October 10, 2004 / Vol. 2, No. 10 / CHINESE OPTICS LETTERS 565

Twist characteristics of the ultraviolet-written long-period fiber gratings

Zijia Zhang (张自嘉)[1], Wenkang Shi (施文康)[1], Kan Gao (高 侃)[2], and Zujie Fang (方祖捷)[2]

[1]*Department of Information Measurement Technology and Instrument, Shanghai Jiaotong University, Shanghai 200030*
[2]*Lab of Information Optics, Shanghai Institute of Optics and Fine Mechanics, China Academy of Sciences, Shanghai 201800*

Received May 9, 2004

Twist characteristics of the ultraviolet-written long period fiber gratings (UV-LPFGs) are investigated in this paper. It was found experimentally that the resonance wavelength of the UV-LPFG shifts to short side proportional to square of the torsion rate, when it is twisted in both directions of clockwise and counter-clockwise, which is different from that of LPFGs written by CO_2 lasers, but similar with that of the corrugated LPFGs. The phenomena can be explained by mechanisms of static compression in twisting and index change caused by photo-elastic effect.

OCIS codes: 060.2310, 060.2340, 060.2370.

Long period fiber gratings (LPFGs) have attracted much attentions in recent years[1−4] due to the practical and potential applications in optical communication and sensing, such as optical fiber band-rejection filters, gain equalizers in erbium-doped fiber amplifiers and fiber sensors for strain, pressure and temperature etc. LPFGs couple the forward-propagating fundamental mode in the core of single mode optical fibers to the fiber cladding modes at some discrete wavelengths, providing one or more attenuation bands in fiber transmission. The cladding modes of the fiber are easily affected by the ambient conditions, therefore LPFGs have higher sensitivity to disturb around the fiber. On the other hand, only when the sensitivity to the disturbance is fully understood and mitigated as possible, LPFG can be used as stabile devices in applications. So it is of much significance to investigate the sensitivity of LPFG to the outer disturbances, and there is quite a lot of work reported for its sensitivities to strain, temperature, refractive index, and twist[1−6].

At present, LPFGs can be fabricated by several methods, such as ultraviolet (UV) laser writing, CO_2 laser heating, and mechanical corrugation. It is recognized widely that UV writing induces some permanent photorefractivities, while CO_2 laser induces internal stress by high temperature. It is worthy to notice that there are differences in their sensitivities to the outer disturbances for the LPFGs made by different technologies. References [5,6] reported investigations in twist characteristics of the LPFGs written by CO_2 lasers. The resonance wavelength of LPFGs written by CO_2 lasers shifts to short or long side when twisted clockwise or anticlockwise. Reference [12] investigated the corrugated LPFGs, and found that the resonance wavelength shifted only to short side. References [7,8] investigated twist characteristics of the fiber Bragg grating (FBG) stuck on a cylinder, in which configuration the gratings suffered mainly from an axial strain. The pure twist characteristics of the LPFGs written by ultraviolet, which are more commonly used, have not yet been investigated.

Figure 1 illustrates the configuration of the experimental setup used for testing the twist characteristic of the UV- LPFG, which is similar to that given in Refs. [5,6]. A is a dialer, which can drive the fiber to twist and can show the twist angle. One end of the fiber was clamped in a small sheet that was inserted in the slot of the dial, and the other end of the fiber was fixed on object B. The small sheet can not only twist the LPFG when the dialer is rotated, but also ensure that the fiber moves slightly along the twist axis in order to eliminate the additional axial strain that would cause measurement error. The LPFG was between A and B. C is a 20-g mass attached to the fiber to keep the LPFG straight. D is a wheel to guide the fiber. The fiber was connected with the broadband source and optical spectrum analyzer (OSA).

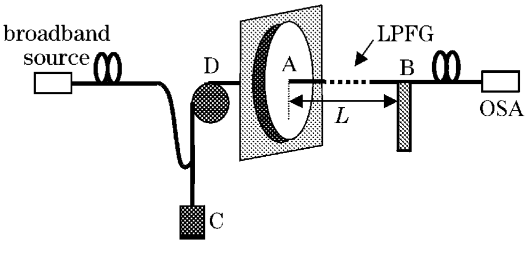

Fig. 1. Schematic diagram of the experimental setup for twisting the LPFG.

