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High-sensitive optical force sensor based on enhanced effective index modulation

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ABSTRACT

A high-sensitive force sensor with large measurement range has been realized by inserting a microbend at the edge of a long period fiber grating (LPFG) written on single-mode fiber. The force sensitivity is improved mainly dependent on the enhanced effective index modulation. Experiment results present that the resonance dip wavelength of the proposed grating varies with applied axial force in an approximate exponential functional manner, and the grating with lower bending radius microbend has higher force sensitivity. A maximum arithmetic mean value of force response ∼−41.24 nm/N is achieved by a microbend edge-inserted grating with a bending radius 1.14 mm, which is almost two order enhanced than that of the original LPFG. In addition, the power-referenced sensitivity is almost a hundred times larger than that of the original LPFG in a certain measurement range. The sensor enables double demodulation of wavelength and energy and is a candidate for force sensors.

1. Introduction

In recent years, fiber force sensors have been widely used because of their unique advantages, such as easy fabrication, small size, fast response and immunity to electromagnetic interference [1–3]. Such a measurement can be realized by use of fiber-device-based schemes, e.g. fiber interferometers [4–7] and fiber gratings (FGs) [8–11]. Traditionally, the fiber force sensors based on interferometer principle were limited in measurement range by their narrow free spectral range. FG is a kind of optical fiber with periodic modulation of refractive index which serves as a wavelength specific dielectric filter or reflector. Many unique properties of FG, e.g. sparse and independent resonance dips, make them more suitable for sensing in larger measurement range than fiber interferometer. However, conventional FGs on single-mode fiber (SMF) show low force sensitivities, for example, only ∼1 nm/N for the fiber Bragg grating (FBG) [8] and ∼0.5 nm/N for the long period fiber grating (LPFG) [10].

Therefore, several techniques were proposed for enhancing the force sensitivity. For example, a pressure-assisted CO_2 laser beam scanning technique [12] and a reduced graphene oxide coating technique [13] were reported, both of which could slightly enhance the force sensitivity at a large measurement range. However, the processing programs were complicated and the force sensitivity-measurement range product (s × r, a parameter like gain-bandwidth product in the fiber communication) almost maintained a constant with that of the conventional FGs. Furthermore, a number of technologies,

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such as carving periodic grooves by CO_2 laser [14], etching by HF solution [15], and writing FGs on the microfibers [16,17] were proposed for increasing force sensitivities. But their s × r were not as high as expected, because the force sensitivities increased at the cost of the fiber diameter reducing, which led to low measurement range and weak structure. We proposed a temperature-independent high-sensitive force sensor based on a phase-shifted LPFG (PS-LPFG) formed by inserting a microbend in the center of LPFG [18]. The force sensitivity was greatly improved but the measurement range sharply decreased, thus the s × r was not so high. An LPFG written on the polymer microstructure fiber [19] with a higher s × r than that of FBGs on glass microfibers was demonstrated, because of the good toughness of the fiber. However, it was constrained by the expensive materials, high temperature sensitivity and difficult splicing with SMFs.

In this paper, we proposed a high sensitivity force sensor with a large measurement range by inserting a microbend at the edge of LPFG. We found that the resonance loss dips of the grating would not split after inserting the microbend at the edge, and the force sensitivity greatly improved while the measurement range did not decrease, thus the force s × r was greatly improved. We theoretically and experimentally investigated this kind of grating and its advantages for enhancing the force sensitivity. The results showed that the force sensitivity increasing mainly depends on the enhanced effective index modulation effect caused by the microbend. The force sensitivities of proposed grating increase almost two magnitude orders than that of the conventional LPFG, meanwhile the measurement was almost the same with original LPFG. The s × r was much larger than that of previous techniques. Meanwhile, the power-referenced sensitivity of this device was also very high in a certain measurement range.

