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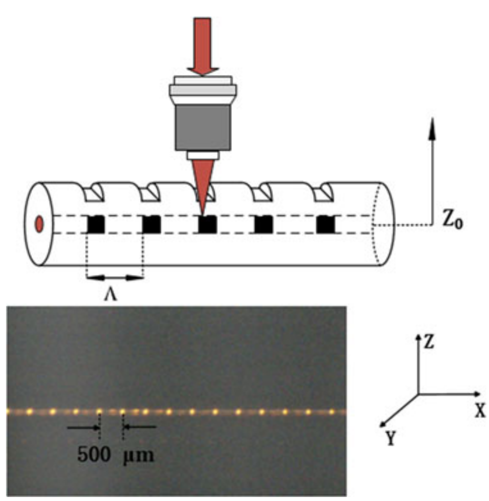

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Long Period Fiber Grating Fabrication by Two-Step Infrared Femtosecond Fiber Laser Exposure

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Abstract: We develop a two-step infrared (IR) femtosecond fiber laser exposure technique to flexibly fabricate long period fiber gratings (LPFGs) with a high peak band-rejection efficiency of 35.4 dB, insertion loss of 4.36 dB, and 3 dB bandwidth of 13 nm. First, we etch periodic corrugations via IR femtosecond laser in the cladding of standard single mode fiber, leading to efficient laser beam-focusing on the cladding as well as stress-optic refractive index (RI) modulation. Then, we carry out femtosecond fiber laser irradiation under the corrugations, to further introduce RI modulation within fiber core. We experimentally investigate the impacts of fabrication parameters including laser focus location and individual exposure time with respect to the transmission spectra of LPFGs. The fabricated LPFG has a temperature coefficient of 114 pm/°C and a polarization dependent loss of 1.78 dB, which may find useful applications in sensors.

Index Terms: Microstructure fabrication, fiber optics and optical communication, gratings, ultrafast process in fiber.

1. Introduction

Long period fiber gratings (LPFGs) show a very wide range of practical applications such as optical communications, optical sensors, and photonic instruments. Traditional LPFGs are fabricated by using UV laser beam to introduce periodic refractive index (RI) changes within the photosensitive fiber core [1]. This RI change is attributed to Ge-doping and its photo-bleachable UV absorption band. In order to facilitate UV grating inscription process, especially for low Ge-doped standard single mode fibers (SSMFs), extra processes need to be implemented such as hydrogen loading at a high pressure [2] or photosensitive ions doping [3], to improve photo-sensitivity of SSMF. After those additional processes, typical LPFGs fabricated by UV exposure show a peak band rejection efficiency of ∼30 dB and an insertion loss of 0.2 dB [3]. However, those processes are suffered from several shortcomings such as time-consuming hydrogen loading, indispensable use of phase mask, and relatively high UV laser maintenance cost. Furthermore, since the RI changes relax even at a low temperature, UV-written LPFGs have an inherent aging-stability problem [4]. Alternative LPFG fabrication techniques are developed by the localized thermal heating using focused CO_2 laser

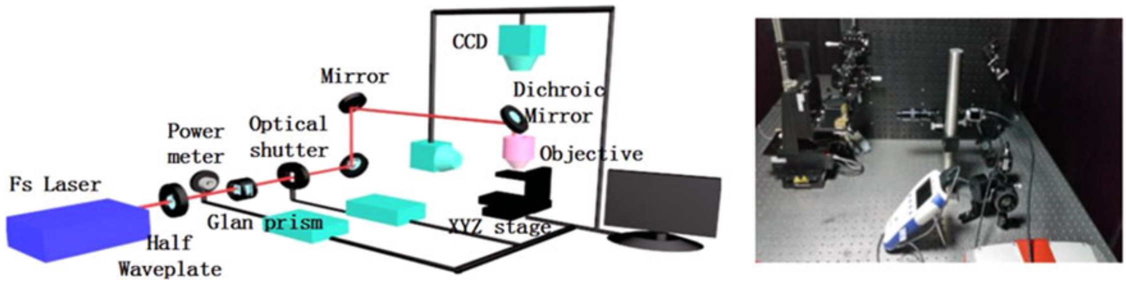

Fig. 1. Experimental setup for LPFG fabrication, the red tube represent pulse laser, while the black tube represent electric connection, and all the holders are not shown.

