

Characteristic research on mechanically induced long-period fiber gratings

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A full experimental characterization of mechanically induced long-period fiber gratings (MLPFGs) fabricated by pressing a plate with periodic grooves against a short length of fiber is presented. This technique enables a good control over the gratings' isolation loss peaks and has high repeatability. The spectra characteristics of MLPFGs are studied with the change of the parameters including pressure, period, and temperature. The produced MLPFGs have low insertion loss (< 0.2 dB) and the loss peaks can be higher than 20 dB. A large tunability of the resonant wavelength (> 14 nm) is achieved through adjusting pressure grooves' period. The center wavelength temperature sensitivities of 0.057, 0.086 nm/ $^{\circ}$ C, and resonant peak temperature sensitivities of 0.230, 0.312 dB/ $^{\circ}$ C, are achieved for jacketed and unjacketed fibers, respectively. These MLPFGs, which are simple and inexpensive, also offer the unique advantages of being tunable, erasable, and reconfigurable.

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Photo-induced long-period fiber gratings (LPFGs) produce interesting notch filters with important applications, in particular, as gain equalizers in fiber amplifiers, as band-rejection filters in lasers, and to alter the spectra of broadband sources. Their success stems from their low loss and flexibility in filter shape design. A well-established technology to produce LPFGs uses ultraviolet (UV) radiation through an amplitude mask^[1]. Two more recent techniques based on the periodical local heating of fiber with CO₂ laser radiation or electric arc discharges^[2,3] have also been demonstrated, and the latter is a far less expensive technique. Nevertheless, since LPFGs have periods of hundreds of micrometers, they can be induced mechanically, i.e., by applying pressure periodically on the fiber^[4]. The fabricated gratings, sharing most of the properties of the non-mechanically induced ones, are also reversible and can be performed keeping the fiber mechanical integrity, whilst preserving their protective polymer coatings. Therefore, these mechanically induced LPFGs (MLPFGs) can be very useful not only in research labs but also as field devices.

In this letter, a rectangular periodic grooved plate is fabricated through mechanical line processing technology (MLPT). A set of parameters (such as pressure, period, and period number) that allow control over the transmission spectra of the gratings is studied quantitatively. The temperature characteristics of gratings for jacketed and unjacketed fibers are also discussed.

LPFGs couple light from the guided mode to cladding modes propagating in the same direction until being completely attenuated by scattering and absorption in the cladding external interface and the curvature losses. The grating spectra are characterized by loss-peaks at wavelengths that satisfy the resonance condition^[5]

$$\lambda = (n_{co} - n_{cl}^i)\Lambda, \quad (1)$$

where λ is the resonance wavelength, n_{co} and n_{cl} are

respectively the effective refractive indices of the fundamental mode and the i th order cladding mode, and Λ is the grating period. The MLPFGs characteristics enable their use as optical communication devices, such as narrowband filters for wavelength division multiplexing (WDM) systems or as gain flatteners for erbium-doped fiber amplifiers (EDFAs). They can also be used as polarizers since they are intrinsically birefringent. On the other hand, they can become polarization insensitive by twisting the fiber before writing the grating. MLPFGs have also been used separately or with other structures in optical sensing of physical parameters such as temperature.

The fabrication process is illustrated in Fig. 1. It is mainly composed of a pressure grooved plate (with period P μ m and depth 300 μ m), a spiral micrometer structure, and a flat plate. The pressure was applied on the grooved plate equally by a special designed spring-driven apparatus. A general single-mode fiber (Corning SMF-28, 8.3- μ m core diameter, 125- μ m cladding diameter, and 0.11 numerical aperture) with or without jacket was placed under the grooved plate straightly, and the spring's elasticity coefficient was 2 kN/m. In the experiments, the

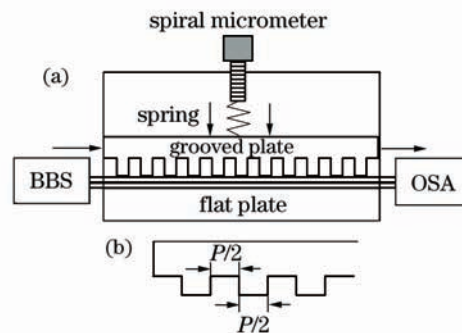


Fig. 1. (a) Side view of a mechanically induced LPFG; (b) schematic of the grooved plate.

evolution of the gratings spectra was monitored by an optical spectrum analyzer (OSA, ANDO AQ 6331), and a light source with the wavelength range of 1450 – 1750 nm was used as the broadband light source (BBS).

The transmission peak-loss^[6] from the fiber core guiding mode the cladding modes can be expressed as

$$T \propto \sin^2(\kappa L), \quad (2)$$

where κ is the coupling coefficient and L is the length of the grating. κ is proportional to the amount of index variation induced by the mechanical pressure.

