Stress-Induced Versatile Tunable Long-Period Gratings in Photonic Crystal Fibers

Hou-Ren Chen, Kuei-Huei Lin, Ja-Hon Lin, and Wen-Feng Hsieh

Abstract—**We report a method for generating versatile tunable long-period gratings (LPGs) in photonic crystal fibers (PCFs). The central wavelength and rejection bandwidth of LPGs can be tuned over a broad spectral range with adjustable transmission loss. Spectral fringes with uneven spacing are observed in chirped LPGs, depending on the interaction length and the amount of chirping between the two ends of the LPG, and can be removed by reducing the chirping and increasing the grating length. By utilizing a stress-induced LPG, gain flattening of an erbium-doped fiber amplifier has also been demonstrated.**

Index Terms—**Long-period fiber grating, mode coupling, photonic crystal fiber (PCF), tunable filter.**

I. INTRODUCTION

PHOTONIC crystal fibers (PCFs) are typically silica optical fibers in which two-dimensional periodic structures with a regular array of tiny air holes are introduced in the cladding region and extend in the axial direction of the fiber [1]. Because the optical properties of PCFs depend on the size and pattern of air holes, various fiber designs have been proposed to acquire several novel properties that are unprecedented in conventional fibers. These novel properties include endless single-mode guiding, extremely high nonlinear optical coefficient, controllable anomalous dispersion in the visible and near-infrared spectral ranges, and enhanced birefringence effect. The unique dispersion and nonlinear properties of PCFs show potential applications in fiber-optic communication and sensor technology [2], and the novel mode guiding characteristics of PCFs have been utilized in the fabrication of fiber gratings.

Fiber gratings can be divided into two major types: fiber Bragg gratings (FBGs) and long-period gratings (LPGs). FBG is based on Bragg reflection of the guided core mode to the core mode of counterpropagating direction. On the other hand, a long-period fiber grating is a fiber device with a typical period of several hundred micrometers. It is a kind of transmission grating based on the coupling of fundamental core mode to a series of copropagation cladding modes, and thus generating rejection bands in the transmission spectrum. The applications of LPGs include band rejection filters, gain flattening of erbium-doped fiber amplifiers (EDFAs), sensor technologies, and dispersion compensation, etc. [3]–[5].

LPGs can be formed in fibers with ultraviolet exposure [6], electric arc discharging [7], or CO_2 laser inscription [8]. It is difficult to change the parameters such as grating period, grating length, resonant wavelength, and maximal transmission loss once the gratings were fabricated in the fibers by those methods. Lim *et al.* fabricated constant-period LPGs in PCF by using mechanical pressure [9]. These LPGs were formed by pressing PCF with a periodically grooved metallic plate. The wavelength of resonant peak could be tuned by adjusting the grating period on the PCF; however, there were no reports on bandwidth-tunable LPGs.

In this letter, we propose a method to generate versatile tunable LPGs in a PCF by using a constant period V-grooved plate. The central wavelength and rejection bandwidth of LPGs can be tuned over a broad spectral range with adjustable transmission loss. Spectral fringes with uneven spacing are observed in chirped LPG. The spectral fringes can be removed by using proper LPG configurations. We have also demonstrated a stress-induced LPG in the gain flattening of an EDFA.

II. EXPERIMENTAL SETUP

A V-grooved plate is constructed by engraving periodic parallel V-grooves on a metallic plate. The plate is 6 cm long and 1 cm wide. The V-grooves are 200 μm in depth and the periodicity is 400 μm. An endless-single-mode PCF (Blaze Photonics ESM-12-01) is sandwiched between the grooved plate and a flat metallic plate [Fig. 1(a)]. The PCF is made of undoped fused silica with a core diameter of 12 μm. Diameters of the air holes in the PCF are 4 μm, and the spacings between adjacent holes are 8 μm. When mechanical stress is applied and increased gradually, we record the transmission spectra of the induced PCF-LPG by launching an unpolarized white-light source into one end of the PCF, while the other end is connected to an optical spectrum analyzer (OSA) (Ando AQ-6315).

