grating (LPFG) with an air cavity structure. The intensity change sensitivity is -1.973 dB/μm.
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The micro-displacement sensor is widely required for precise movement control applied in many industrial and scientific fields, such as micro-electro-mechanical systems and atomic force microscopy (AFM). Compared with the electric-based sensors, the optical fiber based micro-displacement sensors possess lots of superior advantages, such as light weight, high sensitivity and immunity to electromagnetic interference. In recent years, the various optical fiber based micro-displacement sensors are reported, which could be described by two aspects. One is the intensity modulation based sensor, such as Mach-Zehnder interferometer (MZI) fabricated by inserting a section of photonic crystal fiber (PCF) into a single mode fiber (SMF) with two core-offset fusion splicing points with a sensitivity of 0.0024 dB/μm[1], a 2-D micro-displacement sensor formed by a segment of polarization maintaining fiber (PMF) and a movable fiber end face with sensitivities of -0.669 dB/μm along the fast axis and -0.301 dB/μm along the slow axis[2] and a micro-displacement sensor with an improved sensitivity of 1.89 dB/μm formed by a bowknot type taper and a movable fiber end face[3]. The other is the wavelength modulation based sensor. Because of the high sensitivity of the fiber to bending, many wavelength modulation based micro-displacement sensors are performed by bending fiber, such as the displacement sensors by bending SMF-multimode-fiber-SMF structure to obtain a sensitivity of 5.89 pm/μm[4], by bending micro-fiber taper modal interferometer to get a sensitivity of 102 pm/μm[5], and by bending MZI formed by cascading two core-offset joints to obtain a sensitivity of 227 pm/μm[6]. Specially, a semicircular fiber-based micro-displacement sensor has been proposed with a high sensitivity of 1.1 nm/μm[7], but this device is relatively fragile. In fact, the bent fiber based micro-displacement sensor should suffer from the repeated mechanical bending, which may shorten the running period of the device. A compact micro-displacement sensor[8] based on long period fiber grating (LPFG) and an air cavity is reported, and the sensitivity is 226 pm/μm which is almost the same as the bent MZI[6].

In this paper, we propose a micro-displacement sensor based on LPFG and a movable fiber tip. The long period grating is fabricated by the cleaving and splicing method[9,10], and the fiber tip is achieved by a commercial fusion splicer (FITEL S178A). The sensitivity at the peak wavelength is up to 934 pm/μm, which is four times higher than that of the one in Ref.[8]. The intensity change with respect to displacement is also estimated to be 1.973 dB/μm, which is much higher than that of the intensity modulation based sensors previously reported.

The proposed micro-displacement sensor is presented in Fig.1. The inset shows the schematic diagram of the LPFG with a fiber tip structure. The fiber tip points at the cleaved fiber end face following the LPFG and could freely move along the *x*, *y* and *z* directions. The distance between the end face and the LPFG is represented by *L*, and the gap length between the end face and the tip is *d*. The LPFG is based on the waist-enlarged fusion bitapers fabricated by cleaving-splicing method[9,10]. This LPFG

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possesses a broad bandwidth, indicating a large interferometer region, and a very short grating length, suggesting that the proposed sensor is a compact structure.

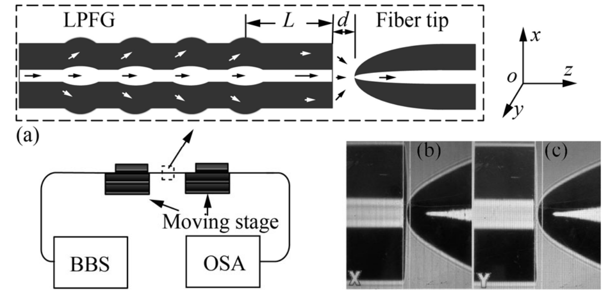


Fig.1 (a) Schematic diagram of the measurement setup; (b) The photograph of LPFG with a tip structure in *x* view; (c) The fiber tip in *y* view

During LPFG fabrication process, the feed length is set to be 60 μm, the discharge intensity is 100, the discharge time is 750 ms, the pitch is designed to be 630 μm, and the SMF in this paper is Corning SMF-28e with a core and cladding radius of 4.1 μm and 62.5 μm, respectively. The achieved LPFG based on waist-enlarged bi-tapers has an enlarged waist diameter of 142 μm, and the taper length is 200 μm.

