Effective single reflection peak from large diameter microfiber Bragg gratings

Kit Man Chung[1], Zhengyong Liu[1], Chao Lu[2], Hwa-Yaw Tam[1]
[1]Photonics Research Centre, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR China
[2]Photonics Research Centre, Department of Electronics and Information Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR China
chungkitman@gmail.com

Abstract: We experimentally demonstrated that the taper length of larger diameter microfibers can be controlled to filter out the higher order modes of LP_{0N} to cladding mode to obtain a single reflection peak.

OCIS codes: (060. 3738) Fiber Bragg gratings, photosensitivity (060.3735) Fiber Bragg gratings; (060. 2370) Fiber optics sensors; (060.2310) Fiber optics; (230. 4000) Microstructure fabrication.

1. Introduction

FBGs written in standard telecommunication optical fibers have found many applications, both in telecommunications and sensing. Recently, gratings inscribed in microfibers have been reported [1-7]. Microfiber Bragg gratings (MFBGs) were used for RI sensing [1,2] and liquid level variation sensing [7]. The doped core of a microfiber is generally too small to play a significant role in guiding light and therefore light is guided by the air-clad tapered waveguides which support multi-mode. Consequently, FBGs written in microfiber tapers exhibit multiple peaks [1] and are not desirable for demodulation and demultiplexing, particularly in sensing applications. In this paper, we present a novel technique to obtain an effectively single reflection mode from a MFBG by controlling the taper length.

2. Fabrication of the microfiber Bragg grating

The microfiber was fabricated using GPX-3400 glass-processing system by Vytran. An illustration of the tapering method of pulling conventional optical fiber into microfiber is shown in Fig. 1 (a). The microfiber can be fabricated with designed dimensions by tapering a standard single mode optical fiber with varying feeding speed while pulling the fiber. The pulling velocity was set to a constant speed of 1-mm/s with initial delay of 0.1 second for heating up the tungsten filament. The operation temperature of the furnace was >1900˚C at the input power of 29-W. The fiber was placed at the center of the furnace. During the fabrication, a minimal tension was applied to taper the fiber from a diameter of 125-µm to 30-µm. The 20-mm long taper lengths and waist length are achieved by pulling the fiber for total 60-mm distance.

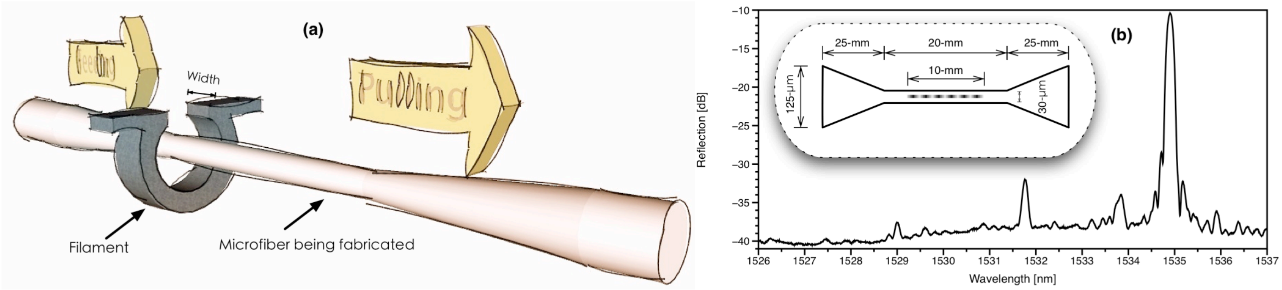

Fig. 1 (a) The illustration of pulling microfibers. (b) The transmission and reflection spectra of the MFBG. The inset shows the dimensions of the MFBG.

A microfiber with a waist diameter of 30-µm and taper and waist lengths of 25-mm and 20-mm, respectively, was fabricated for our experiment. In order to enhance the taper's photosensitivity for FBG inscription, the optical fiber was hydrogen loaded at 25˚C for over 60 hours. A bend-insensitive G.657 optical fiber from Silitec which has higher germanium concentration than SMF28 fiber, was used. Since the photosensitive core diameter (~2-µm) is very small, hydrogen diffuses out rapidly [8], so the FBG inscription has to be made right away after the optical fiber was removed from the hydrogen chamber.