As shown in Fig. 1, LPGs are induced in PCF when mechanical stress is applied. A constant-period LPG can be obtained if the PCF is straight [Fig. 1(b)]. However, LPGs become chirped (i.e., with continuously changed periodicity) when PCF is bent [Fig. 1(c)–(f)] with properly translating or rotating the V-grooved plate. Either single-LPG [Fig. 1(c)] or dual-LPG [Fig. 1(d)] can be generated in the bent PCF. The amount of chirping is controlled by the curvature of bent PCF as well as the angle of the V-grooved plate against the fiber axis, and the LPGs are chirped with varying effective grating periods along the PCF.

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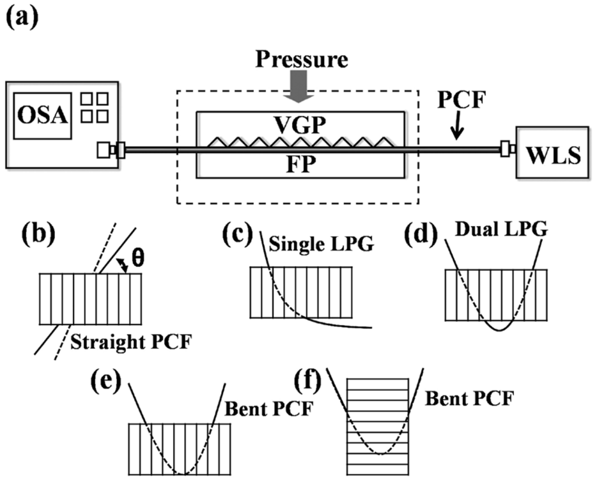

Fig. 1. (a) Schematic of the experimental setup and generation of LPGs in PCFs by mechanical stress. WLS: white-light source; VGP: V-grooved plate; FP: flat plate. (b) Constant-period LPG made by using V-grooved metallic plate. (c) Single-LPGs can be induced by pressing one part of the bent PCF. (d) Dual-LPGs can be induced simultaneously by pressing two separate parts of the bent PCF. (e) Chirped single-LPG. (f) Chirped single-LPG by rotating 90° of the V-grooved metallic plate.

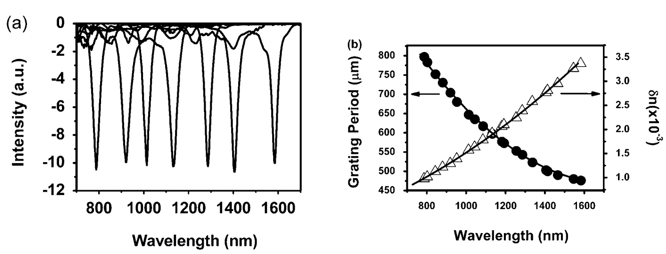

Fig. 2. (a) Measured transmission spectra of constant-period gratings obtained by adjusting the angle between the straight PCF and the V-grooves. (b) Resonant wavelengths measured at different grating periods, as well as the calculated effective indexes differences with respect to resonance wavelengths.

III. Results and Discussion

Fig. 2 shows the transmission spectra for constant-period LPGs made by tuning the angle of the grooved plate against the axes of straight PCFs. The effective periodicity $\Lambda_{\rm eff}$ of the grating increases with the angle θ

$$\Lambda_{\rm eff} = \frac{\Lambda_0}{\cos\theta} \tag{1}$$

where Λ_0 is the periodicity of V-grooves and θ is the angle between PCF and the normal of V-grooves [Fig. 1(b)]. For an LPG fabricated with a conventional fiber, the transmission spectrum has dip at the wavelength corresponding to resonance with various cladding modes, and the resonance wavelength increases with increasing grating periodicity [10]. However, the resonance wavelength of PCF-LPG decreases with increasing grating periodicity, as shown in Fig. 2. The center wavelength of LPG can be tuned from 790 to 1590 nm as the effective period is reduced from 805 to 470 μm, and the grating length is increased from 1.2 to 1.9 cm. Accordingly, the rejection bandwidth has been changed between 10 and 35 nm. The transmission loss of the constant-period LPG can be further increased to 18 dB, but the PCF will be broken if the applied mechanical stress is too large.

