Refractive Index Sensitivity of Tilted Long Period Fibre Gratings Written in Thinned Cladding Fibre

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Abstract. We demonstrated the fabrication of tilted long period fibre gratings written in the thinned cladding fibre by CO$_2$ laser. The refractive index characteristics of the gratings with different tilted angles were investigated experimentally. The experimental results show that the grating with larger tilted angle has higher sensitivity to the surrounding refractive index changes.

1. Introduction
Long period fibre gratings (LPFGs) have attracted wide attention in the last few decades. LPFGs have been demonstrated to measure curvature [1], pressure [2], twist [3], temperature [4], strain [4][5], as well as refractive index (RI) [5] in highly corrosive and electromagnetic environments. Due to its extraordinary high sensitivity on SRI, LPFGs have been exploited as a RI sensor in biological and chemical applications. The index sensitivity of the LPFGs can be increased by various methods, such as applying an overlay of high RI [6], changing the tilt angle of LPFGs [7-8] and reducing the cladding diameter [9-11].

Compared with the conventional LPFGs, tilted LPFGs (TLPFGs) make the LP$_{01}$ core mode couple to the forward-propagating cladding modes with dissimilar azimuthal order. Recently, TLPFGs were fabricated by CO$_2$ laser with a tilt angle up to 80° [7-8]. Due to the increased asymmetry of index modulation of TLPFGs, the sensing characteristics of the gratings may change. Another method to increase the index sensitivity is reducing the fibre cladding including the hydrofluoric (HF) acid etching [9], tapering the fibre [10] and reaction-ion etching (RIE) [11].

The thinned cladding fibre (TCF) used in our experiment has a thin core and cladding diameter compared with the conventional single-mode fibre (SMF). The SMF-TCF-SMF (STCS) structure, which is formed by the TCF spliced between two conventional SMFs, has been verified to be a RI sensor [12]. In this paper, we demonstrate the fabrication of TLPFGs with different period and tilt angles in TCF the using CO$_2$ laser. It can be found that the writing efficiency of the TLPFGs can be increased for the gratings with large tilt angles. The refractive index characteristics of TLPFGs were investigated experimentally. The RI sensitivity of TCF-TLPFG is found to be higher with the increasing tilt angle of the TLPFGs.
2. Experimental results and discussion

2.1. STCS structure
Figure 1 shows the transverse RI profile of the TCF measured by a RI profiler (S14, Photon Kinetics). The TCF has a core diameter of 5.6 µm and a small cladding diameter of 80 µm. The RI of the core is 0.012 larger than that of the cladding. The TCF was spliced with two conventional SMFs. The schematic diagram of the STCS structure is shown in figure 2(a). A small part of the incident light travels into the fibre cladding of the TCF at the SMF-TCF splicing point. Then the light travels through the core and cladding of the TCF, is combined together at the TCF-SMF splicing point. An in-fibre Mach-Zehnder (M-Z) interferometer is formed in the STCS structure. The wavelength separation of the interference fringes will decrease as the TCF length increases [12]. The contrast of interference fringes is only 1 dB, so the coupling between core mode and cladding mode is weak. Figure 2 (b) shows the picture of the spliced point of SMF and TCF by use of a commercial fusion splicer (Fujikura FSM-100P+).
2.2. Gratings fabrication

We wrote the TLPFGs in the TCF by irradiating the fibre from one side with a CO$_2$ laser (CO$_2$-H10, Han’s Laser). The average power of the CO$_2$ laser and the frequency of the laser pulses were 0.6 W and 5 kHz, respectively. The laser beam was focused on the exposed fibre (with its jacket removed) to a spot with a diameter of ~30 µm, which was computer programmed to scan across the fibre point wise in the transverse direction at a controlled particular speed. Transverse scanning was advanced along the fibre with each step equal to the grating period. The transmission spectra of the LPFGs were measured with a supercontinuum broadband source (NKT Photonics) and an optical spectrum analyzer (OSA, AQ6375, YOKOGAWA). The resonance wavelength and contrast of the LPFGs were measured after every scanning cycle of CO$_2$ laser. The TLPFG were fabricated with different period $\Lambda$ (400 µm, 500 µm and 600 µm) and different tilt angle (0°, 10°, 45° and 60°), respectively. For the TLPFG with period of 400 µm, the writing energy density of the CO$_2$ laser was 4.8615, 4.5837, 3.6114 and 3.0558 J/mm$^2$ when the tilt angle was 0°, 10°, 45° and 60°, respectively. It is obvious that the writing energy density of the CO$_2$ laser is much lower than that used for the grating fabrication in conventional SMF and the writing efficiency can be improved with the increased tile angle. The transmission spectra of the TLPFGs are shown in Figure 3. It can be found that the transmission spectrum is more complex when the tilt angle is larger than 45°, because the LP$_{01}$ core mode couple to not only the LP$_{0m}$ (m=2, 3, 4...) cladding modes but also the LP$_{1n}$ (n=1, 2, 3...) cladding modes.

