Long-period prating fabricated by periodically tapering standard single-mode fiber

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We fabricated an asymmetric long-period grating (LPG) by periodically tapering a section of standard single-mode fiber using a resistive filament heating. The LPG exhibits large peak transmission attenuation of −30.31 dB with only 22 periods in a 1.0 cm long optical fiber and possesses unique characteristics for sensing applications. The bending and strain sensitivities are 1.74 nm m and 1.11 pm/$\mu\varepsilon$, respectively. The polarization dependent loss is large, up to 11.65 dB, which is caused by an asymmetric index profile in the cross section of the tapered LPG. © 2008 Optical Society of America

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1. Introduction

Long-period gratings (LPGs) are attractive fiber-optic devices that are being used in communication and sensing applications. Various approaches for fabricating LPGs have been developed. Generally LPGs can be made using UV laser exposure to form a periodic refractive index variation along the core of a fiber [1]. However, the UV laser based fabrication method has some inherent limitations. It requires hydrogen loading and annealing to the fiber, and is not applicable to nonphotosensitive fibers, such as bismuth fibers or phosphorus-doped fibers. Non-UV laser writing techniques have also been reported. Davis *et al.* reported a method based on CO_2 laser-induced residual stress relaxation [2]. Hwang *et al.* used a fusion splicer to fabricate LPGs by introducing periodic microbends to a fiber [3]. Recently, Wang *et al.* demonstrated very strong resonant LPG that was written by a focused CO_2 laser to carve periodic grooves on the cladding surface of a fiber [4].

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In this paper we propose and demonstrate a novel LPG fabrication method that uses resistive filament heating to periodically taper a standard single-mode fiber (SMF). The asymmetric LPG obtained has a large peak transmission attenuation of −30.31 dB with only 22 periods over a 1.0 cm long fiber. The bending and strain responses have been experimentally studied. The polarization dependent loss (PDL) of this LPG is quite large and can be tuned with applied strain.

2. Fabrication and Theory

The experimental setup is shown in Fig. 1(a). A Vytran GPX3400 glass processing system (Vytran Co., Morganville, N. J.) is employed. Resistive filament heating in conjunction with fiber tension was employed to fabricate the LPG. An optical fiber (Corning SMF-28) is positioned at the center of an "Omega" shaped tungsten resistive filament loop [inset of Fig. 1(a)], while its ends are fixed on two fiber holder blocks (FHBs) with linear stages. An electrical current that flows through the filament raises its temperature, and heats the optical fiber. With proper filament design, the temperature of a localized fiber section can be rapidly raised to its soften-

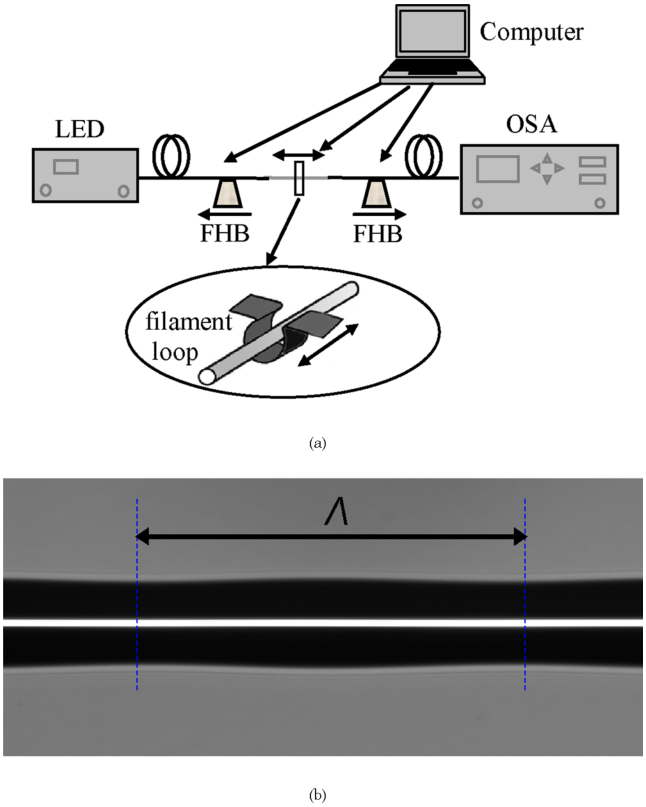

Fig. 1. (Color online) (a) Experimental setup for LPG fabrication. (b) Photograph obtained from a CCD camera showing a section of LPG fabricated by resistive filament heating; Λ is 457 μm.