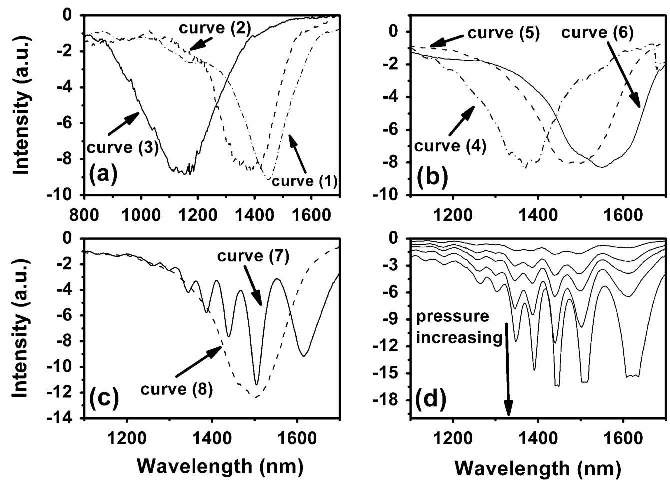

Fig. 3. Transmission spectra for (a) chirped single-LPG, and (b) chirped single-LPG by rotating 90° of the V-grooved metallic plate. (c) Spectral fringes can be obtained from chirped single-LPGs, and the fringes can be eliminated with proper configuration. (d) Spectral fringes with different pressures.

According to the coupled-mode theory, the resonance wavelength $\lambda_{\rm res}$ and the effective grating pitch $\Lambda_{\rm eff}$ are related by the phase-matching condition [3]

$$\lambda_{\rm res} = \Lambda_{\rm eff}[n_{\rm eff}^{\rm co}(\lambda) - n_{\rm eff}^{\rm clad}(\lambda)] \tag{2}$$

where the effective indexes of the core mode $n_{\rm eff}^{\rm co}(\lambda)$ and the cladding modes $n_{\rm eff}^{\rm clad}(\lambda)$ can be obtained as functions of the resonant wavelengths. When the grating is tilted, the number of periods in the same length of LPG and thus $\Lambda_{\rm eff}$, according to (1), will also be changed which allows the core mode coupling to the copropagating cladding mode with different propagation constant or wavelength based on (2).

Using (1) and (2), the difference of effective index δn of the core and cladding modes was calculated from the experimental data of Fig. 2(a). As shown in Fig. 2(b), δn is in the order of 10^{-3}, and increases with the central rejection wavelength. Using beam propagation method simulation for the effective indexes of core and cladding modes (not shown here) and the transmission spectra, we found that the calculated results match quite well with experimental data by only considering coupling between the core mode and the lowest cladding mode. It reveals that the resonant coupling occurs mainly between the core mode and the lowest copropagating cladding mode.

Chirped LPGs can be generated in a symmetrically bent PCF by pressing the PCF with a constant period V-grooved plate as in the configurations of Fig. 1(e) and (f). Fig. 3(a) shows the transmission spectra of various chirped single-LPGs. The transmission spectra in Fig. 3(a) are obtained from the bent PCFs as in Fig. 1(e) for different curvatures with curve (1) $<$ curve (2) $<$ curve (3). Due to the bending of PCF, the periodicity of LPG along PCF decreases first, and then increases. According to (2), each section of the bent PCF-LPG will have different resonance wavelength, and the superposition of individual transmission spectrum will lead to a large overall LPG bandwidth. As the curvature of PCF increases, the amount of chirping and effective periodicity differences will increase, leading to the broadening of spectral dip in the transmission spectrum [Fig. 3(a)] and the

