Long Period Fiber Gratings Inscribed by Periodically Tapering a Fiber

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***Abstract*— A promising technique for inscribing long period fiber gratings (LPFGs) was demonstrated by only using a commercial splicer. The commercial splicer was developed secondarily to build up a new program for periodically tapering a single mode fiber. High-quality LPFGs with a low insertion loss of ∼1 dB and a large resonant attenuation of more than −30 dB were achieved. The achieved periodic tapers exhibited an excellent reproducibility with a small error of less than ±0.3 μm. To the best of our knowledge, it is the minimum reproducibility error of tapers achieved by arc discharge technique so far. Near mode fields of three LPFG samples with different pitches were observed to investigate the mode coupling in the taper-inscribed LPFGs. In addition, the resonant wavelengths of our taper-inscribed LPFGs exhibited a blue shift first and then red shift with an increased number of grating periods, resulting from residual stress relaxation together with physical deformation.**

***Index Terms*— Long period fiber gratings, periodic tapers, optical fiber sensors, optical fiber devices.**

I. Introduction

Long period fiber gratings (LPFGs) have been increasingly used in a wide variety of fields including optical fiber sensors, gain-flattening filters, wavelength rejection filters, and tunable filters [1]–[5]. At first, LPFGs are inscribed by exposure of photosensitive fiber to UV radiation [4]. After that, several non-UV methods have been demonstrated to inscribe LPFGs on both photosensitive fibers and non-photosensitive fibers, such as the CO_2 radiation [5], [6], femtosecond laser radiation [7], ion-beam irradiation [8], periodic microbends [9], [10], and periodically tapering with heating source [11], [12]. Moreover, electric arc discharge has drawn wide attention in recent years because arc discharge technique is much simpler and does not need expensive laser equipment [13]–[17]. In the published setups, however, the electrodes and the translation stage are usually separated each other so that the alignment and stability of the system are the first challenge [18]. In addition, a mass has to be attached to one end of the employed fiber in order to keep the fiber under a constant axial tension. Such a mass seriously influences fabrication efficiency, resonant dip and insertion loss of the achieved LPFGs [19]. As well known, arc discharge often leads to tapering of the fiber. Unfortunately, the shape profile of the taper is seriously influenced by electric current, arc duration and the weight of the mass [20], resulting in a poor reproduction of the tapers and a large repeatability error of up to 5 μm [21].

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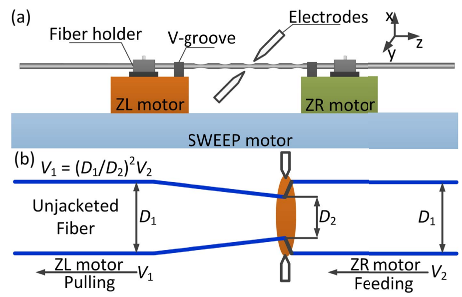

Fig. 1. Schematic diagrams for (a) inscribing a LPFG with periodic tapers by employing a commercial splicer machine and (b) inscribing desired taper.

In this letter, a promising technique was demonstrated to inscribe high-quality LPFGs by periodically tapering a standard single mode fiber (SMF) with a commercial fusion splicer. The taper profile was finely controlled by two motors with a precision of 0.01 μm, exhibiting an excellent repeatability with a small error of less than ±0.3 μm. Moreover, transmission spectra and near mode fields of the inscribed LPFGs with periodic tapers were investigated, followed by discussion on the evolution of resonance dips.

II. Fabrication Technique

In our experiment, as shown in Fig. 1, a commercial splicer machine (Fujikura, ARC master FSM-100P+) was employed to inscribe LPFGs by means of periodically tapering an optical fiber. Compared with traditional fusion splicers, besides ZL and ZR motors, this machine has a SWEEP motor which can move the fiber fixed by the left and right fiber holders along the fiber axis with a maximum moving range of +/−18 mm and a precision of 0.01 μm. This is due to the fact that the two fiber holders are placed on a translation stage that can be driven by the SWEEP motor. The FSM-100P+ commercial splicer is originally designed to splice various types of special fibers [22], such as photonic crystal fibers, polarization maintaining fiber, and large diameter fibers up to 1200 micron cladding diameter. But the FSM-100P+ does not have a ready program for tapering periodically an optical fiber. In other words, the standard functions of the FSM-100P+ splicer does not include the inscription of LPFGs. Here, we carried out, for the first time, the second development of the splicer by means of building up a new program for tapering periodically a fiber to inscribe a high-quality LPFG. Such a program can be saved in the program store of the splicer and be transplanted to any FSM-100 series splicers for LPFGs inscription. Furthermore, the program is performed easily by pushing only one button, like standard fusion program.