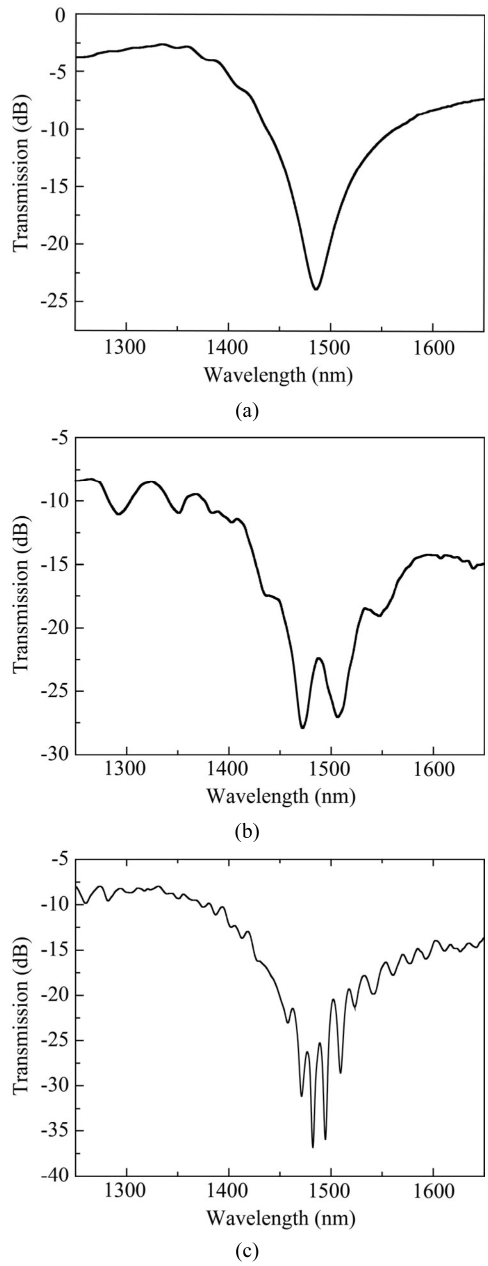
The fiber tip is fabricated as follows: Firstly, the parameters in splicer are preset to be discharge power of 100 and discharge time of 180 ms. Secondly, the SMF with a bare section is put into the splicer, and the fiber is stretched by adjusting the "ZL" and "ZR" motors with a step of 5 μm. Thirdly, the fiber is tapered by the arc discharge. And then, the fiber tip with a length of 400 μm and a tip aperture of about 3 μm is achieved via several times of discharge. Fig.1(b) and (c) show the LPFG with tip structure in *x* and *y* views with d=0.

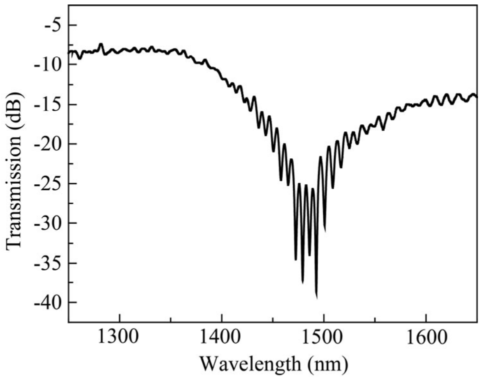
When the light propagates through the proposed sensor, the cladding modes will be excited by the LPFG, then partly coupled back to the fiber core by the fiber tip, and thus the interferometer fringe from the MZI is formed. After passing through the MZI, the phase difference ψ between the core and cladding modes could be written as $\psi=2\pi\Delta n_{\rm eff}L_{\rm eff}/\lambda$, where $\Delta n_{\rm eff}$ and $L_{\rm eff}$ are the effective index difference and the effective optical path difference between core and cladding modes, respectively, and λ is the wavelength in the interferometer region which will be the attenuation peak wavelength when $\psi=2(n+1)\pi$ is satisfied. Thus the distance between two adjacent attenuation peak wavelengths $\Delta\lambda$ (i.e., the free spectral range (FSR)) is approximately expressed as $\Delta\lambda=\lambda^2/(\Delta n_{\rm eff}L_{\rm eff})$.