irradiation [5], focused ion-beam irradiation [6], and electric arc discharge [7]. These processes can obviate hydrogen loading process and show a high thermal stability of LPFGs up to ∼1000 °C [8], [9] even for non-photosensitive fibers, which has a high peak rejection efficiency of 47 dB [10], [11]. However, these thermal processes are fallen behind the conventional UV irradiation method in terms of the output uniformity and consistency during LPFG fabrication. Recently, focused infrared (IR) femtosecond laser pulse irradiation has been proposed to induce a permanent RI change in the SSMFs [12]–[14]. The extremely small focused IR femtosecond laser size and nonlinear multi-photon absorption mechanism offer a great chance to realize three dimensional fabrication in optical fibers, indicating of great application prospect in optical devices. However, when the first LPFG is made by IR femtosecond laser, this method is suffered low band rejection efficiency and high insertion loss [12]. With the advancement of precise position technique for femtosecond laser beam, the LPFG insertion loss can be reduced to 0.26 dB, but the peak rejection efficiency is still below 25 dB [12], [15]. In order to achieve high band rejection efficiency, large RI modulation must occur, and the increment of RI modulation is in proportional to laser irradiation power for traditional femtosecond fabrication method. Due to the cylindrical shape and disparity in the laser processing threshold for cladding and core, the laser irradiated through the cladding is refocused, within the cladding and only a fraction of power can reach the core [16]. The further increase of power would in turn bring large insertion loss [12]. Thus, low band rejection efficiency seems to become an inherent problem of LPFGs fabricated by IR femtosecond laser. Periodic corrugations at the cladding are also used to fabricate LPFGs with a band rejection efficiency of ∼17 dB, which particularly show a high potentials in mechanical sensor applications [17], [18]. However, this technique has not been fully investigated in conjunction with laser radiation techniques, despite wide spread of femtosecond laser processing of materials including optical fibers [19]–[21].

In this submission, we combine two methods, corrugation and IR femtosecond laser inscription in order to solve the inherent problems in prior femtosecond laser processing for LPFGs. Using a single IR femtosecond laser, we pursue both laser corrugation and grating inscription, for the first time. By laser corrugation technique we can provide periodic flat surface at the cladding, which can significantly reduce problematic lens effects in the grating writing process. More precise laser beam position and irradiation power management across the fiber are realized. Thus, a LPFG with 35.4 dB band rejection efficiency are fabricated. To the best of our knowledge, it is the highest band rejection efficiency achieved by IR femtosecond laser fabrication technique.

2. Experimental Setup and Results

The experimental setup of LPFG fabrication is schematically shown in Fig. 1. We use a ytterbium doped fiber laser (Satsuma, Amplitude System) at $\lambda = 1030$ nm, which has the pulse width of 270 fs, the repetition rate of 250 kHz. The average output power is ∼5.4 W, which can be continuously adjusted by a combination of half wave-plate and Glan prism. Optical shutter and its controller (SH05, SC10Thorlabs) are used to vary the laser irradiation time. The laser beam is focused on the SSMF to be fabricated by a 20X objective (NA = 0.40). In order to monitor the fabrication process,