Our designed program includes three main steps. The first and second steps are to inscribe the down-taper section and up-taper section, respectively. Here, arc current and arc duration are manually selected to approximately 11 mA and ∼4 s, respectively. When arc discharge is down, the two ends of the fiber are synchronously stretched by the left and right fiber holders those were driven by the ZL and ZR motors, respectively. As a result, a taper is created at the discharged section of the fiber. Thirdly, the fiber is moved by a grating pitch, e.g. 650 μm, along its axis via the SWEEP motor in order to create another taper at a new location of the fiber.

The detail LPFG inscription can be carried out by the designed program as follows. When a standard SMF (Yangtze Optical Fiber and Cable Co., Ltd.) with a short unjacketed section was fixed by the left and right fiber holders, the designed program was performed repeatedly for a number of times until a desired LPFG transmission spectrum was observed. Consequently, a LPFG with periodic tapers was inscribed on the employed fiber.

In order to understand our designed program, we give the fabrication principle of the taper as shown in Fig. 1(b). When arc discharge is done to form a heat zone, the unjacketed fiber is fed from the right side of the heat zone by using the ZR motor with a constant speed V_2 (typically 0.04 μm/ms) and pulled from left side of the heat zone by using the ZL motor with a variable speed V_1. The feeding and the pulling directions are the same. But the feeding and pulling speeds are different, which control the tapering ratio. According to material conservation, the glass fed into the heat zone should be equal to the glass pulled out from the heat zone. Hence, the pulling speed is determined by the equation $V_1 = (D_1/D_2)^2 V_2$, where D_1 and D_2 are the cladding diameter of SMF and the local diameter of the taper, respectively. As a result, a desired taper is created by means of controlling the feeding speed of ZR motor and the pulling speed of the ZL motor as discussed above.

Summarizing the fabrication technique above, our proposed technique employs only a commercial splicer, i.e. FSM-100P+, and no other devices are required to inscribed LPFGs. In contrast, the traditional arc discharge techniques for inscribing LPFGs not only employ a commercial splicer but also require an additional translation stage, a mass and a computer that is used to control the translation stage [18], [21]. In traditional techniques, the fiber is clamped by the holder fixed on the top of the translation stage, instead of the holders of the splicer. Therefore, the alignment and stability are the first challenge due to the separation between the electrodes and the translation stage [18]. Furthermore, in the traditional techniques, tapers are created by the drawing force of the mass that attached to one end of the fiber. Consequently, the shape profile of the taper is seriously influenced by electric current, arc duration and the weight of the mass [20]. Compared with traditional technique, our proposed technique is conducted to build up a portable program in the commercial splicer. This technique avoids the alignment problem and the influence of the mass and has a few advantages of compactness, integration, stability, flexibility, simplify operation and high precision. Therefore, our proposed technique could be used to inscribe high- quality LPFGs with a good reproduction of tapers.

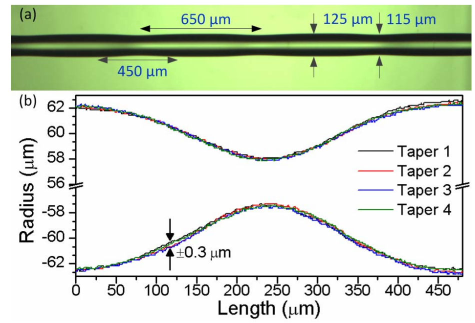

Fig. 2. (a) Image of the LPFG inscribed by periodically tapering a SMF, (b) shape profiles of four tapers.

III. Experimental Results and Discussion

Fig. 2(a) illustrates microscope image of the LPFG inscribed by periodically tapering the SMF. The measured grating pitch of the LPFG is about 650 μm. Each taper has a waist diameter of about 115 μm and a length of about 450 μm. To evaluate the reproducibility of the tapers, we randomly chose four tapers in the LPFG and measured their shape profiles by use of a digital graph processing technique [23], as illustrated in Fig. 2(b). It can be found from Fig. 2(b) that the radius error at any axis position of each taper profile, i.e. the reproducibility error of tapers, is less than ±0.3 μm, which is one order of magnitude smaller than the reproducibility error (i.e. 5 μm) of the taper produced by attaching a mass to the fiber end [21]. To the best of our knowledge, it is the minimum reproducibility error of the tapers achieved by arc discharge technique so far [21], [22], [24]. Such an excellent reproducibility attributes to our designed program, which can synchronously control the arc discharge and translation devices with a high precision. Firstly, electrodes, V-grooves and translation stages are integrated in the splicer, avoiding the alignment problem between each other. Wind protector of the splicer can provide a relatively stable environmental during tapering the fiber. Secondly, a pre-alignment between V-grooves ensures that the fiber remains in the same position relative to the electrodes. The last but most important, the shape profile of the taper is finely controlled by the translation stages with a precision of 0.01 μm in the Z direction.