The pressure grooved plate with the period of 620 μm and period number of 80 was chosen. The evolution of a grating fabrication as the pressure increasing from 20 to 50 N in steps of 10 N is shown in Fig. 2. The grating grows almost linearly with the pressure, whilst its resonant wavelengths remain almost unchangeable. The growth rates of the first, second, and third modes are about 0.3, 0.5, 0.42 dB/N separately. Because the transmission loss peak is a periodic function, the second mode appears over-coupled phenomenon. As a result of the slow and constant growth of the grating, it is possible to have a good control over the isolation of the loss peaks. Gratings produced using this technique are reversible, i.e., after being unwinded, the initial transmission of the fiber is recovered. Their formation relies on the photo-elastic effect and micro-deformations of the fiber.

This technique of producing MLPFGs offers high repeatability, with the difference in the isolation of the loss-peaks for two gratings written in the same conditions being below 1%. Another advantageous feature of this design is that one can adjust the grating period by changing the angle between the fiber and the grooves^[7]. Similarly, the length of fiber under pressure, which controls the linewidth of the notches, can easily be changed. Finally, one can tune the depth of the notches by adjusting the pressure. When the perturbation is removed, the transmission of the fiber returns to its initial spectrum. Thus a wide range of filter functions can be generated with the same grooved plate and fiber. More importantly, as we can see from Fig. 2, one of the resonant wavelengths caused by the first mode falls in the third telecommunication window. The pressure response extracted from Fig. 2 is illustrated in Fig. 3, where

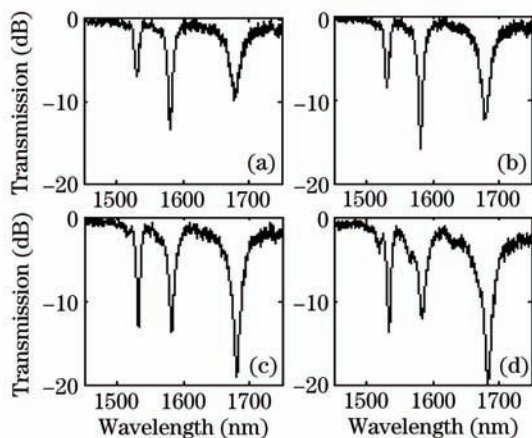


Fig. 2. Transmission spectra of MLPFG with different pressures of (a) 20, (b) 30, (c) 40, and (d) 50 N.

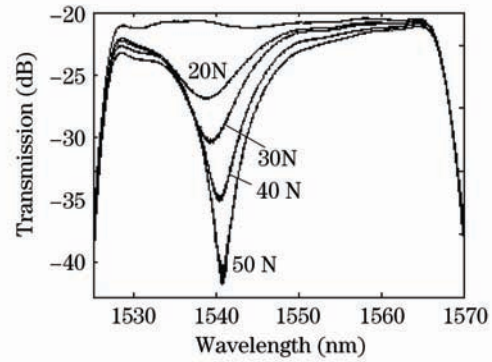


Fig. 3. Measured transmission spectra of MLPFGs with different pressures.

the pressure increases from 20 to 50 N. The produced MLPFGs have low insertion loss (< 0.2 dB) and the isolation of the loss-peaks can be higher than 20 dB. Furthermore, this technique applied to etched fibers demonstrates excellent control over the gratings spectra. This property can be very useful in the fiber sensing and optical communication areas. Therefore, in the following experiments, all fabrication parameters and temperature response were tested in the C-band of communication window. The above experiments were carried out with $\kappa < \pi/(2L)$, where L is the fiber length. When $\kappa > \pi/(2L)$, which means the cladding mode couples back to the fiber core guiding mode, over-coupled phenomenon^[8] will occur.

The dependence of the positions of loss peaks on the grating period according to the resonance condition is shown in Fig. 4. The period P ranged from 600 to 630 μm (in step of 6 μm). For these gratings, it has been experimentally verified that the position of the resonant wavelength is mainly decided by the period of the pressure grooves. With the period increasing, the resonant wavelength will shift to longer wavelength side. If technical limitations concerning the period of the grooves are considered or if high precision on the positioning of the peaks is required, the tunability of the resonant wavelengths of a grating can be achieved by using angle tuning method between fiber and pressure grooves.