ing point in a very repeatable and controllable manner. The filament loop has a diameter of 900 μm, is 625 μm wide, and 25 μm thick. The filament's axial position is controlled by a stepper motor with 800 nm axial motion per step. The tension is applied to the fiber by moving the two FHBs in opposite directions. The tungsten filament heats the fiber for ~500 ms while the tension in the fiber creates a local biconic taper. After the taper is produced, the filament loop is moved to a new location where another biconic taper of identical dimension will be produced. The separation between two adjacent tapers defines the period (Λ) of the LPG. The fiber is allowed to cool for several seconds before forming a new taper to ensure that it is not affected by the residual heat from the previous taper.

The velocity of the FHBs was set to 60 μm/s during the tapering process. A section of the LPG with periodic tapers is shown in Fig. 1(b). The period Λ of this LPG is 457 μm and the diameter of the taper waist is ~110 μm. A light-emitting diode (LED) light source and an optical spectrum analyzer (OSA) are used to monitor the transmission spectrum profile of a LPG. Figure 2 illustrates the transmission spectra of the LPGs with various tapers or grating period numbers of 4, 7, 10, 13, 16, 19, and 22. It can be seen that, with an increase of the number of the grating period, the resonant wavelength of the LPG shifts toward shorter wavelength, the transmission attenuation increases, and the 3 dB bandwidth of the transmission spectrum decreases. A high quality LPG with a large peak attenuation of more than 30 dB at the resonant wavelength of 1566.59 nm was obtained after 22 taperings.

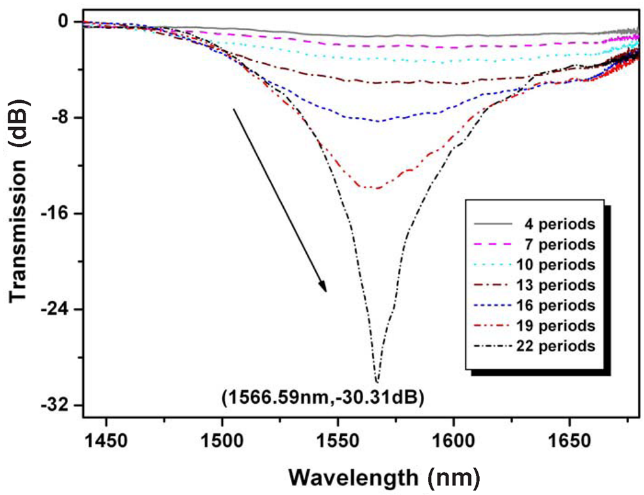

Fig. 2. (Color online) Transmission spectrum evolution of the LPG with the grating pitch of 457 μm while periods vary from four to 22.

According to the couple-mode theory, the peak transmission attenuation of an LPG is determined by the coupling coefficient [5], which is a function of index change and modal overlap between the guided mode and cladding modes in the fiber. In our case, the achieved high refractive index variation was due to the local release of the mechanical stress of the fiber by resistive filament heating. The refractive index modulation in the periodic taper based LPG can be express as

$$\Delta n = \Delta n_{\text{residue}} + \Delta n_{\text{taper}}, \tag{1}$$

where n_{residue} is the initial refractive index perturbation induced by the residual stress relaxation as a result of the high local temperature, which can be tailored by adjusting the discharge time, the electrical current of the filament, and the constant strain during the tapering process. n_{taper} is the refractive index perturbation caused by the periodic tapering of the fiber and can be controlled by presetting the velocity of the FHBs.

