Several mechanically-induced long-period gratings by a grooved plate

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Received March 11, 2003

A simple method to mechanically induce a long-period fiber grating (LPFG) by a grooved plate is improved. The transmission spectra of a grating under different pressures and other types of gratings are experimentally investigated. This method is simple and reconfigurable and offers large spectra tunability. This type of LPFG has potential applications in gain flattening in erbium-doped fiber amplifiers (EDFA) and will be of particular use in filter design.

OCIS codes: 060.2280, 060.2340, 050.0050, 350.2460, 050.2770.

Recently, Long-period fiber gratings with low insertion loss and low back-reflection have attracted particular interests in wavelength-division multiplexing (WDM) system. Numerous applications of LPFGs, such as gain equalizer[1], mode converter[2], fiber sensor[3] and band rejection filters[4], have been demonstrated.

In principle, LPFG is a kind of transmission grating based on the coupling between the fundamental core mode and the co-propagating lossy cladding modes. And the wavelengths, at which mode coupling takes place, are determined by the phase-matching condition $n_{\rm eff} - n_{\rm cl}^{\{n\}} = \lambda_n/\Lambda$, where $n_{\rm eff}$ and $n_{\rm cl}^{\{n\}}$ denote the effective index of the fundamental core mode, i.e., $\rm LP_{01}$ mode and the nth cladding mode at λ_n, respectively, and Λ is the grating period. It can be seen that LPFGs are wavelength selective and discrete loss peaks can be observed at those resonant wavelengths in their transmission spectra.

One usually fabricates a LPFG by UV radiation, which introduces a periodic index change in the fiber core[4]. Although the UV radiation method has been popularly used, it is expensive and time-consuming. In addition, once the photo-induced LPFGs have been fabricated, it is difficulty to alter their spectra profiles. Alternate methods have been reported involving the use of physical fiber deformation[2], core-index variation produced by $\rm CO_2$ lasers or electric arcs[5,6] and periodic microbends produced by electric arcs[7]. More recently, S. Savin *et al.* reported a new type of mechanically induced LPFG[8]. It offers unique advantages of being tunable, erasable and reconfigurable.

In this letter, further study and experiments have been given to this simple and inexpensive method. The transmission spectra of a grating under different pressures are studied in detail. Furthermore, some special LPFGs such as chirped LPFG, phase-shifted LPFG, step-changed LPFG[9] and cascaded LPFG have been successfully mechanically induced by the same single grooved plate. This gives the method more tunabilty and makes it have potential applications in gain flattening in EDFA or broadband sources.

The side view of the mechanical setup is shown in Fig. 1. The grooved plate, made of copper, is 3 cm long and 1 cm wide. The groove, with the shape similar to sinusoidal curve, is about 125 μm deep. The fiber with fiber jacket under the grooved plate is standard G.652 single mode fiber. A grating period of 673 μm was chosen for the sake of easy manufacture. Except the step-changed and cascaded LPFGs, the pressures were applied on the plate vertically and evenly.

Figure 2 shows the transmission spectra of a grating under different pressures. The transmission spectra were measured with a broadband erbium-doped fiber superfluorescence source. The relationship between the pressures is as follows: $P_1 < P_2 < P_3 < P_4 < P_5 < P_6$. The strength of other pressures in each diagram is between the two marked pressures. In Fig. 2(a), it is clear that higher pressures, and thus higher index modulation, cause stronger mode coupling indicated by the depth of the notches. Figures 2(b) and (c) show that the depths of the loss peaks at the wavelengths of 1545 and 1590 nm vary in the similar way as reported in Ref. [8]. The 1590-nm loss peak reached its maximum first and then began to decrease after a certain point while the 1545-nm loss peak continued to increase until reached its own maximum. This behavior is due to the different mode-coupling coefficient for the two cladding modes. The wavelength shift of the peaks, obvious at 1545 nm, can be attributed to the induced positive change in the core mode effective index, which is not negligible any more when the pressures are high enough. The broadening of the bandwidth of

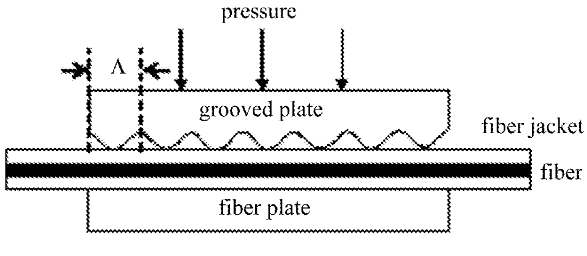

Fig. 1. Side view of a mechanical setup.