2. Theoretical analysis and grating fabrication

According to the coupled-mode theory, the grating is a perturbation to the effective refractive index n_{eff} of the guided mode, described by

$$\delta n_{eff} = \bar{\delta} n_{eff} \left(1 + \upsilon \cos\left[\frac{2\pi}{\Lambda} z + \phi(z)\right]\right) \tag{1}$$

where $\bar{\delta} n_{eff}$ is the averaged effective index modulation over a grating period. υ is the fringe visibility of the index change, Λ is the nominal period, and $\phi(z)$ is the description of grating phase.

When a microbend is inserted in a LPFG, the effective refractive indexes of the core mode and mth cladding mode in the microbend region will change due to the structure deformation and arc discharge, which causes $\bar{\delta} n_{eff}$ and $\phi(z)$ changed. The will turn to be a PS-LPFG after inserting the microbend [18]. One resonance loss dip will split into two dips when a phase shift is inserted in the center of LPFG, but it will remain single when a phase shift is inserted at the edge of LPFG [20], as shown in Fig. 1. Fig. 1 shows the simulated spectral responses of PS-LPFG for different locations of the π phase shift, where L is the grating length. When the π phase shift is located at the center of the grating, the resonance loss dip splits into two, and the spectral separation between the two resonance loss dips is the widest one among different locations. When the location of the π phase shift is moved toward either end of the grating, the separation reduces. In fact, the resonance loss dip remains as single when the distance between π phase shift and the grating edge is less than $5L/40$.

High force sensitivity is obtained by measuring the separation between the two loss dips, but the measurement range is lower because the separation between the two loss dips decreases with the increasing applied axial force. Thus, in order to eliminate the limit of the force measurement range, the microbend is inserted at the edge of a LPFG in this paper, and the structured configuration is shown in Fig. 2. The direction of the CO_2 laser was along + y axial. The rectangle in Fig. 2 demonstrates the microbend region, where Λ and L are the grating period and length of the conventional LPFG, respectively, and l is the length of the microbend ($l < \Lambda$). The original LPFG is divided into three regions by the microbend, and the lengths of the three regions are l_1, l and l_2 ($l_2 < L/40$), respectively.

Fig. 3 shows the transmission spectra of LPFGs after inserting different microbends at the edge. The LPFGs were written on conventional SMF by using a high-frequency CO_2-laser system (CO_2-H30, Han's laser). The grating period and length of the LPFG were 600 μm and 4.8 cm respectively. An optical spectra analyzer (OSA YOKOGAWA, AQ6370) with a resolution of 0.02 nm and a broadband light source (HINA OS-EB-D-1250-1650-1-FC/APC) were used to record the transmission spectra. The microbend was fabricated like in ref [18], and the inset figures in Fig. 3 were optical microscope images of the microbend region. The bending direction was set along -y direction, namely the opposite direction of the CO_2 laser. After measurement, the lengths of microbends were both ~300 μm; and the bending radiuses were 2.82 mm and 1.14 mm, respectively.

From Fig. 3 we can see that all the resonance dips shift toward a longer wavelength after microbends inserted, and the lower bending radius is, the farther the resonance loss dips shift. The most resonance dip depths increase, but a few decrease because of the over coupled effect. The transmission loss was high, which needs to increase the sensitivity of the OSA. Fig. 3(b) shows the simulated light transmission characters in the 2.82 mm-microbend. Most of the light energy was couple form the core mode to the cladding mode after light pass the microbend. After calculation, the transmission loss caused by the shape of the microbend was −13.42 dB. The inserting loss of the 2.82 mm-microbend in Fig. 3 in the manuscript was −14.56 dB. It means that the inserting loss of the microbend was mainly caused by the shape of the microbend. After several tested, the microbend we manufactured was proved could return well after stretching. Therefore, the large inserting loss nearly not affect the force measurement accuracy.

In order to analyze the spectra of the proposed grating in this paper, we simulate the resonance loss dip wavelength of PS-LPFG change with the phase-shifted value when the phase shift locates at the edge of grating, as shown in Fig. 4. It can