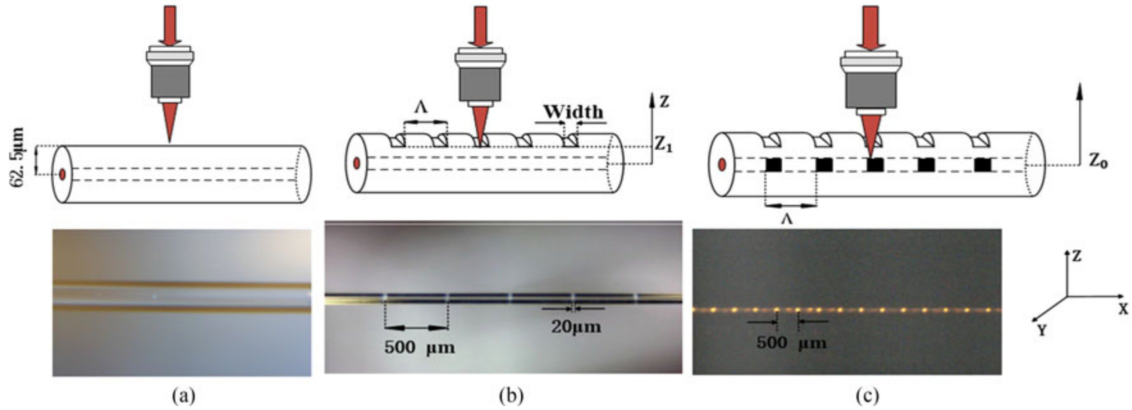

Fig. 2. Schematic diagram of two step LPFGs fabrication technique. (a) SSMF to be fabricated, (b) the first step with corrugation times N = 20. (c) the light propagation after two-step fabrication.

two CCD camera are used. One is on the top of dichroic mirror, while the other one is set at the XY plane, as shown in Fig. 1. The SSMF is placed on the three-dimension motion stage, whose motion ranges at X, Y, Z direction are 100 mm, 100 mm, and 50 mm, respectively. The motion resolution is 50 nm, and the maximum speed 300 mm/s. Light from the amplitude spontaneous emission (ASE) resource is launched into the SSMF to be fabricated, and its transmission spectrum is monitored by optical spectrum analyzer (AQ6370C,Yokogawa) with a resolution of 0.02 nm.

2.1. Experimental Schematic Diagram

Schematic diagram of two-step LPFG fabrication technique is illustrated in Fig. 2. The first step to fabricate corrugations on the fiber cladding is shown in Fig. 2(b). Firstly, after the removal of plastic coating, the SSMF is put into the fiber clamp, with a caution to avoid weight-induced macro-bending. We use CCD camera to identify the focused beam and we set its location at Z_1, which is far from the fiber core, $Z = Z_0 = 0$ μm. Then, we move the fiber stage in the transverse direction to make corrugations with the width of ~20 μm on the fiber cladding. This is repeated along the fiber axial direction with the designated LPFG period (Λ). In the second step, we move the motion stage to make laser beam focus back to $Z_0 = 0$ μm, and move the stage along the fiber axial direction to make laser scan the fiber core. In order to evaluate the effect of individual steps, we start to fabricate LPFG by making corrugations and inscribing grating, respectively. Note that laser corrugation process can provide a band rejection characteristics of LPFGs without inducing RI changes in the core [17].

2.2 Transmission Spectral Results

Transmission spectra of fabricated corrugations are summarized in Fig. 3 for various laser focal position Z_1. Here the corrugations have a period of 500 μm, extending to the processed length of 20 mm. Average laser power is 788 mw, the scanning velocity 0.3 mm/s and corrugation repetition N = 20 times. We find that, when the laser position is close to the cladding (a larger Z_1), the laser power is not sufficiently high to induce nonlinear optic RI modulation in the fiber core. With the reduction of Z_1 location, the band rejection efficiency gradually becomes deeper, and the insertion loss also increases accordingly. At $Z_1 = 0$ μm, the band rejection efficiency reaches 20 dB but with high insertion loss around 10 dB, which is less interested for practical applications.

We then investigate impacts of the scanning times M in the second step, which is the number of transverse motion of the laser beam at a fixed position Z_1. Fig. 4 shows the transmission spectra for various M. Here, $Z_1 = 0$ means the center position of the fiber core. The average laser power and laser scanning velocity are 400 mw and 0.3 mm/s, respectively. When the scanning times of M = 1

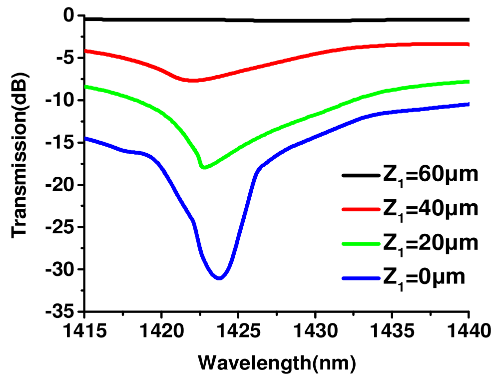

Fig. 3. Transmission spectra of laser corrugations for various Z1 locations.

