Ultra-widely tunable long-period holey-fiber grating by the use of mechanical pressure

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We report an ultra-widely tunable long-period holey-fiber grating, which combines the wide-range single-mode behavior and transverse strain sensitivity of the holey fibers with the advantages of mechanically induced long-period fiber gratings. We obtain a versatile widely tunable long-period holey-fiber grating with attractive transmission spectral characteristics for optical communications, fiber-based amplifiers, and lasers. The mechanically induced long-period holey-fiber grating shows a continuous tuning range over 500 nm, more than 12 dB depth notches with less than 0.75 dB out-of-band losses, and bandwidth control from 10 to 40 nm. © 2007 Optical Society of America

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1. Introduction

Long-period fiber gratings (LPFGs) are a special class of Bragg fiber gratings that can be fabricated by changing the refractive index periodically in the fiber core. This periodical perturbation couples energy from the fundamental mode (LP_{01}) in the fiber core to cladding forward unguided modes (LP_{0m}). The coupling is highly efficient at a wavelength given by the phase-matching condition $\lambda = (n_{co} - n_{cl})\Lambda$, where n_{co} and n_{cl} are the effective index of the core and cladding, respectively, and Λ is the grating period.[1] To accomplish this, several fabrication techniques have been proposed. The first method used in germanium-doped fibers was the UV radiation.[2,3] However, since LPFGs require a large perturbation period in the range of 100–1000 μm and the spreading out of germanium-free microstructured optical fibers,[4] other methods such as thermal and mechanical pressure have been extensively explored in recent years.[5–10]

Mechanically induced LPFGs are of particular interest since they are versatile and can be implemented in almost any type of fiber. In mechanically induced LPFGs the fiber is subject to periodical stress, which results in alternated regions under compression and stretching that modulate the refractive index via the photoelastic effect. The main advantages of mechanically induced LPFGs are the wide tuning range and bandwidth control, and they are erasable and reconfigurable.[10,11] These characteristics make mechanically induced LPFGs an attractive option when a broadly tunable nonreflecting band-rejection filter is required for applications such as the elimination of communication channels, or to remove Stoke orders in cascaded Raman-based lasers and modulators. Furthermore, they can be used as dynamic gain equalizers in fiber amplifiers or lasers,[12] as well as key components in tunable and reconfigurable cascaded LPFGs in multiwavelength Raman lasers, all-fiber Mach–Zehnder interferometers, and wide-band polarization-dependent loss compensators.[13–15] In addition, mechanically induced tunable LPFGs could find applications in the fiber sensor field. Recently, P. Steinvurzel *et al.* reported a novel wide thermal tuning method in a mechanically induced long-period fluid-filled photonic-bandgap fiber grating,[16] and this method promises potential applications in all-fiber temperature sensors. For all these applications it would be useful to develop simple and inexpensive flexible mechanically induced tunable LPFGs.

Different techniques of mechanically induced tunable LPFGs have been reported in standard com-

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munication fibers and microstructured optical fibers, where corrugated plates, strings, and springs have been used to apply periodical mechanical stress on the optical single-mode fiber to induce the effective index modulation to obtain the coupling of light from the fundamental mode to antisymmetric LP_{1m} modes.[17–19] One of the most relevant characteristics that share these techniques is their tunability by simple adjustment of the mechanical stress period. Mechanically induced LPFGs offer a tuning range at least one order of magnitude wider than other methods reported in tunable permanent recorded LPFGs with similar isolation loss and linewidth.[20–22] Among these mechanical techniques reported for temporal inscription of tunable LPFGs, techniques based on corrugated plates present some practical advantages, such as simple control of the resonance wavelength and bandwidth, as well as simple implementation.

A key parameter in the LPFG design is the type of optical fiber used. In this matter, microstructure optical fibers, also called holey fibers (HFs), can offer unique properties such as endlessly single-mode behavior, engineering dispersion, and highly polarization-dependent broadband coupling compared with standard step-index fibers.[23,24,15] Moreover, holey fibers have been demonstrated to be an adequate medium to implement LPFGs. Compared with LPGs written in standard step-index fibers, holey fibers offer more stable performance against changes in temperature, strain, and the refractive index of the medium that surrounds the cladding.[9] All these features make holey fibers an excellent platform for the engineering of mechanically induced tunable LPFGs.