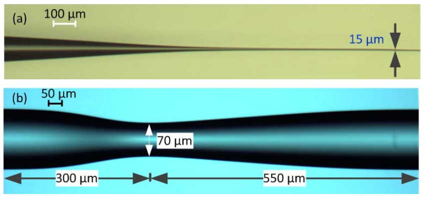

Fig. 3. Microscope images of the created tapers with (a) a symmetric shape profile (small waist diameter of 15 μm) and (b) an asymmetric shape profile (large waist diameter of 70 μm).

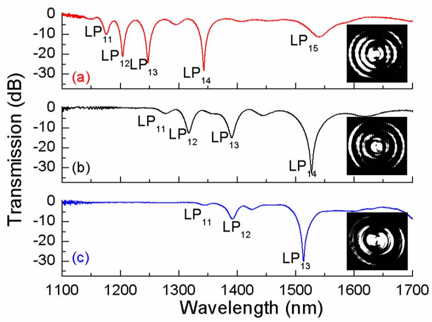

Fig. 4. Transmission spectra of three taper-inscribed LPFGs (a) LPFG_1 with a pitch of 550 μm, (b) LPFG_2 with a pitch 650 μm, and (c) LPFG_3 with a pitch of 730 μm. Inserts: near mode fields corresponding to the three LPFGs' resonant wavelength of 1538.32, 1525.06 and 1513.43 nm, respectively.

Moreover, we can control the tapering process of fiber to achieve a desired taper by means of modifying our designed program. According to the fabrication principle of the taper as discussion in the last section, we can modify the designed program to control the feeding speed of ZR motor and the pulling speed of the ZL motor. Therefore, we can create tapers with desired diameter and shape profile. In order to evaluate this capability, we created two desired taper samples. The first sample has a symmetric shape profile with a down-taper transition length of 2 mm, a uniform waist length of 1 mm and an up-taper transition length of 2 mm. The local diameter of the taper can be gradually reduced to 15 μm in the waist region. Due to the field range limitation of our microscope, the microscope image of only a section of taper is illustrated in Fig. 3(a). The second sample, as shown in Fig. 3(b), has a down-taper transition length of 300 μm, an up-taper transition length of 550 μm and a waist diameter of 70 μm, exhibiting an asymmetric shape profile along the fiber axis. In a word, such flexible and high-precision tapering process can achieve various kinds of tapers which would find wide applications in mode filtering [24], laser beam shaping [25] and optical fiber sensing [26].

We inscribed three LPFG samples, i.e. LPFG_1, LPFG_2, and LPFG_3, with different grating pitches of 550, 650, and 730 μm, respectively, in order to investigate mode coupling in the taper-inscribed gratings. A supercontinuum light source (NKT Phonics, Superk Compact) and an optical spectral analyzer (YOKOGAWA, AQ6370C) were employed to monitor the transmission spectrum of the inscribed LPFG during grating inscription. As shown in Fig. 4, within the wavelength range from 1100 to 1700 nm, five, four and three resonant dips were observed in the transmission spectrum of LPFG_1, LPFG_2 and LPFG_3, respectively. And each LPFG has a strong coupling attenuation of up to −30 dB at the resonant wavelength and a low insertion loss of about 1 dB.

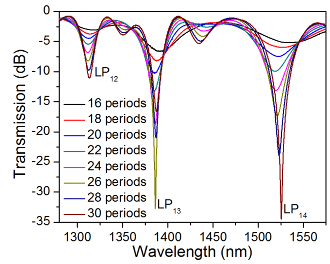

Fig. 5. Transmission spectrum evolution of LPFG_2 with a pitch of 650 μm while the number of grating period increases from 16 to 30.