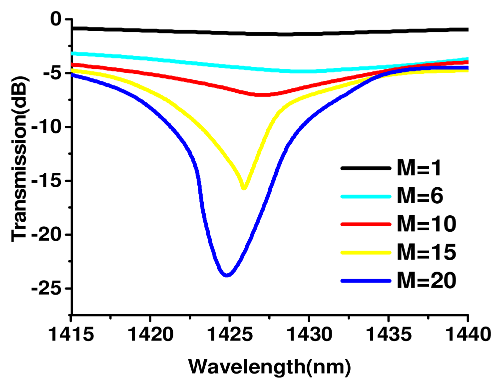

Fig. 4. Transmission spectra of grating inscription for various scanning times M.

is set, there exists less power focused on the fiber core. Thus, the transmission spectrum keeps unchanged. With the increment of scanning time M, the band rejection efficiency appears with the growing insertion loss. Under the condition of M = 20, the band rejection efficiency reaches −24 dB, while the insertion loss does not show much difference in comparison with M = 15.

In the above experiment, we investigate two kinds of LPFGs by making corrugations at fiber cladding and inscribing grating by IR femtosecond laser irradiation at the fiber core, separately. The transmission spectral show both steps can generate grating effect, but with different band rejection efficiency and insertion loss. Compared with the second irradiation step, the first corrugation step is more destructive, and consequently introduce more RI change but also introduce high insertion loss. As for the second irradiation step, the results of Fig. 4 are consistent with prior point-by-point fabrication technique [13] in terms of the peak band rejection efficiency. It is noted that we can provide a highly precise control of both corrugation parameters on the fiber cladding, and the amount of laser induced RI change in the core by optimizing the IR femtosecond laser processing.

In the following experiment, we combine two steps in order to take the individual advantages. In the first step, we set the location Z_1 to 40 μm, scanning velocity 3 mm/s, laser power 788 mw, corrugation times N = 20, and with a designated period of 500 μm. As a result, we obtain a periodically distributed corrugations, without too much insertion loss. Then, in the second step, we move the fiber stage to make laser focus locate at $Z_0 = 0$ μm, and reduce the laser power and scanning speed to 400 mw and 0.3 mm/s, respectively. For every grating period, we set the scanning times M = 20. Fig. 5 shows the transmission spectra with the fabrication length. With the increment of fabrication length, the resonate wavelength shifts towards the shorter wavelength region, and the band rejection efficiency is increased. In particular, the spectrum shape become sharper. The peak attenuation can reach −35.4 dB at 1425.80 nm under the condition of 25 mm

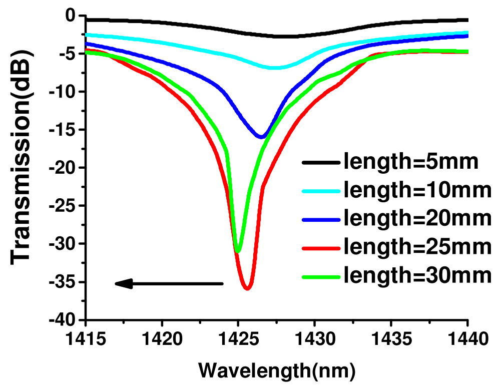

Fig. 5. Transmission spectral of two-step exposure for various LPFG grating length.

length. When the fabrication length continuously increases, the peak attenuation is reduced, due to the occurrence of over-coupling [22].

According to mode coupling theory, for a uniform LPFG, the optimal coupling at the resonance wavelength is obtained under the condition of $\kappa L = \pi/2$, where κ is the coupling coefficient, and L is the grating length [17]. When $\kappa L < \pi/2$ is satisfied, the light is not fully coupled into cladding mode, while for $\kappa L > \pi/2$, light will couple back to core mode, after coupling with cladding mode. Therefore, precise manipulation of coupling condition has to be satisfied. The variation of κL is mainly due to the variation of κ, which is proportional to the RI modulation, while a change of L has a relatively small impact [11]. Traditional IR femtosecond laser fabrication technique need to focus the laser beam on the SSMF core, in order to generate substantial RI modulation. High band rejection efficiency of transmission spectrum is expected with the increase of the laser irradiation time and power, which may bring severe insertion loss of LPFG. Using our proposed two-step fabrication, as shown in Fig. 2, we not only introduce the RI modulation by traditional depositing energy on the fiber core, but also inscribe the asymmetric corrugations to enhance the RI modulation. An axially periodic etched structures at one side of SSMF will induce lateral bends in corrugation section of the fiber [23], which will bring RI modulation due to the photo-elastic effect. As a result, a LPFG with band rejection efficiency of -35.4 dB and low insertion loss can be secured. Finally, we characterize primary sensing parameters for the fabricated LPFG. A 5g mass is placed at one side of SSMF to relax the external stress.