In this paper, we present a simple widely tunable long-period holey-fiber grating by the use of mechanical pressure. The experimental results show a tuning range over 500 nm, a depth notch of 12 dB with less than 0.75 dB loss out-of-band, and adjustable bandwidth from 10 to 40 nm. These characteristics and its simple implementation make it an attractive widely tunable long-period holey-fiber grating with potential applications in optical communications and all-fiber devices.

2. Experiment and Results

In this proposal, the mechanically induced tunable long-period holey-fiber grating (LPHFG) is obtained by pressing an adjustable half-semicircular section of a single-mode holey fiber on a radial corrugated grooved plate (CGP) by a flat plate as is shown in Fig. 1(a). This simple radial design permits one to select the period (Λ) by adjusting the bending radius R to obtain a continuous tunability of the long-period holey-fiber grating from near-infrared to visible. Figure 1(b) shows a photograph of transversal section of the holey fiber; it has an 11 μm core and 125 μm cladding diameter with 5 μm hole diameter and lattice pitch of 11 μm. We used this holey fiber in the tunable LPG setup to achieve single-mode operation from near-infrared to visible without intermodal coupling between core modes.

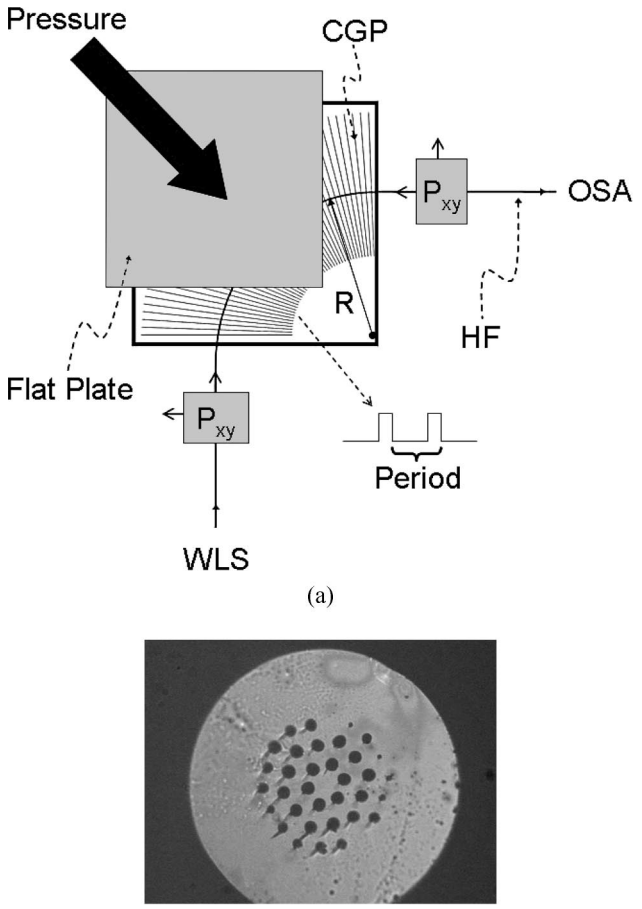
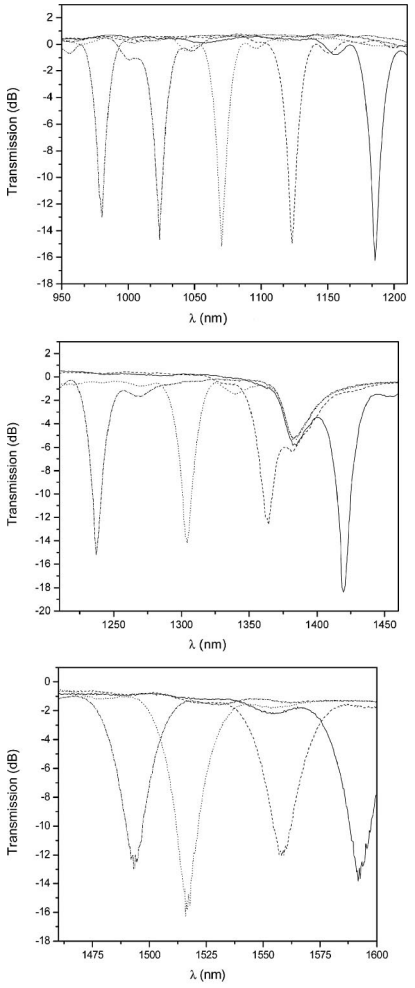