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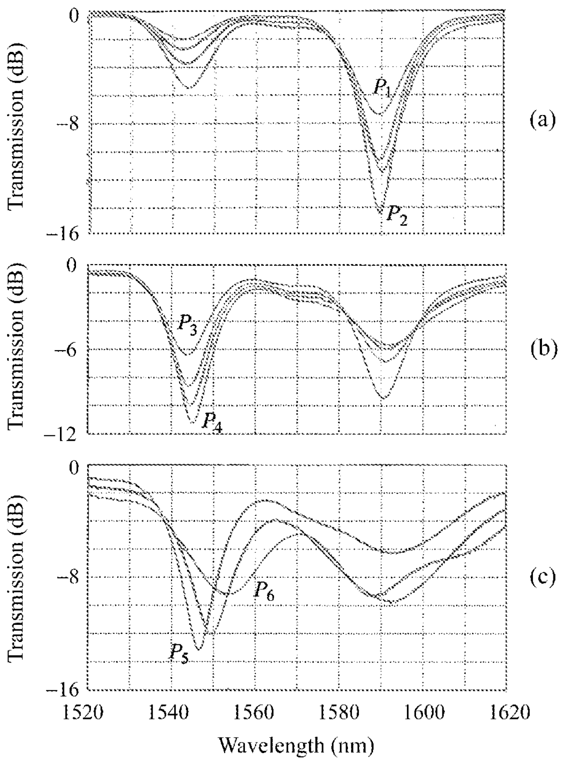

Fig. 2. Transmission spectra of a grating with different pressures ($P_1 < P_2 < P_3 < P_4 < P_5 < P_6$).

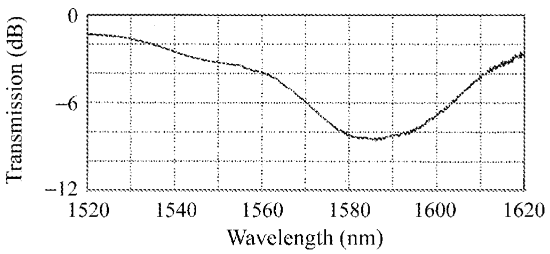

Fig. 3. Transmission spectrum of a quasi-linear chirped grating.

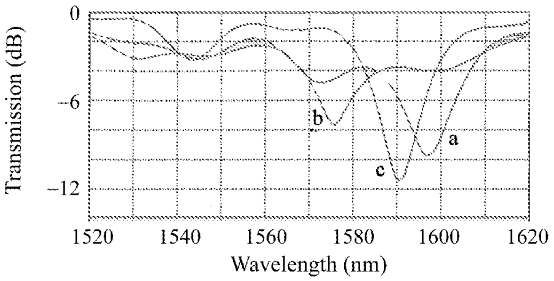

Fig. 4. Transmission spectra of two phase-shifted gratings.

the loss peaks is due to the stronger mode coupling[10], i.e., the bandwidth of the loss peak is proportional to the coupling coefficient, which is increasing with the pressures in this case. The wavelength-shift and the bandwidth broadening are different according to different types of fibers. The typical 3-dB bandwidth ranges from 5 to 32 nm. In Fig. 2(a), the out-of-band loss is typically less than 0.2 dB for wavelengths < 1530 nm and is about 0.8 dB at long wavelengths, which is comparable with conventional LPFG. Additional loss was added with increasing pressures, as indicated in Figs. 2(b) and (c).

Figure 3 illustrates the spectrum of a quasi-linear-chirped LPFG. By placing the fiber along a specific curve, which was numerically simulated by Matlab, we can introduce a quasi-linear-chirp on the grating period and achieve a wider bandwidth[11]. The bandwidth is about 36 nm and the out-of-band loss is 1.2 dB, higher than that in Fig. 2(a) as expected. The fiber was loosely placed in order to go along the curve, so the loss became correspondingly higher plus the bending loss. Since we cannot place the fiber along the exact path as the curve goes, the LPFG is not strictly linearly chirped. However, this method presents considerable flexibility that the chirp value can be changed and nonlinear chirp can be achieved by changing the curve. Furthermore, one can adjust the grating length or the pressures to realize optimum spectral control.

Phase-shifted LPFG, as indicated in Fig. 4, was mechanically induced by winding one or two brass wire(s) in a single groove in the middle of the plate. The wire with a diameter of 125 μm has a circular cross section. In Fig. 4, curve ‘a’ is the spectrum with only one wire in the groove and curve ‘b’ with two wires while the pressure of ‘a’ was a little higher. Curve ‘c’ is the original spectrum without any phase shift. The wire(s) broke the uniformity of the grating and the periodicity of the index modulation, introducing a phase-shift in the spectrum. The phase shift induced by the wire(s) is about $\pi/2$ and $3\pi/2$, respectively[12]. One can get other phase shifts by placing other materials or shapes of stuffs in the groove. In addition, exact π phase shift can be obtained by physically eliminating one peak in the middle of the plate at the cost of physical damage to the groove.

