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Femtosecond laser fabrication of long period fiber gratings by a transversal-scanning inscription method and the research of its orientational bending characteristics

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ABSTRACT

In order to make the whole fiber core modified, an improved point-by-point inscription method (called a transversal-scanning inscription method) is proposed to fabricate long period fiber gratings (LPFGs) by using femtosecond laser. LPFGs with an attenuation depth of 16 dB are achieved within the wavelength range of 1580–1680 nm. We have compared the bending properties of LPFGs fabricated by the line-by-line scanning inscription method and the transversal-scanning inscription method at the orthogonal directions. It is found that increasing scanning area using the transversal-scanning method can enhance the bend sensitivity obviously. The resulting curvature sensitivities are $-4.82\ \mathrm{nm/m^{-1}}$ and $-1.63\ \mathrm{nm/m^{-1}}$ at the 0° and 90° bend orientations respectively, within the curvature range from $1.75\ \mathrm{m^{-1}}$ to $3\ \mathrm{m^{-1}}$ in the experiment. The LPFG-I fabricated by the line-by-line scanning inscription method experiences red-shift, while the LPFG-II fabricated by the transversal-scanning inscription method experiences blue-shift.

1. Introduction

Curvature is an important physical parameter which should be necessarily monitored in some areas, such as smart structures, bridge engineering, aircraft health monitor and medical treatment. LPFGs present obvious advantages in the field of bending sensing [1,2], because they own many advantages of wavelength-selective operation, small size, low back-reflection and low insertion loss [3,4]. Several research works of fiber-optic bend sensors based on the fiber gratings [5], twin core fiber (TCF) [6,7], the single-mode–multi-mode–single-mode (SMS) fiber structure [8], photonic crystal fibers (PCFs) [9,10], and corrugated long period fiber grating structure [11] have been demonstrated. LPFGs have been widely investigated as wavelength-modulated curvature sensors, which give a maximum sensitivity of $14\ \mathrm{nm/m^{-1}}$ and a range of $0–5\ \mathrm{m^{-1}}$ [12]. But the LPFGs used in the bending experiments are special optical fibers (photosensitive B/Ge co-doped single-mode fiber) and need to use a 30 mm long amplitude mask with a period of 430 μm.

The application of femtosecond pulses is generally connected with a multi-photon absorption which leads to the creation of refractive index change permanently not only in the fiber core, but also in the fiber cladding [13,14]. Fabricating LPFGs by femtosecond laser usually uses the point-by-point inscription method. The manufacturing parameters of LPFGs are flexible and controllable. Because of the existence of the optical fiber dimensional deviation (concentricity and diameter) and the error of CCD-based image positioning system, the method needs a high positioning accuracy to control the alignment of the focus within the fiber core along the length of the fiber. Zhou and Li have improved the point-by-point inscription method [15,16]. The authors reduce the sensitivity to misalignment between the core and focus by scanning a rectangular part of the fiber. They successfully obtain FBGs and LPFGs, respectively. However, the processing efficiency is very low (about 55 min to process one LPFG with a length of ~40 mm) because they need to scan too many times (about 30–50 times) in a single period. In addition, Chah has used the femtosecond line-by-line inscription method to induce highly birefringent fiber Bragg gratings in the standard single-mode optical fiber [17]. The modified area is more extended by covering the whole core and controlling the line length.

In some previous works, the studies on the bending properties of LPFGs fabricated by femtosecond laser are mainly focused on the photonic crystal fiber (PCF) [2,18]. Moreover, LPFG-based bending sensors on the standard SMF-28 optical fiber have maximum bending sensitivity of $8.78\ \mathrm{nm/m^{-1}}$ with the curvature range of $0–5\ \mathrm{m^{-1}}$ in the theoretical simulation results [19]. Allsop has first reported bending characteristics of LPFGs asymmetric cladding index

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modified using an 800-nm femtosecond laser in the standard single-mode fiber (SMF-28). However, the realization of the grating is completely different and the resulting curvature sensitivities are only $-1.62\ \mathrm{nm/m^{-1}}$ and $+3.82\ \mathrm{nm/m^{-1}}$ [20].

In this paper, a new improved point-by-point inscription method is adopted to improve the inscription efficiency and reduce the sensitivity to misalignment between the core and focus. Through this method, LPFGs with the attenuation depths of 16 dB are obtained. The maximum sensitivities of wavelength-curvature are $-1.63\ \mathrm{nm/m^{-1}}$ and $-4.82\ \mathrm{nm/m^{-1}}$ at the orthogonal bend orientations. It is found that bending curvature is more sensitive when bend along the direction of light transmission and the bending sensitivity can be enhanced by increasing the modified regions significantly.

2. Experimental setup

A schematic diagram of the femtosecond laser fabrication system and detection is shown in Fig. 1. LPFGs are fabricated by using an amplified 800 nm femtosecond laser system (Spectra-Physica). The pulse width and the repletion rate are 120 fs and 1 KHz, respectively. The setup for LPFG fabrication has been described in Fig. 1. The laser beam is focused into the fiber core by a 10× microscopic objective (NA = 0.25) and the fiber samples are fixed on a five axis computer-controlled translation stage (*x* axis, *y* axis and *z* axis movement, *y* axis and *z* axis rotation) with a resolution of 5 nm. The inscription process is observed through a charged coupled device camera mounted upon a microscope. The energy employed in the inscription process is 1.8 mW measured before the microscope objective.