The measured setup of the proposed sensor is shown in Fig.1(a). The LPFG is fixed by a fiber holder, and the fiber tip is moved by a translation stage with a step accuracy of 0.1 μm in *x* or *y* direction and 5 μm in *z* direction. The transmission spectrum of the sensor is monitored by an optical spectrum analyzer (OSA) with a broadband source (BBS) as the light source.

The transmission spectrum of the only LPFG is presented in Fig.2(a). The 10-dB bandwidth is about 126 nm, and the center wavelength is 1485.6 nm. The transmission spectra of LPFG with a fiber tip structure are obtained as shown in Fig.2(b)-(d) with different cleaved lengths between fiber end face and the LPFG when d=0. The FSR decreases as the L increases, which is governed by the relationship mentioned above, which indicates that the transmission spectrum could be controlled and designed according to the actual need.

The transmission spectrum changes with respect to displacement variation along the *x* direction are measured and recorded as shown in Fig.3 when L=3.38 cm and d=0. In Fig.3(a), only several transmission spectra are presented corresponding to the displacement of 2 μm to 10 μm with an interval of 2 μm. The attenuation peaks located at wavelength of 1542.44 nm are tracked and

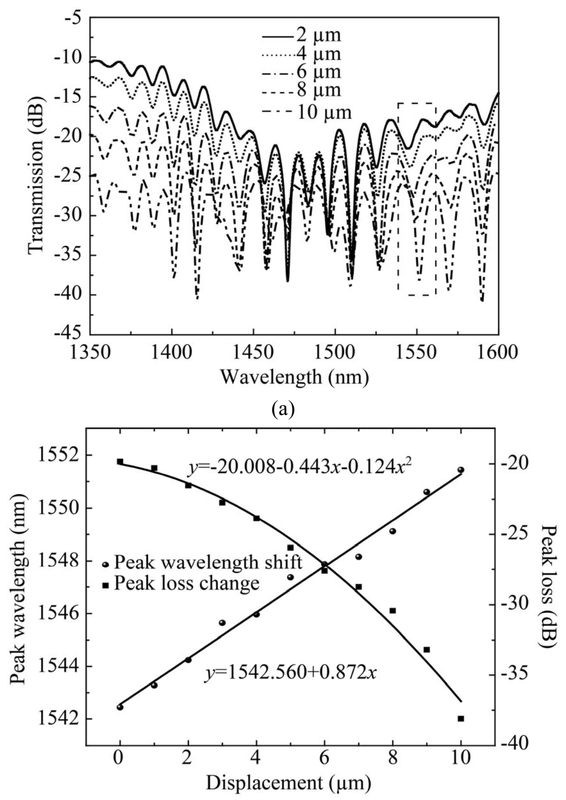




(d)

Fig.2 Transmission spectra of (a) LPFG only, and LPFG with a tip structure with (b) *L*=1.10 cm, (c) *L*=3.38 cm, and (d) *L*=6.00 cm