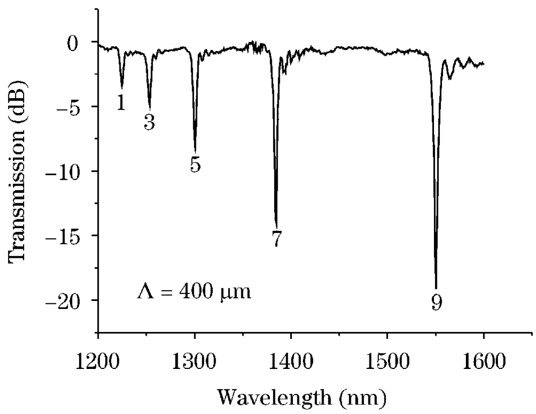

Fig. 2. The transmission spectrum of LPFG with the period 400 μm before twisted.

Two LPFGs written by UV were tested. The period and length of LPFG-1 were 400 μm and 6 cm, respectively. There were 5 loss peaks in the range between 1200 and 1600 nm, corresponding to the cladding mode order 1, 3, 5, 7, and 9, respectively, as shown in Fig. 2. The total length of the twisted fiber was 12 cm. The twist characteristic of the loss peak with a mode order 9 was tested. The resonance wavelength, peak loss, and 3-dB bandwidth of the loss peak were tested to be 1550.24 nm, -18.96 dB, and 9.2 nm, respectively.

The period and length of LPFG-2 were 450 μm and 4 cm, respectively. There were 4 loss peaks totally between wavelength 1200 and 1600 nm, corresponding to the cladding mode order 1, 3, 5, and 7. The total length of the fiber twisted was 8 cm. The loss peak with a mode order 7 was tested, which had the resonance wavelength of 1553.04 nm, peak loss of -6.5 dB, and 3-dB bandwidth of 10.8 nm.

The transmission spectra were measured for the two LPFGs at varied twist angle for both clockwise and counter-clockwise directions. The torsion rate was set to change between 0 and 52 rad/m. Between the steps of twist testing, a short period of time was taken to make the strain stabilize. Figure 3 shows the change of the resonance wavelength of the LPFGs with the torsion rate γ for the two LPFGs, showing that the resonance wavelength shifts decreasingly with the torsion rate, and approximately proportional to the square of the rate for both twist directions. It was found additionally that the peak loss amplitude and 3-dB-bandwidth did not change almost.

It is well known that the resonance loss peak position of the LPFGs is determined by the phase matching condition, expressed as

$$\lambda_{\text{p}} = (n_{\text{co}} - n_{\text{cl}}^{1\nu})\Lambda, \tag{1}$$

where n_{co} and $n_{\text{cl}}^{1\nu}$ are the effective indexes of the core mode and 1ν-th cladding modes being coupled, respectively; Λ is the period of the grating. When a LPFG is twisted, all of the three parameters will be changed.

In the case of larger torsion applied to a fiber, it is necessary to consider its compression in the axial direction. Denote the torsion rate as $\tau = \mathrm{d}\phi/\mathrm{d}z$, and the polar position as r. A displacement in the azimuth direction $\mathrm{d}l = r\tau \mathrm{d}z$ will occur, which cause a strain in the axial direction, expressed as

$$\varepsilon_z = \frac{\delta(\mathrm{d}z)}{\mathrm{d}z} \approx \frac{1}{2}r^2\tau^2. \tag{2}$$

The torsion of the whole cylinder gives a stress $f = E\tau^2R^2/4$ and an average strain $\bar{\varepsilon} = \tau^2R^2/4$, and the grating period can be compressed as $\Delta\Lambda = \tau^2R^2\Lambda/4$.

The fiber torsion also makes the refractive index increased by the photo-elastic effect. According to the general theory[10], index increment caused by torsion can be written as

$$\Delta n = n_0^3 p_{44}\tau r/2, \tag{3}$$

where p_{44} is the photo-elastic coefficient for shearing. A linearly polarized optical wave in the fiber can be decomposed as two circularly polarized waves with equal powers. The two waves have different indices in a twisted fiber: $n_+ = n_0 + \Delta n/2$ and $n_- = n_0 - \Delta n/2$. The effective index can be approximately regarded as an integration of the dielectric constant over the optical mode in the range of far away from cut-off

$$n_{\text{eff}}^2 \approx \int n^2 \left|\vec{E}\right|^2 \mathrm{d}x\mathrm{d}y \propto (1/2)\int (n_+^2 + n_-^2)\left|\vec{E}\right|^2 \mathrm{d}x\mathrm{d}y$$
$$= n_0^2 + <\Delta n^2>/4, \tag{4}$$

which gives $\Delta n_{\text{eff}} \approx <\Delta n^2>/(8n_{\text{eff}})$. Here $<\Delta n^2>$ will have different values for the core and cladding modes since they have quite different distribution. Obviously, the index increase for the cladding modes $\Delta n_{\text{eff}}^{\text{clad}}$ will be larger than that for the core mode $\Delta n_{\text{eff}}^{\text{core}}$ due to the factor r^2 in the integration. It is worthy to notice that both of the index changes are proportional to the square of torsion rate τ.