Now we analyze how the pressure grooves' length affects the isolation of the loss peaks of the performed gratings and their bandwidth^[9]. Normalized bandwidth of LPFG can be expressed as

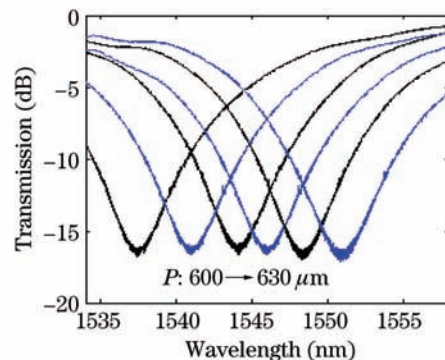


Fig. 4. Measured transmission spectra of MLPFGs with different groove period P from 600 to 630 μm with a step of 5 μm .

$$\frac{\Delta\lambda}{\lambda} \cong \frac{\lambda}{\Delta n L} \left(1 + \frac{4\kappa}{\pi} L\right)^{1/2}, \quad (3)$$

where $\Delta\lambda$ is the bandwidth, Δn is the variation of the refractive index. We can infer that the full-width at half-maximum (FWHM) of the grating is determined by the period pressure grooves' length. Generally speaking, the 3-dB bandwidth of these gratings is typically in the range of 10–30 nm. The spectra of grating with pressure grooves' period of 600 μm , period numbers of 60, 80, 90 (corresponding to the fabricated grating length of 36, 48, and 54 mm, respectively) were tested, as shown in Fig. 5. In order to get obvious contrast, the pressure is chosen properly when testing every spectrum. As we can see, with the length of grooves increasing, the FWHM will be narrower.

In order to investigate the temperature behavior of these gratings, the designed device was put into a

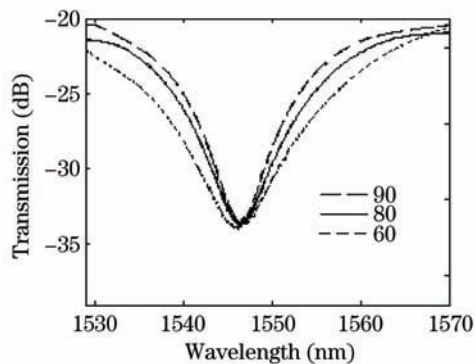


Fig. 5. Measured transmission spectra of MLPFGs with different grooves' period numbers.

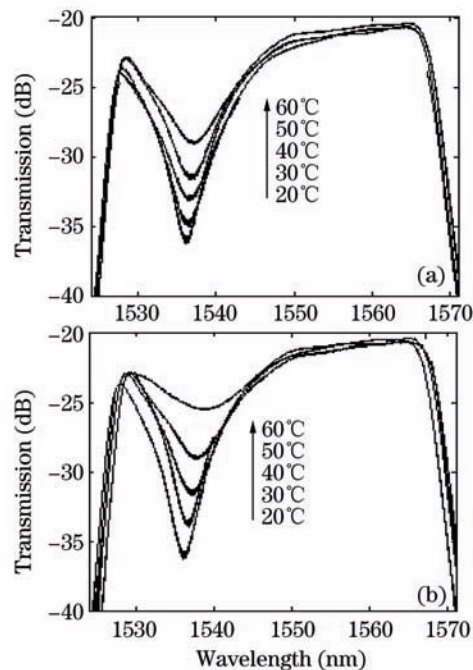


Fig. 6. Measured transmission spectra of MLPFGs with different temperature for (a) jacketed fiber and (b) unjacketed fiber.

thermostat. The temperature measurement was performed using a C-band amplified spontaneous emission (ASE) source as the light source and an OSA to monitor the resonant peak. Fabricated gratings with jacketed and unjacketed fibers were heated from 25 to 60 $^{\circ}\text{C}$. The wavelength-temperature sensitivities obtained for jacketed and unjacketed fibers were 0.057 and 0.086 $\text{nm}/^{\circ}\text{C}$, respectively, as shown in Fig. 6. During the same temperature range, the optical power losses of the resonant peak changed 0.230 and 0.312 $\text{dB}/^{\circ}\text{C}$, respectively. The resonant peak decreased gradually and the resonant wavelength shifted to longer wavelength with the temperature increasing. So the temperature factor would affect the unjacketed fiber more sensitively, which was easy to be understood.

In conclusion, a simple, flexible, and low-cost technique to mechanically induce MLPFGs was proposed. The response of the gratings to external applied pressure demonstrated excellent control over the gratings' spectra. The produced MLPFGs have low insertion loss (< 0.2 dB) and bandwidths ranging from 10 to 20 nm, and the isolation of the loss peaks can be higher than 20 dB. Through a proper choice of the fabrication parameters and by changing the pressure of the spring device, it is possible to control the isolation with a precision better than 0.1 dB. A large tunability of the resonant wavelengths was achieved through adjusting pressure grooves' period. The center wavelength temperature sensitivities of 0.057, 0.086 $\text{nm}/^{\circ}\text{C}$, and resonant peak temperature sensitivities of 0.230, 0.312 $\text{dB}/^{\circ}\text{C}$ for jacketed and unjacketed fiber were investigated, respectively. These advantageous properties enable MLPFGs to have potential important applications in communication and sensing areas.

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