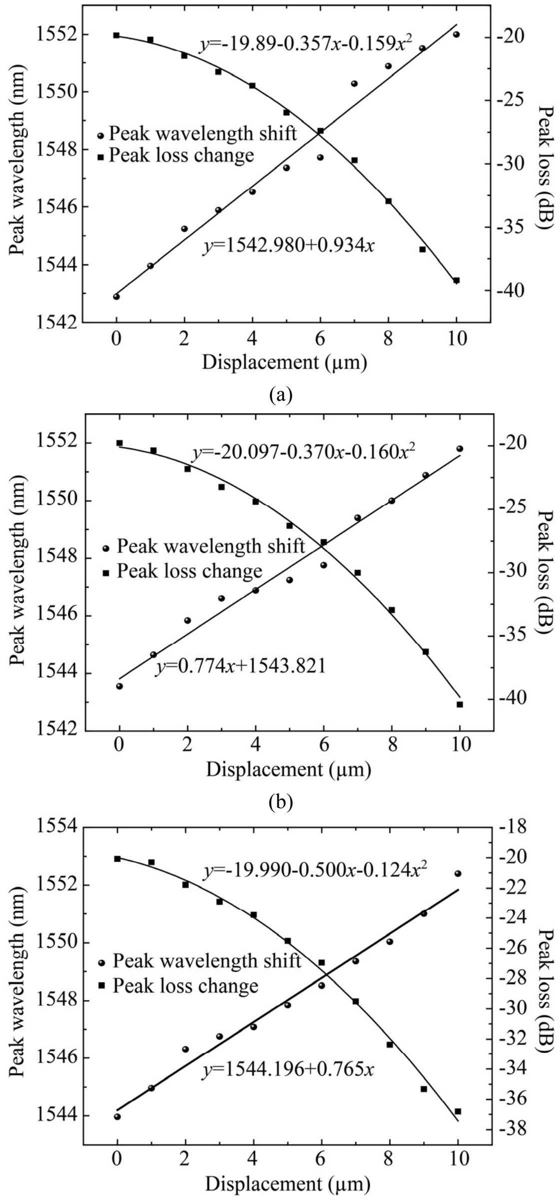
marked by the dashed frame. Both the peak wavelength shifts and peak loss changes of the tracked attenuation peaks are plotted in Fig.3(b). The linear and parabolical fittings are carried out for peak wavelength shift and peak loss changes, respectively. A slop of 872 pm/μm is obtained for the peak wavelength shift. The sensitivity of the peak loss change is also estimated to be -1.685 dB/μm by a linear fitting, which is not presented in this paper. Both the intensity change and wavelength shift possess high sensitivities.



(b)

Fig.3 (a) Transmission spectra for different displacements along the *x* direction when *L*=3.38 cm and *d*=0; (b) Peak wavelength shift and peak loss change with respect to displacement

The transmission spectrum changes with respect to the displacement are repeatedly investigated under *d*=10 μm, 20 μm and 30 μm, respectively. The peak wavelengths and peak losses are also tracked and plotted in Fig.4. The sensitivities are 934 pm/μm and -1.956 dB/μm for *d*=10 μm, 774 pm/μm and -1.973 dB/μm for *d*=20 μm, and 765 pm/μm and 1.744 dB/μm for *d*=30 μm. respectively.



(c)

Fig.4 Peak wavelength shifts and peak loss changes with respect to displacement under (a) *d*=10 μm, (b) *d*=20 μm, and (c) *d*=30 μm

From the experimental results, the sensitivities of the peak wavelength and peak loss are 765—934 pm/μm and -1.685—-1.973 dB/μm, respectively, which are 4—158 times higher than that of the bent fiber-based sensors except the semicircular fiber based one, and 1—828 times higher than that of the intensity modulation based displacement sensor reported previously. Both the intensity change and wavelength shift possess high sensitivities, indicating a potential application in the displacement sensor whatever the intensity modulation or wavelength modulation is required.

In conclusion, a novel all-fiber micro-displacement sensor based on the LPFG with a tip structure has been investigated in this paper. The displacement sensor could be modulated by intensity change or by wavelength shift whose sensitivities could be up to -1.973 dB/μm and 934 pm/μm, respectively, which suggests a highly sensitive micro-displacement sensor. Moreover, the proposed sensor also has other many advantages of easy to fabricate, cost-efficient, and so on, which indicates a great potential sensing application.

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