3. Characterization of the LPG

A. Bending Sensitivity

To investigate the bending sensitivity of the tapered LPG, we bend the fiber with a fabricated LPG in the middle by fixing one end of the fiber and pushing the other end toward the fixed end with the use of a translation stage. The curvature of the fiber was calculated by considering the bent fiber as the arc of a circle [6]. As a result, we achieved curvatures ranging from 0 to 20 m^{-1}. Figure 3(a) shows the results of the bending experiment for the tapered

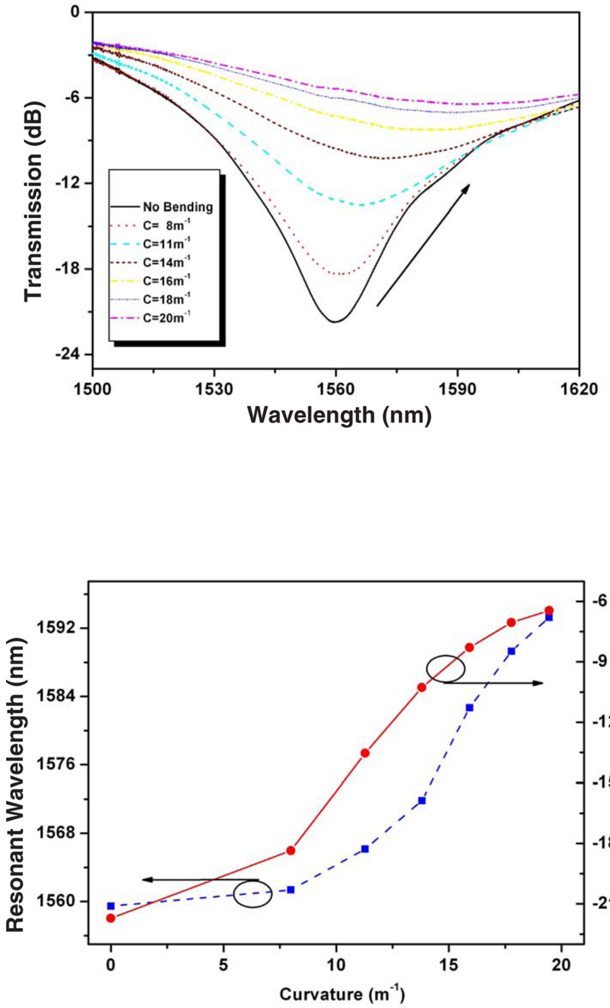

Fig. 3. (Color online) (a) Transmission spectrum evolution of the tapered LPG. (b) Variations of the resonant wavelength and the peak attenuation corresponding to different curvatures introduced to the tapered LPG.

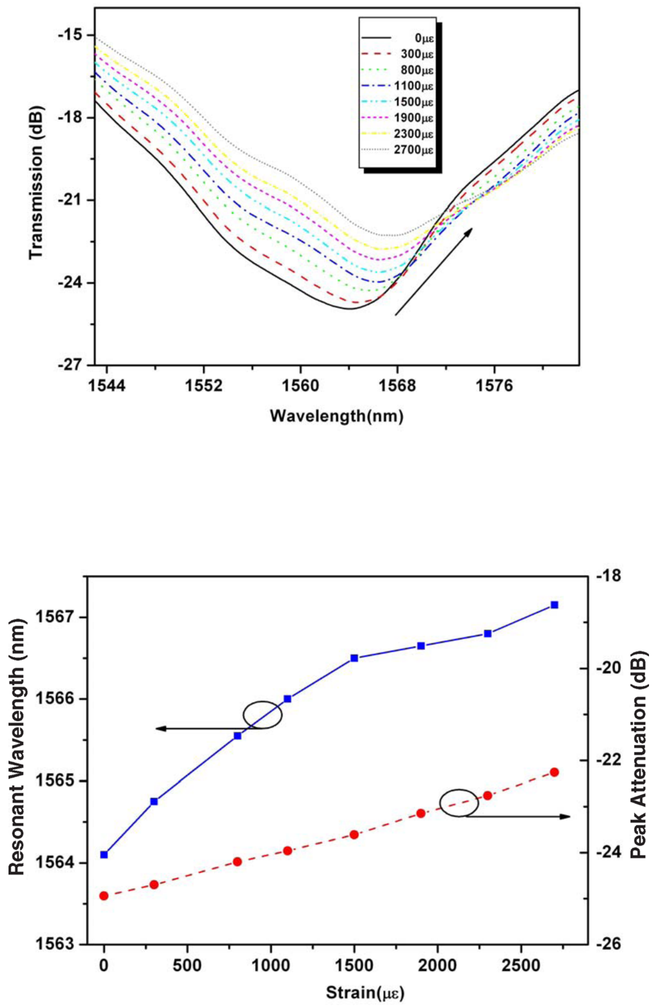

Fig. 4. (Color online) (a) Transmission spectrum evolution of the tapered LPG. (b) Variations of the resonant wavelength and the peak attenuation corresponding to different tensile strain applied to the tapered LPG.