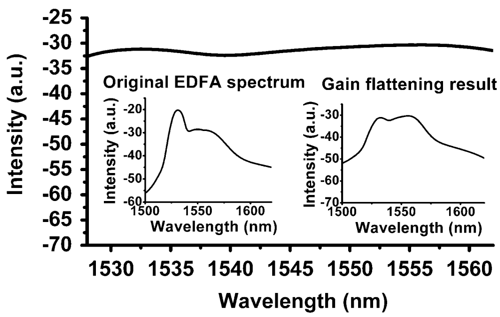

Fig. 4. Gain-flattened EDFA spectrun between 1528 and 1562 nm by using the chirped LPGs. Insets are original EDFA spectrum and gain flattening result, the pump current of the EDFA is 28 mA.

resonant wavelength is shifted from 1447 to 1137 nm. The 3-dB rejection bandwidth is changed from 131 to 250 nm. Fig. 3(b) shows the transmission spectra for the chirped single-LPG when the V-grooved metallic plate is rotated by 90° as in Fig. 1(f). In this case, the periodicity of LPG along PCF increases first, and then decreases, which is contrary to Fig. 1(e). The results in Fig. 3(b) are obtained for bent PCF of different curvatures: curve (4) $<$ curve (5) $<$ curve (6). The center wavelength of this PCF-LPG is shifted from 1363 to 1549 nm, and the 3-dB rejection bandwidth is changed from 147 to 195 nm. While monitoring the transmission spectrum on an OSA, we released the mechanical pressure applied on the PCF and found that the transmission spectrum restored to the original background spectrum almost instantly ($<$0.5 s). The main technical drawback of this stress-induced LPG is the tendency to drift in the adjustment of angle and curvature for PCF in practical applications. Nevertheless, it would be a useful laboratory tool as a versatile tunable filter.

By using the configuration of Fig. 1(c), we found that the chirped single-LPG would show spectral fringes [Fig. 3(c)], and the modulation depth increases with increasing pressure [Fig. 3(d)]. The fringe spacing could be unevenly ranging from 43 to 110 nm as curve (7) in Fig. 3(c), depending on the interaction length and the amount of chirping between the two ends of the LPG. With chirped single-LPG configuration of reduced chirping and increased grating length (from 2.4 to 3.3 cm), we find that the spectral fringes will disappear in the rejection band [curve (8)]. Therefore, chirped single-LPG can be fabricated with the configuration of Fig. 1(c) to either generate or eliminate the modulation peaks.

As an application, we have used the stress-induced LPG in the gain flattening of EDFA. Insets of Fig. 4 show the original EDFA output spectrum, with EDFA pump current of 28 mA. The amplified spontaneous emission spectrum of EDFA shows a peak around 1532 nm. By cascading a PCF-LPG and carefully adjusting the direction of V-grooved plate, the PCF bending, and the mechanical pressure, EDFA spectrum has been flattened within ± 1 dB for spectral range between 1528 and 1562 nm. Because the central wavelength, the rejection bandwidth, and the transmission loss of the stress-induced LPG can be tuned over a broad range, a versatile gain-flattening filter is generated according to the power level and spectral range of the EDFA.

IV. Conclusion

In this letter, we generated both broadband chirped LPGs and constant-period LPGs in a bent PCF by using a constant period V-grooved plate. The central wavelength and rejection bandwidth of LPGs can be tuned over a broad spectral range with adjustable transmission loss. Mechanically induced LPGs show resonant wavelength tuning range over 800 nm, and the 3-dB bandwidth can be controlled from 10 to 250 nm. Transmission loss of the constant-period LPG can be increased to 18 dB, but the PCF will be broken if the applied mechanical stress is too large. Spectral fringes with uneven spacing were observed in the rejection band of chirped single-LPG, depending on the interaction length and the amount of chirping between the two ends of the LPG, and can be removed by reducing the chirping and increasing the grating length. We have also demonstrated gain flattening of an EDFA in the spectral range between 1528 and 1562 nm using a stress-induced LPG.

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