Fiber Bragg grating (FBG) was inscribed at the center of the taper waist. The FBG was fabricated using standard phase mask technique with a 1061.5-nm pitch phase mask. A 248-nm pulsed KrF excimer laser with pulse energy and rate of 13-mJ and 200-Hz was used as the writing beam. The reflection spectrum of the FBG written in the taper is shown in Fig. 1(b). The length of the apodized FBG was 10-mm long. The apodization profile was achieved by scanning the writing beam at the taper waist using a Hamming profile with maximum velocity of 5-mm/s. The grating spectrum was measured using an interrogator by Micron Optic, Inc. (model SM-125) which has a 5-pm resolution. The peak wavelength and 3-dB bandwidth of the FBG are 1534.895-nm and 0.135-nm, respectively. The reflection of the FBG was slightly less than 10%. The reflections peaks coupled from other modes are significantly weaker than the main peak and have only 0.1% or -30-dB reflection. Reflections of the higher order modes are at least 20-dB smaller than the fundamental mode, making it an effectively single mode FBG.

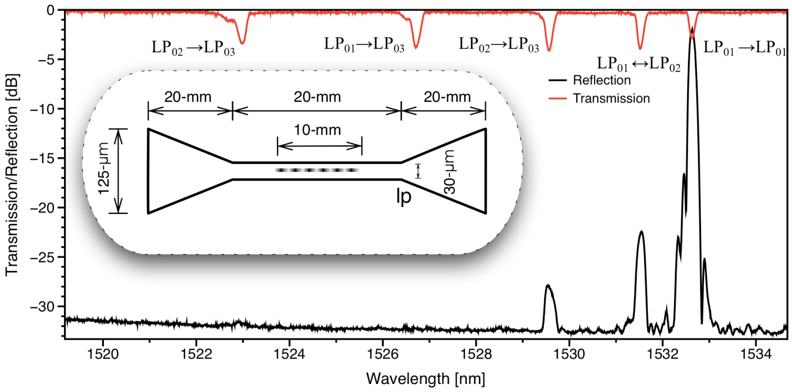

Fig. 2. The transmission and reflection spectra of an MFBG with the dimension shown in the inset.

The large diameter microfiber was guided by the air and cladding because of its small core, the diameter of which is smaller than the mode field diameter. The Δn between the air and silica is quite large (~0.445). As a result, the microfiber is a multi-mode waveguide. It is the fact that an FBG was written in the photosensitive core of the microfiber. Therefore, only LP_{0N} modes which carries a certain percentage of power guided within the core are reflected by the MFBG.

Figure 2 shows the transmission and reflection spectra of an effectively single reflective mode MFBG. In the transmission spectrum, it is obvious that there are several notches that are the combined results of the LP_{0N} modes that reflect back to the core mode and LP_{0M} modes that reflect to the cladding modes. Therefore LP_{0M} modes do not present in the reflection spectrum, but only have losses in the transmission spectrum, while LP_{0N} modes can be observed in both reflection and transmission spectra. One point worthy noting is that the maximum transmission losses of the corresponding modes are close to the power carried by the modes within the core of the microfiber.

3. Ray analysis and experiment results

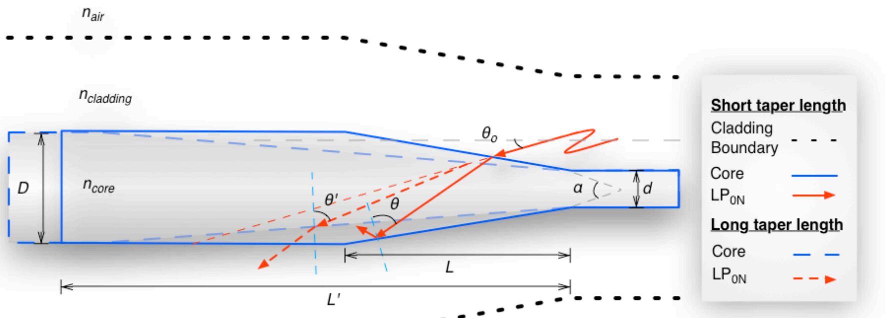

Fig. 3. Illustration of the refraction and reflection using ray analysis of a LP_{0N} mode for the short and long taper lengths.

