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Fiber optic accelerometer based on grating inscribed over innermost-clad of multi-clad fiber

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ABSTRACT

A special fiber Bragg grating (FBG) that is inscribed over the core and innermost depressed-index cladding of a short multi-clad fiber (MCLF) by femtosecond laser side-illumination technique is proposed and demonstrated for orientation-dependent measurement, experimentally. Splicing the MCLF with standard single-mode fiber (SMF) provides a cladding-mode generation mechanism via core mismatch, and then "cladding FBG" in MCLF can simultaneously generate two resonances in reflection. The cladding mode shows a significant response to fiber bending due to novel refractive-index profile of MCLF and coupling in the splicing junction. And the asymmetry "cladding FBG" configuration relatively to fiber core center enables it to perform strong orientation-dependent response to the fiber bending. These two properties are well applied to measure acceleration with high resolution of 0.02 m/s^2 and orientation-dependence. The cladding and core mode also present linear wavelength-shifting with temperature variation but no intensity fluctuations. Furthermore, the accidental power perturbation or cross-sensitivity can be calibrated out by monitoring the fundamental core mode resonance.

1. Introduction

The unknown acceleration measurement is a key issue for seismic detection and health monitoring of super architectural buildings, etc. As a promising sensing technology, various fiber devices are proposed to measure acceleration. A classical suggested sensing mechanism is utilized the strain-induced wavelength changes of a fiber Bragg grating (FBG) to monitor the acceleration variation [1–4]. For those sensors, the performance is subject to packaging materials and interrogation system, and the inevitable temperature cross-sensitivity. For simplifying the assembly and interrogation system, much effort has been taken for studied intensity-based fiber device for vibration and acceleration measurement, such as the modulation based on FBG chirp induced by nonuniform-strain [5,6]. Another cladding-mode-power referenced method based on tilted fiber Bragg gratings (TFBGs) is widely adopted and immune to above downsides [7–9]. The TFBG device can excite the amount of backward-propagating cladding modes and "ghost" mode via nontrivial grating structure of which ghost shows great response to bending perturbations of the fiber with orientation-dependence. While the TFBG-based sensors usually require designed cladding-mode-coupling configurations in order to reintroduce the cladding modes back to upstream core for low-loss interrogation [10,11]. Meanwhile, the fabrication including the grating inscription and coupling-enhancement processing is complex. In our prior work, we chose a "cladding" Bragg grating as the orientation-dependent accelerometer depending on its bending-sensitivity and asymmetric structure [12,13]. However, the cladding mode in reflection in single-clad fiber presents small signal-to-noise ratio, and is also easily affected by the surrounding refractive index, since the grating is positioned in the single outside cladding of the fiber.

In this paper, we propose an orientation-dependent acceleration sensor using the grating inscribed over core and innermost cladding of a multi-clad fiber (MCLF). The special MCLF containing a photosensitive and depressed cladding is the key to achieve simultaneous grating formation in the fiber core and innermost cladding. FBG fringes are periodically formed in the fiber core and innermost cladding, resulting in a fundamental core mode resonance and a cladding mode resonance via downstream FBGs in reflection and a departure from pure cylindrical symmetry. The cladding-mode easily produces bending-induced power-loss because bending (deflecting) fiber can disturb backward cladding mode inflection via to the core-to-cladding coupling perturbation in the splicing junction and the coupling between outer and innermost cladding due to the weak power restraining capacity of innermost cladding. Based on this, the cladding-mode resonance is highly-sensitive to fiber-bending induced by the acceleration, and performed well for high-resolution acceleration measurement. Moreover, that asymmetrical configuration (because the cladding FBG is located at one side of fiber axis) enables sensor to realize obvious orientation dependence. The fundamental core mode is unaffected by fiber-bending, so it can be utilized to monitor power fluctuations and temperature perturbations.

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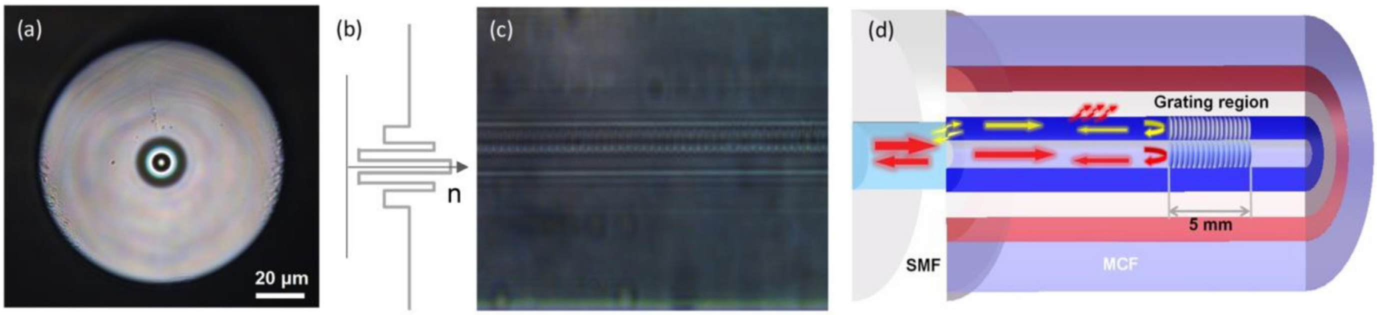

Fig. 1. (a) Photomicrograph of the MCLF cross section; (b) refractive index profile the MCLF-cross section; (c) photomicrograph of gratings inside MCLF; (d) schematic of the vector grating.