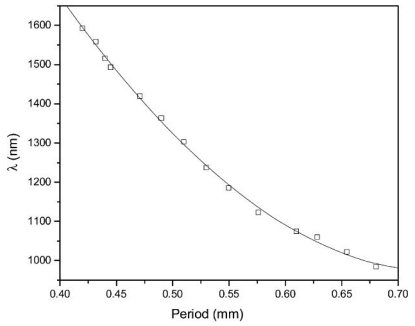
Fig. 1. (a) Schematic of experimental mechanically induced LPHFG setup. (b) Cross-sectional image of the holey fiber.

The novel corrugated metallic plate was fabricated with a radial step grooved pattern, which contains 60 step grooves, and each one has 360 μm diameter and 900 μm depth. The CGP design permits one to change continuously the period (Λ) by adjusting the bending radius R, according to the expression $\Lambda = (\pi/120)R$; here R and Λ are in millimeters. For this particular design, Λ varies from 393 to 1308 μm. In a full period, the press section on the fiber varies with $\Lambda - 360$ μm. The dimensions of the CGP and the cover flat plate are 50 mm long and 50 mm wide, and the half-semicircular grooved sector in the corrugated plate has internal and external radii of 15 mm and 50 mm, respectively.

In the spectral transmission characterization of a LPHFG, the signal from an unpolarized white light source (WLS) was launched into one end of the HF through a fiber connector (FC) fiber adapter, while the other end was coupled to the optical spectral analyzer (OSA). Then, the fiber was laid in half-semicircular form over the grooved plate employing two x–y translation stages (P_{XY}), and a simple manual press system was used to push the cover flat plate on the CGP. The transmission spectrum of the long-period holey fiber grating for different values of Λ is



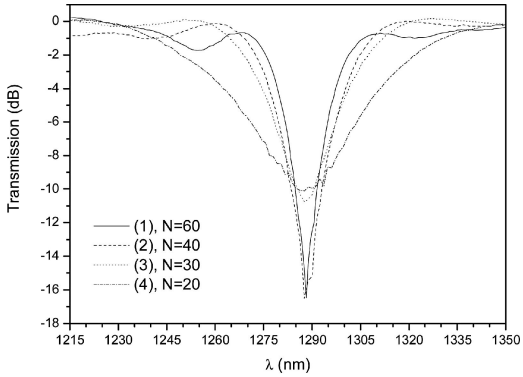
(a)



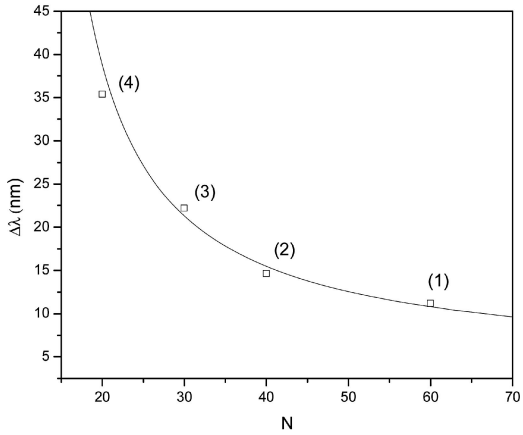
(b)

Fig. 2. (a) Transmitted spectrum of the LPHFG for different periods. (b) Central peak shift with period variation.