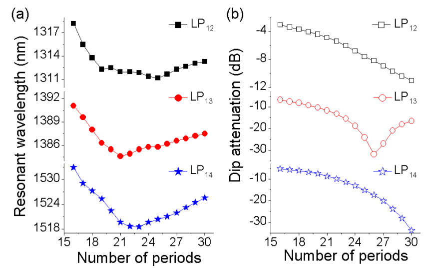

Fig. 6. Evolutions of (a) resonant wavelength and (b) the corresponding dip attenuations at each resonant dip, i.e. LP_{12}, LP_{13}, and LP_{14}, of LPFG_2 while the number of grating periods increases from 16 to 30.

A tunable laser (EXFO, FLS-2600B) with a tunable wavelength range from 1510 to 1610 nm was connected to one end of a LPFG sample as a single wavelength light source. Another end of the LPFG sample with periodic tapers was cleaved at the last grating period, i.e. taper, to observe near mode field by use of a near-infrared camera. Inserts in Fig. 4 illustrate the observed near mode fields at the longer resonant wavelength, i.e. 1538.32, 1525.06, and 1513.43 nm, of LPFG_1, LPFG_2, and LPFG_3, respectively. Intensity distribution of near mode field pattern illustrated in Fig. 4 indicts that the observed resonant dips of LPFG_1, LPFG_2, and LPFG_3 correspond to the coupling from the fundamental mode to the LP_{15}, LP_{14}, and LP_{13} cladding modes, respectively. Thus, the cladding modes corresponding to other resonant dips of each LPFG sample are determined sequentially, as shown in Fig. 4.

Transmission spectrum evolution of LPFG_2 with an increased number of grating periods, i.e. tapers, is illustrated in Fig. 5, in which transmission spectra of LPFG_2 with more than 16 tapers are illustrated because dip attenuation in the grating spectrum is too small to be measured before the 16$^{\text{th}}$ taper is created. Evolutions of resonant wavelength and the corresponding dip attenuation at each resonant dip, i.e. LP_{12}, LP_{13}, and LP_{14}, with the increased number of grating periods are illustrated in Fig. 6. It is interesting to be found from Figs. 5 and 6(b) that dip attenuations corresponding to the LP_{12} and LP_{14} cladding modes gradually grow with the increased number of grating periods whereas the value corresponding to the LP_{13} cladding mode grows first and then reduces after the 26$^{\text{th}}$ taper is created due to the over-coupling from the LP_{13} cladding mode to the fundamental mode.

As shown in Figs. 5 and 6(a), resonant wavelengths of LPFG_2 exhibit a blue shift first and then a red shift with an increased number of grating periods. It is the reason for this that refractive index modulation mechanisms in the taper-inscribed LPFGs include two facts: residual stress relaxation and physical deformation. Residual stress in the arc-discharge area of the fiber core is relaxed due to the fast local heating-cooling process, which results in a decrease of effective refractive index in the fiber core [5], [27]. According to phase matching condition [4], the decrease in effective refractive index of the fundamental mode results in a blue shift of resonant wavelength. Therefore, the resonant wavelength shifts toward the shorter wavelength with the increased number of grating periods, as shown in Fig. 6(a). On the other hand, as shown in Fig. 2, the fiber diameter decrease at the taper region is up to $\sim$8%. Therefore, the physical-deformation-induced perturbation in effective refractive index of the fiber has to be considered. In case a large number of tapers are created, the equivalent fiber diameter in the whole grating region could be considered to be decreased due to the cumulative effect of the local diameter decrease at each taper region, which results in an increase in effective index difference between the fundamental mode and the cladding modes, as reported in Fig. 3(b) in reference [28]. Therefore, the resonant wavelength shifts towards the longer wavelength, rather than the short wavelength, after the number of the created tapers increase to a certain value [4]. For example, as shown in Fig. 6(a), the resonant wavelength corresponding to the LP_{14} cladding mode shifts towards the longer wavelength after the 23rd taper is created.

IV. Conclusion

In conclusion, an improvement technique was demonstrated to inscribe high-quality LPFGs with periodic tapers by use of only a commercial splicer. No other devices are required to inscribe a LPFG with a dip attenuation of up to -30 dB and a low insertion loss of about 1 dB. Such a technique has a few advantages of compactness, integration, stability, flexibility, simplify operation and high precision. The shape profile of the periodic tapers was finely controlled by two motors with a high precision of 0.01 μm, avoiding the influence of the attached mass in the traditional method. The periodic tapers exhibited an excellent reproducibility with a small error of less than $\pm$0.3 μm. Refractive index modulation mechanisms in the taper-inscribed LPFGs include two facts: residual stress relaxation and physical deformation.

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