We also got step-changed LPFG by changing the position and strength of the applied pressures. Figure 5(a) shows the spectra corresponding to the pressures with equal strength but varying positions. A parameter α is defined as $\alpha = L_p/L$, where L_p is the length of the plate on which pressure is applied and L is the total length of the plate. The notch depth decreases as α decreases from below to above ($\alpha = 2/3$, $7/12$, $1/2$, $1/3$) because the length of the grating was shortened and less guided mode power would be coupled to cladding modes. Figure 5(b) indicates the effect of increasing pressures from above to below on the spectra with $\alpha \equiv 1/2$. The notch becomes deeper and asymmetrical, and its wavelength shifts to longer wavelength by 7 nm. The increasing pressures on one half of the plat would lead to higher refractive index change than the other half, and the index modulation was different between the two parts, which was responsible for the asymmetry of the notch profile. Obviously, one can alter the spectrum by changing the parameter α and the pressure simultaneously or by changing the material of the grooved plate so that bigger index change between different positions can be realized.

Finally, we cascaded two LPFGs with different periods together by placing two segments of fiber under the plate and changing the angles between the fibers and the grooves. The spectra are illustrated in Fig. 6. One interesting thing about this type of LPFGs is that the notches profile can be tailored by changing the pressures. When the pressures on the two gratings were equal, the

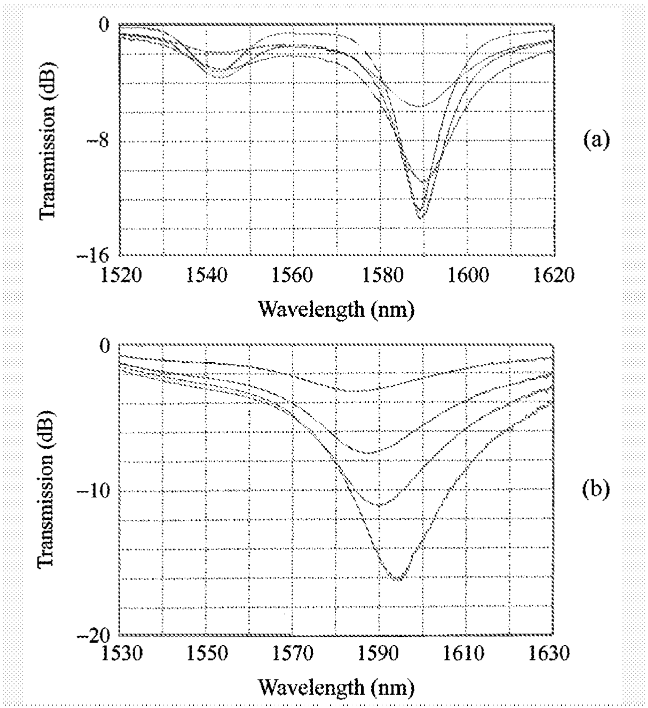

Fig. 5. Transmission spectra of step-changed gratings. (a) The same pressure with different positions; (b) the same position with different pressures.

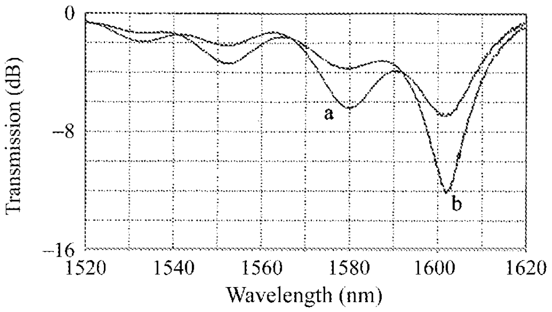

Fig. 6. Transmission spectra of two cascaded gratings with equal but azimuthally different pressures.

spectrum exhibited symmetry (curve 'a') that the two notches had approximately equal depths. Otherwise the unequal pressures would induce different index modulation in the two gratings and therefore the spectrum was asymmetrical (curve 'b'). Apparently the tunability of such gratings was enhanced greatly.

In conclusion, we have demonstrated the large spectra tunability of a type of mechanically induced LPFG by a grooved plate. In addition, chirped LPFG, phase-shifted LPFG, step-change LPFG and cascaded LPFG have been investigated by using the same grooved plate. These kinds of LPFGs should have potential applications such as gain flattening filters and other applications requiring spectral control.

This work was supported by the National Natural Science Foundation of China under Grant No. 60137010. K. Chen's e-mail address is backupchen@eyou.com, Q. Sheng's e-mail address is shengqq@nankai.edu.cn.

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