2.3 Characterization Results

We conduct the temperature sensing experiment with the help of a heating oven. The temperature is increased from 20 °C to 100 °C, with a step of 5 °C. The transmission spectra are recorded at each step after the temperature is stabilized for 20 minutes. Fig. 6 illustrates the resonant wavelength shift with the temperature. It is clear that when the temperature increases, the resonant wavelength is shifted toward the longer wavelength. The corresponding temperature coefficient is around 114 pm/°C. Referred from Fig. 5, we can see that there may occur mode over-coupling during our fabrication process at room temperature. Consequently, the enhanced band rejection efficiency induced by such corrugation structure will be degraded with a typical coefficient of about 0.25 dB/°C [24]. Therefore, the temperature operating range no more than 100 °C is recommended for the LPFG fabricated by our two-step method.

Since we use femtosecond laser exposure, there would be an asymmetric index profile on the cross section of LPFG. Hence, an obvious polarization dependent loss (PDL) exists in the LPFG, as shown in Fig. 7. The fabricated LPFG presents a PDL of about 1.78 dB. The relatively low PDL can mainly be attributed to the following reasons. Although we fabricate asymmetric corrugations on the fiber cladding to increase refractive index modulation, it has tinny influence on the asymmetry of the cross section index profile, because the corrugation area is confined within the outer area

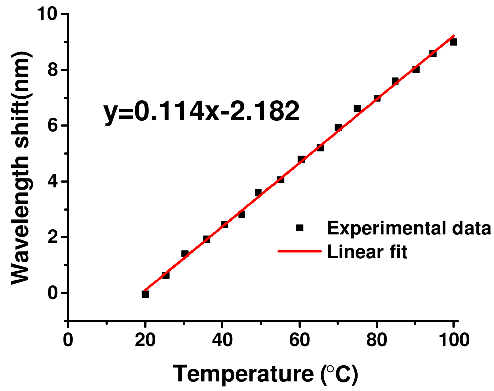

Fig. 6. Resonant wavelength shift with respect to temperature.

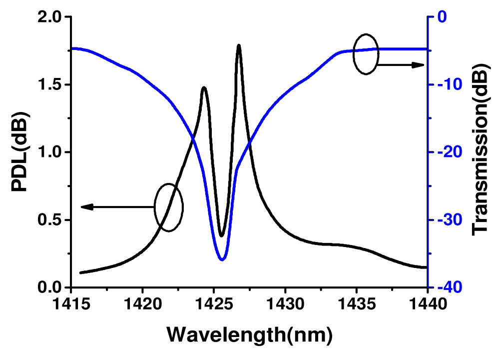

Fig. 7. PDL and loss of fabricated LPFG.

of the fiber cladding. Moreover, the multiple scanning of the second step induces a structure cross the fiber core, leading to a much more symmetric index distribution.

3. Conclusion

We experimentally fabricate long period fiber grating with a band rejection efficiency of −35.4 dB and an insertion loss of 4.36 dB, by use of two-step infrared femtosecond fiber laser exposure. Although the performance of LPFG is improved, both the fabrication time and cost are unchanged in comparison with traditional infrared femtosecond laser fabrication method [12], [21], [25]. Relationship between fabrication parameters including corrugation fabrication depth, scanning time, fabrication length, and transmission spectral are experimentally investigated. The temperature coefficient of fabricated LPFG is about 114 pm/°C at a range from 20 °C to 100 °C, while a relatively low PDL of 1.78 dB is obtained. Compared with traditional infrared femtosecond laser fabrication method [12], [21], [25], our two-step fabrication method possesses both high band rejection efficiency and high temperature sensitivity, but has small temperature operation range. Such LPFG fabrication technique is suitable for applications in optical sensing area.

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