illustrated in Fig. 2(a), where we can observe a tunable range of at least of 600 nm from 970 to 1580 nm and depth notches from 12 to 16 dB. In all cases, the out-of-band loss was less than 0.75 dB. The entire transmission spectrum was separated in three sections to avoid confusion of overlap between the principal notches and second-order notches. In central Fig. 2(a), we can observe an absorption band in $\lambda = 1382$ nm that corresponds to the water absorption remnant in the holey fiber. Figure 2(b) shows the central resonance wavelength of the LPHFG as a function of the period, where we can observe the typical redshift of the resonance wavelength while the period grating is increased. In this case, we observe a nonlinear dependence between the wavelength center and the size period because of the influence of the bending radius of the holey fiber. We have found from the experimental data that the dependence of the center wavelength on the grating period can be approximately fitted by a third-order polynomial, i.e., $\lambda_{\text{center}} = \sum_{i=1}^{4} c_i \Lambda^{t-1}$, where Λ is the grating period and the coefficients c_i are given by $c_1 = 4095.08$, $c_2 = -7870.59$, $c_3 = 4082.77$, and $c_4 = 1149.82$. On other hand, we did not find any limitation in the bending radius to reach the L communication band. In this region, a bending radius of 16 mm was necessary to have a resonance peak at 1591 nm, which is larger than the critical bending radius for the single-mode holey fibers.



(a)



(b)

Fig. 3. (a) Transmitted spectrum notch ($N = 20$, 30, 40, 60 and $\Lambda = 0.514$ mm). (b) Bandwidth notch ($\lambda = 1288$ nm and $\Lambda = 0.514$ mm).

The bandwidth ($\Delta\lambda_0$) of the LPHFG keeps approximately constant in the tuning range, as can be observed in Fig. 2(a); however, the bandwidth control of the LPHFG can be realized by changing the number of the periods (N) in the grating according to $-\Delta\lambda_0/\lambda = 2/N$. Figure 3(a) illustrates the transmis-

sion spectrum bandwidth variation for different numbers of periods at $\lambda = 1288.2$ and $\Lambda = 0.514$ mm. In this figure we can observe a wider bandwidth when we decrease the number of periods, which is accompanied by a reduction in the notch depth. Figure 3(b) shows the behavior of the bandwidth as a function of the number of periods. The notch depth depends directly of the pressure on the flat plate; however, if the pressure is increased excessively, we observe a reduction of the notch depth and instability. Also the bandwidth of the LPHFG can be adjusted by introducing an aperiodical pitch in the holey fiber over the corrugated plate. For $N = 40$ and a small monotonically variation in the period, the bandwith was almost constant, but for a lineal change of 12 μm, we found that the bandwidth could increase from 15 to 20 nm, although the isolation loss decreased to 8 dB. Finally, it was not possible to test the polarization dependency of the proposed LPHFG. However, since the pressure in one direction induces asymmetrical stress and deformation on fiber structure, which results in induced linear birefringence, we can predict that the change in input polarization states in the mechanically induced LPHFG indeed results in distinctive resonance wavelength for each eigenpolarization state, as reported by D. Lee *et al.*[15]

According to these results, the proposed long-period holey-fiber grating offers a wide tunable range from visible to near-infrared with simple selective resonance wavelength center and bandwidth control. Mechanical tests on the fatigue of the holey fiber were not realized. But the experimental results showed that the same fiber can be used under many repetitive cycles of pressure without loss of mechanical fiber integrity. Also, the engraved gratings preserve their transmission spectra for days. One technical drawback of this mechanically induced LPHFG, for several specific applications, is its tunability in real time, since it is limited by the response time of the mechanical system involved in the bending fiber adjustment and the press rig. With these characteristics and limitations, the proposal configuration promises to be very useful in the laboratory for diverse applications in the development of all-fiber devices.

3. Conclusions

We propose a simple ultra-widely tunable long-period holey-fiber grating based on mechanical stress. The long-period holey-fiber grating shows a continuous tuning range over 500 nm with simple selective center wavelength, more than 12 dB depth notches, with less than 0.75 dB out-of-band loss, and bandwidth control from 10 to 40 nm. Additionally, the configuration offers to be erasable and reconfigurable in the fiber and low-cost implementation. This mechanically induced LPHFG promises to be useful in fiber optical filtering operations.

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