Therefore, both the grating period change and effective index change will cause the resonance wavelength decrease, and proportional to the square of torsion rate. The mechanisms presented here give a coincident explanation of the experimental results.

The twist characteristics of UV-LPFGs are different from that of LPFGs written by CO_2 lasers, which the resonance wavelength shifts linearly with the torsion rate[5,6], and to either short or long side for clockwise or counterclockwise twisting. However, the twist characteristics of UV-LPFGs are similar with that of the corrugated LPFGs[9]. The mechanisms discussed here may be play similar roles for the corrugated LPFG.

UV-LPFGs can be used as sensors for strain, temperature, ambient refractive index and so on. The experimental results and theoretical discussion presented in this

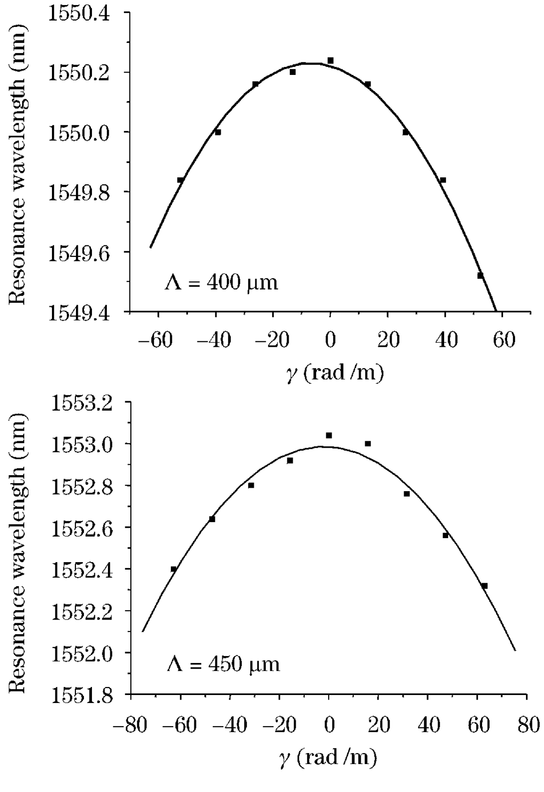

Fig. 3. Shifts of the resonance wavelength of UV-LPFG with twist rate.

paper provide a further insight of the twist characteristics of UV-LPFGs, and may be useful in related device development and device packaging.

Z. Zhang's e-mail address is zzj126@sjtu.edu.cn.

References

1. V. Bhatia and A. M. Vengsarkar, Opt. Lett. **21,** 692 (1996).
2. X. W. Shu, L. Zhang, and I. Bennion, J. Lightwave. Technol. **20,** 255 (2002).
3. H. Patrick, A. Kersey, and F. Bucholtz, J. Lightwave Technol. **16,** 1606 (1998).
4. Z. J. Zhang and W. K. Shi, Chin. Opt. Lett. **1,** 573 (2003).
5. Y. P. Wang, Y. J. Rao, A. Z. Hu, X. K. Zeng, Z. L. Ran, and T. Zhu, Acta Opt. Sin. (in Chinese) **22,** 1096 (2002).
6. Y. J. Rao, Y. P. Wang, and Z. L. Ran, J. Lightwave Technol. **21,** 1320 (2003).
7. W. G. Zhang, S. Z. Yuan, Z. W. Xu, Y. L. Huang, J. Zeng, G. Y. Kai, X. Y. Dong, and J. J. Yang, Chin. J. Lasers (in Chinese) **A29,** 808 (2002).
8. W. G. Zhang, Z. W. Xu, and X. P. Yang, Acta Opt. Sin. (in Chinese) **22,** 1070 (2002).
9. O. V. Ivanov and L. A. Wang, Appl. Opt. **42,** 2264 (2003).
10. H. Tai and R. Rogowski, Optical Fiber Technol. **8,** 162 (2002).