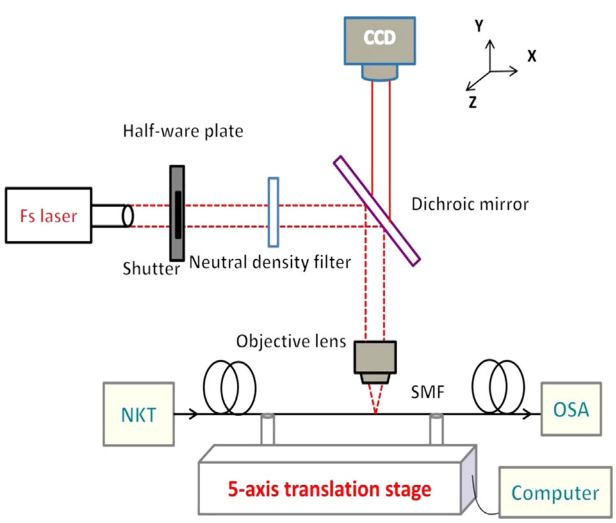

Fig. 1. Schematic diagram of the femtosecond laser fabrication system and detection.

The optical fiber is a standard communication fiber (SMF-28) with a core diameter of 8.2 μm, a cladding diameter of 125 μm and a numerical aperture of 0.14. Before the LPFGs fabrication, the polymer coating of the samples is removed and cleaned. The transmission spectrum of the fiber grating is monitored by connecting a light source (NKT, wavelength range 600–1700 nm) and an optical spectrum analyzer (OSA) (Agilent86142B, min resolution 0.06 nm, wavelength range 1100–1700 nm). In order to obtain a clear etching pattern, the cross sections of LPFGs are soaked in 1 mol% hydrofluoric (HF) aqueous solution to be etched for 2 min at room temperature. Then the transversal cross-sectional morphology of the modified regions could be observed using a scanning electron microscope (SEM).

Fig. 2 shows the beam path during the laser inscribing process with the step of 2 μm and the microscope image of the fabricated LPFG. A rectangular area scanning in the fiber core can be realized by control program. The size of the scanning area depends on the scanning times *n*, the step Δz and the inscription length in one period *L*. The values of *n* and Δz usually are assigned as 2–5 times and 1.5–3 μm in a single cycle. Those parameters are related to the objective lens and the inscription energy. The average width of the inscription region fabricated by the line-by-line scanning inscription method is about 2.5 μm at 1.8 mW energy as shown in Fig. 3(a). Therefore, the values of *n* and Δz are set up as 3 and 2 μm in the experiment, respectively. A rectangular area of $12\ \mu m \times L\ \mu m$ is formed after the laser scanning as shown in Fig. 2(b). The scanning width is 12 μm, as compared with the fiber core diameter of 8.2 μm. It makes sure that the focused beam scans over the whole fiber core in the *z*-direction, and reduces the misalignment sensitivity and scanning times in a single cycle. Those improve the inscription efficiency (only 12 min to process one LPFG of 60 periods) and alleviate the platform vibration.

3. Results and discussion

During the inscribing process, the inscription energy, the translation speed, the inscription length and the grating period are 1.8 mW, 50 μm/s, 100 μm, and 592 μm, respectively. Fig. 4 shows the transmission spectra of LPFGs fabricated by the line-by-line scanning inscription method and the transversal-scanning inscription method. Two LPFGs, labeled as LPFG-I (70 periods) and LPFG-II (60 periods, scanning times: 3 times, $\Delta z = 2\ \mu m$), are fabricated with identical periods and energy but different inscription methods, respectively. The maximum LPFG resonances of ~11 dB and ~16 dB are achieved at 1632 nm and 1634 nm, respectively. The background losses of two LPFGs are both less than 1 dB as shown in Fig. 4.

During the bending experiments, a series of microgrooves with different radius are fabricated on a metal board by computer numerical control (CNC) machine. The bending directions have been marked before holding fiber processing. The samples are put into

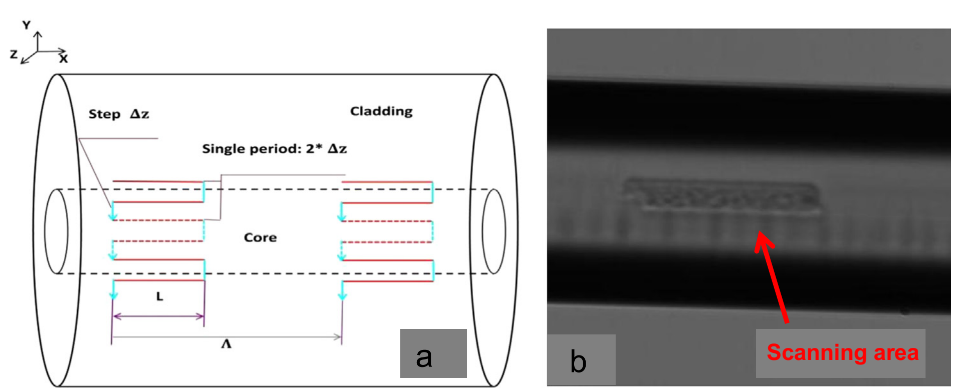

Fig. 2. (a) Scanning path during the laser inscribing process and (b) microscope image of an inscribed LPFG.