2. Fabrication and principle

The MCLF sensing structure, comprising gratings inscribed in both the core and innermost cladding, is shown schematically in Fig. 1(d). We employed a custom single mode MCLF which was designed with special index-profile (as shown in Fig. 1(b)) for suppressing cladding modes, but permit coupling to the core of light Bragg reflected from gratings written in the photosensitive innermost cladding. As shown in the cross-section of Fig. 1(a), MCLF has four cladding layers surrounding a 4 μm diameter single mode core. The diameters of the cladding layers are 9 μm, 14 μm, 22 μm and 120 μm. This specific fiber can provide a cladding waveguide effect over the innermost cladding, so that the cladding mode will propagate along the fiber cladding with low loss. This is the key to improving the signal-to-noise of cladding mode output power. The grating in the innermost cladding effectively resonantly reflects the cladding mode into the adjacent core, which then permits that Bragg reflected light to propagate into the attached SMF.

The grating fabrication was performed by a Ti: sapphire laser system, which operates at 800 nm with pulse width of 100 fs (TEM00 spatial mode, 1 kHz repetition rate), and a phase-mask technology. And before the fabrication, the MCLF used was processed with 15-day hydrogen-loading under 60 ˚C and 10 MPa. The femtosecond laser beam was specially focused on one side of the core-to-innermost-cladding interface of the MCLF (1 μm core offset) during the fabrication then FBG were inscribed synchronously in fiber core and innermost cladding due to femtosecond laser self-focusing [14]. The exposure time lasted only 5 s, and the overall FBG length was approximately 5 mm. The photomicrograph of the periodic damage of gratings region is shown in Fig. 1. (c), it can clearly be seen that the uniform grating plates are formed through core and innermost cladding. Both gratings formation mechanisms are consistent with type-II grating using femtosecond laser [15–17], in which the refractive index (RI) of grating region is modified due to a densification induced by the multiphoton ionization that causes local melting and rapid quenching in the dielectric material during femtosecond-laser exposure time. The RI modifications are interpreted by the convergent-divergent changes of the dielectric material accordingly to the optical pattern fringes. As shown in the schematic diagram of MCLF-FBG of Fig. 1.(d), The SMF-to-MCLF core mismatch at the junction acts as a bridge to couple and recouple the cladding mode between the core of upstream SMF and the innermost cladding of downstream MCLF, meanwhile, the downstream FBG in both the core and cladding resonantly reflect two peak modes (core mode and cladding mode) based on phase matching conditions. Thus, such a configuration generates two peak resonant reflections that respectively correspond to the core grating and the cladding grating (seen in Fig. 2). Due to the RI difference between core and innermost cladding, the cladding mode resonance (on the short wavelength side) is located about 1.68 nm away from core mode resonance, as shown by the label in Fig. 2. In addition, it is important to note that the reflection-index (RI) of innermost cladding is especially depressed compared to the core and outer cladding, as shown in Fig. 1.(b),

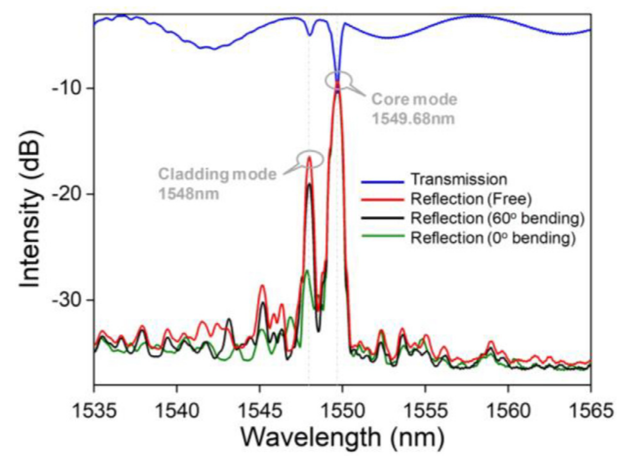

Fig. 2. Transmission and comparison of reflections versus different bending directions.

which can improve the cladding modes propagation loss in innermost cladding induced by deflecting or bending fiber.

In here, the MCLF is inserted between two SMFs, therefore, the portion of core mode of the injected light propagating in the lead-in SMF couples into innermost cladding of the MCLF and then excites multiple cladding modes via the core mismatch. The excited cladding modes and the remaining core mode continue to propagate along the MCLF until reaching the downstream FBGs (both of core-FBG and cladding-FBG), where they are reflected back at two different wavelengths determined by the effective mode refractive index and grating period [18]

$$\lambda = 2n_{eff}(m)\Lambda \tag{1}$$

where n_{eff} *(m)* is the *m*th effective RI of the MCLF ($m = 1$ represents the core mode and $m > 1$ represent cladding modes), Λ is the Bragg grating period. As a result, the wavelength separation between core resonance and its corresponding cladding resonance was 1.68 nm. Fig. 2 shows the reflection and transmission spectra of the grating, including clearly cladding mode resonance and core mode resonance.

For the proposed core-mismatch configuration, the coupling coefficient of the *i*th-order mode b_i in the MCLF can be given by [19,20]

$$b_i = \frac{\int_0^{2\pi}\int_0^{\infty} E(r,\theta,0)\Psi_i(r,\theta) r dr d\theta}{\int_0^{2\pi}\int_0^{\infty} |\Psi_i(r,\theta)|^2 r dr d\theta} \tag{2}$$

where $E(r,\theta,0)$ is the field distribution of the core mode in SMF, $\Psi_i(r,\theta)$ is the field profile of the *i*th-order mode in MCLF, consisting of core mode ($i = 1$) and cladding modes ($i > 1$). For the cladding modes, after propagation distance z within the innermost cladding of MCLF section,