LPG. Note that the resonant wavelength of the LPG shifts to longer wavelength, while the peak attenuation decreases with the fiber curvature. Figure 3(b) shows the measured data. The maximum bending sensitivities can be as high as 1.74 nm m and 0.76 dB m in terms of wavelength and transmission attenuation, respectively. The tapered LPG is extremely sensitive to bending and it could be developed into bend sensors for use in structural applications.

B. Strain Sensitivity

In order to study the strain characteristic of the tapered LPG, an external stretching force was applied to the LPG with a resonant wavelength of 1564.1 nm and a peak transmission attenuation of about 25 dB. Figure 4 shows that with increasing tensile strain, the resonant wavelength shifts to 1567.15 nm and the peak attenuation decreases to 22 dB. The average strain sensitivity is 1.11 pm/$\mu\varepsilon$ up to the maximum strain of 2700 $\mu\varepsilon$. Note that the strain sensitivity of the tapered LPG is less than that of traditional LPGs fabricated by a UV laser, 1.52 pm/$\mu\varepsilon$.

C. PDL Measurement

The "Omega" shaped tungsten resistive filament loop causes asymmetrical heating on the fiber because it is not a full circle. Consequently, it induces an asymmetric index profile within the cross section of the tapered LPG and introduces a large PDL. The measured maximum PDL is up to about 11 dB, much higher than the typical value, ~1.2 dB, of the conventional UV-induced LPGs [7]. However, the PDL can be tuned by applying tensile strain to the LPG. Figure 5 illustrates the PDL evolution with tensile strain. The high PDL of the tapered LPG could be employed to make all fiber polarizers.

4. Conclusions

In conclusion, asymmetric LPGs with a large peak attenuation of −30 dB have been fabricated by periodically tapering standard SMFs with resistive filament heating. The tapered LPG exhibits short

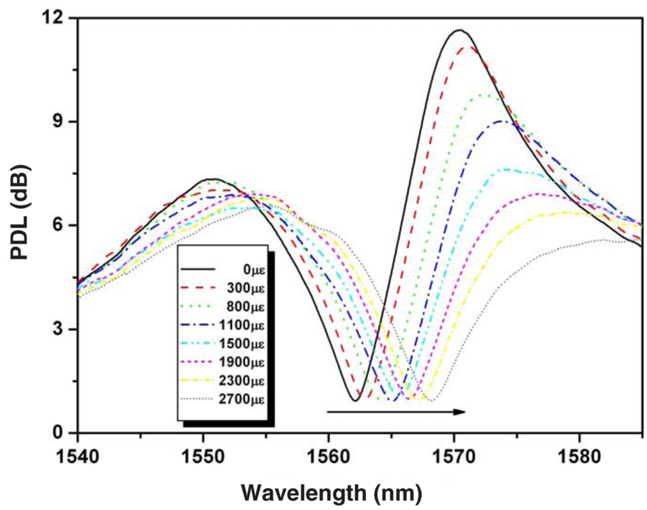

Fig. 5. (Color online) PDL evolution of the tapered LPG with different tensile strains.

length, high sensitivity to fiber bending, and relatively lower sensitivity to applied tensile strain. The maximum bending sensitivity is 1.74 nm m and strain sensitivity is 1.11 pm/$\mu\varepsilon$. The polarization dependent loss is very large (more than 11 dB) because of the asymmetric index profile in the cross section of the fiber. Experimental results show that the PDL can be tuned by applied strain. The proposed technique for LPG fabricating is applicable to any type of optical fiber, including the nondoping photonic crystal fiber and others. Because of the short length of tapered LPG, it is relatively easy to package and employ in practical sensing applications.

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