![Figure 3](image-url)
2.3. RI characteristics of TLPFG

We studied the RI characteristics of the TCF-TLPFG. The index range of the RI liquid used in our experiment is from 1.335 to 1.455. Among the resonance dips of each TLPFG, we selected the dip which is the most sensitive to the surrounding RI (SRI). Figure 4 shows the variations of resonance wavelength on SRI for different TCF-TLPFGs, and it can be found that all the selective resonance dips shift toward shorter wavelengths with the increase of the SRI. The selective resonance wavelength for TCF-TLPFG with period of 400 µm is 1688 nm (0°), 1729.8 nm (10°), 1606.6nm (45°) and 1721 nm (60°), respectively. When the SRI is 1.455, the correspondent wavelength shift is -62, -73, -61 and -67.2 nm, respectively. The selective resonance wavelength for TCF-TLPFG with period of 500 µm is 1724 nm (0°), 1792.8 nm (10°), 1695nm (45°) and 1731 nm (60°), respectively. When the SRI is 1.455, the correspondent wavelength shift is -133.8 , -188.4, -36.4 and -84 nm, respectively. The selective resonance wavelength for TCF-TLPFG with period of 600 µm is 1716 nm (0°), 1746 nm (10°), 1853.6nm (45°) and 1732 nm (60°), respectively. When the SRI is 1.455, the correspondent wavelength shift is -69.6, -78.8, -111.8 and -42.6 nm, respectively.

Moreover, we can calculate the RI sensitivity which is defined by $S_r = \Delta \lambda / \Delta n$, where $\Delta \lambda$ is the resonance wavelength shift and $\Delta n$ is the SRI variation. Figure 5 shows the RI sensitivity of different TCF-TLPFGs. By comparison, we can find that the TCF-TLPFGs with the same period and different tilt angles have different RI sensitivity. As shown in figure 5(a), the RI sensitivity of the TCF-TLPFG
whose period is 400 \( \mu \text{m} \) with the tilt angle of 10° is higher than that of the other gratings. When the SRI ranges from 1.435 to 1.455, the correspondent RI sensitivity of the TLPFG with the tilt angle of 0°, 10°, 45° and 60° is 1670, 2020, 1756 and 1740 nm/RIU, respectively. As shown in Figure 5(b), the RI sensitivity of the TCF-TLPFGs whose period is 500 \( \mu \text{m} \) with the tilt angle 0°, 10°, 45° and 60° is 3700, 5220, 1200 and 1520 nm/RIU, respectively, when the SRI ranges from 1.435 to 1.455. The selective resonance wavelength for TCF-TLPFG with the tilted angle of 10° is the most sensitive to the SRI. As shown in Figure 5(c), the RI sensitivity of the TCF-TLPFGs with period of 600 \( \mu \text{m} \) with the tilt angle of 45° is much higher than that of the other gratings. When the SRI ranges from 1.435 to 1.455, the correspondent RI sensitivity of the TLPFG with tilt angle of 0°, 10°, 45° and 60° is 1940, 2260, 3280 and 1156 nm/RIU, respectively. Therefore it can be found that the RI sensitivity of TLPFG can be higher with the increasing tilt angle. The RI sensitivity of the TLPFG with the same tilt angles is not the same when the grating periods are different, because the TLPFGs with different tilt angles and grating periods couple the LP\(_{01}\) core mode to different order cladding modes.

![Graph](a) Sensitivity (nm/RIU) vs. Refractive Index for different periods and tilt angles.

![Graph](b) Sensitivity (nm/RIU) vs. Refractive Index for different periods and tilt angles.

![Graph](c) Sensitivity (nm/RIU) vs. Refractive Index for different periods and tilt angles.

**Figure 5.** The refractive index sensitivity of TCF-TLPFG with different periods and tilt angles. (a) \( \Lambda = 400 \mu \text{m} \), (b) \( \Lambda = 500 \mu \text{m} \), and (c) \( \Lambda = 600 \mu \text{m} \).

### 3. Conclusion

In conclusion, we have demonstrated the fabrication of the TLPFGs with different period and tilt angles in the TCF by CO\(_2\) laser. It can be found that the writing efficiency of the TLPFGs can be
increased for the gratings with large tilt angle. And the cladding modes of LP\textsubscript{0m} and LP\textsubscript{1n} modes are excited by the LP\textsubscript{01} core mode when the tilt angle is larger than 45°. The index characteristics of the gratings were investigated experimentally. The RI sensitivity of TCF-TLPFG can be higher with the increasing tilt angle.

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4. **References**

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