Figure 3 illustrates the refraction and reflection using ray analysis at the taper region of the microfiber. This analysis does not provide the exact solution to the coupling but aims to give a simple qualitative approach to prove that the coupling of the LP_{0N} modes back to the LP_{01} mode depends on the slope of the taper region. The microfiber diameter and the diameter of the single mode fiber are fixed at d and D. The slope of the fiber is then determined by the taper length. The LP_{0N} mode is defined as the mode higher than the LP_{01} mode and reflected by the MFBG located at the center of the taper waist. The scale of the diagram is exaggerated for better illustration purpose. In this illustration, LP_{0N}, annotated by red arrow, can be coupled back to the core by the short taper length but can not be coupled back to the core with long taper length. In this ray analysis, there are two conditions that determine the feasibility of the mode coupling into the core. They are the two angles of θ_o and θ. θ_o is the incident angle to the core of a given LP_{0N} mode. In general, the higher the order, the larger is the angle. For LP_{01}, θ_o is closed to zero. Meanwhile, θ is the angle of the given mode reflecting (refracting) to the core (cladding). If θ satisfy the condition of total internal reflection, the LP_{0N} mode can be coupled to the core. The relationship is given by the following equations:

$$\theta = \sin^{-1}\left[\frac{n_{cladding}}{n_{core}}\sin\left(\frac{\pi}{2}-\frac{1}{2}\alpha-\theta_o\right)\right]+\alpha, \tag{1}$$

$$0 \le \theta_o < \frac{\pi}{2}-\sin^{-1}\left(\frac{n_{air}}{n_{cladding}}\right), \tag{2}$$

$$\alpha = 2\tan^{-1}\left(\frac{D-d}{2L}\right). \tag{3}$$

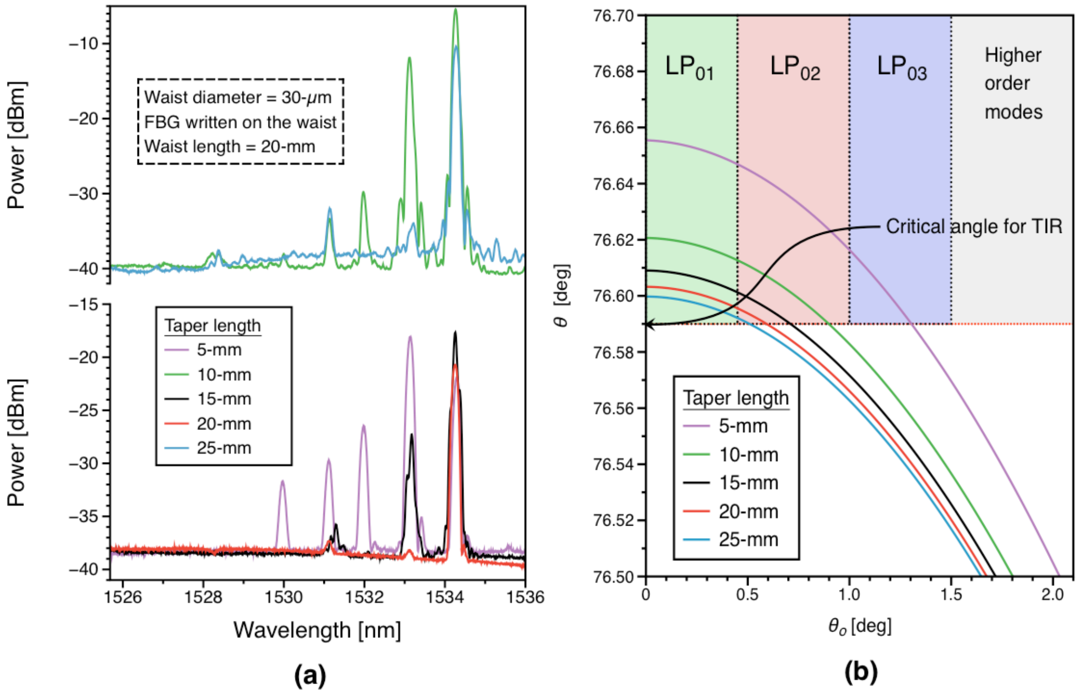

Fig. 4 (a) Experimental results of microfiber FBGs with different taper lengths. (b) Simulation result of ray analysis for different taper lengths.

The angle θ for any given θ_o can be obtained, if the values of the taper design parameters D, d and L are known and substituting them into Eq. (1) and (3). Figure 4(a) shows the reflection spectra with taper lengths of 5, 10, 15, 20 and 25-mm. The calculated result of the incident angles θ and θ_o for the corresponding taper lengths are shown in Fig 7. (b). The calculated results agree very well with the experimental results. For taper length of 20 and 25-mm, the grating was effectively single reflective mode. For taper length of 15-mm long, apart from the LP_{01}→LP_{01}, LP_{02}→LP_{01} mode was also observed. For even shorter taper lengths, LP_{02}→LP_{02} and LP_{01}→LP_{03} were also able to re-couple to the core mode. The existence conditions of LP_{02}→LP_{01}, LP_{02}→LP_{02} and LP_{02}→LP_{03} are determined by the existence of the mode forward propagating LP_{02} mode was excited to the microfiber from the taper region. For shorter taper length, the higher order modes were more likely to be excited.

In the calculated results, the areas of the LP_{01} (green), LP_{02} (pink), LP_{03} (blue) and higher order mode (gray) indicate the band of power of the corresponding mode. The width of the band the mode covers is roughly estimated by the experiment result in Fig. 4(a). The experiment shows that taper lengths ≥ 20-mm, 10~15-mm and 5-mm result effectively one, two and five reflection peaks.

4.Conclusion

A novel technique to obtain an effective single reflection peak from a MFBG is reported. The fabrication of microfiber by tapering and inscription of apodized FBG in the microfiber were experimentally demonstrated. The spectra results are in vey good agreement with the predicted results obtained by the ray analysis. This study provides a robust solution to re-couple only the fundamental mode back to the single mode fiber. The capability of designing a MFBG reflecting singe reflection peak enables multiplexing as well as ease of demodulation, is highly desirable for sensing applications in particular.

5. References

[1] Y. Zhang, B. Lin, S. C. Tjin, H. Zhang, G. Wang, P. Shum, and X. Zhang, "Refractive index sensing based on higher-order mode reflection of a microfiber Bragg grating," Opt. Express **18**, 26345–26350 (2010).
[2] Y. Ran, Y.N. Tan, L.P. Sun, S. Gao, J. Li, L. Jin, and B.O. Guan, "193nm excimer laser inscribed Bragg gratings in microfibers for refractive index sensing," Opt Express 19, 18577–18583 (2011).
[3] H. Xuan, W. Jin, and M. Zhang, "CO2 laser induced long period gratings in optical microfibers," Opt. Express **17**, 21882–21890 (2009).
[4] H. Xuan, W. Jin, and S. Liu, "Long-period gratings in wavelength-scale microfibers," Opt Lett **35**, 85–87 (2010).
[5] W. Ding and S. R. Andrews, "Modal coupling in surface-corrugated long-period-grating fiber tapers," Opt Lett **33**, 717–719 (2008).
[6] G. K. akarantzas, T. E. Dimmick, T. A. Birks, R. Le Roux, and P. S. J. Russell, "Miniature all-fiber devices based on CO2 laser microstructuring of tapered fibers," Opt Lett **26**, 1137–1139 (2001).
[7] B. Lin, S. C. Tjin, Y. Zhang, B. Dong, and J. Hao, *Microfiber Bragg Grating for Liquid-Level Variation Sensing* (SPIE, 2011), Vol. 7753, p. 77537K.
[8] M. L. V. Tse, K. M. Chung, L. Dong, B. K. Thomas, L. B. Fu, K. C. D. Cheng, C. Lu, and H. Y. Tam, "Observation of symmetrical reflection sidebands in a silica suspended-core fiber Bragg grating," Opt Express **18**, 17373–17381 (2010).