Strain-insensitive and high-temperature long-period gratings inscribed in photonic crystal fiber

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We fabricate and demonstrate strain-insensitive and high-temperature long-period gratings in endlessly single-mode photonic crystal fiber by use of focused pulses of a CO₂ laser and a periodic stress relaxation technique without geometrical deformation and elongation of the fiber. The thermal dependence of mode coupling at 1299.59 nm is 10.9 pm/°C from 24 to 992 °C, whereas the coefficient of strain sensitivity is −0.192 pm/με up to the maximum strain of 2.74%. It is found for what is believed to be the first time that, in contrast with the traditional fiber case, the coupling resonance shifts toward shorter wavelengths under applied strain, indicating that the refractive index of the core is decreased as a result of the rebuilding of tension attributed to the stress-elastic effect, and the cladding modes is highly dispersive because of airholes arranged in the fiber cladding. © 2005 Optical Society of America

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Long-period gratings (LPGs), which satisfy the phase-matching condition between the fundamental core mode and a set of forward-propagating cladding modes in an optical fiber, are fiber-optic components that are widely used in optical telecommunications and sensors because they have many advantages, such as low backreflection and insertion loss, insensitivity to electromagnetic interference, polarization independence, and cost effectiveness. It was reported that LPGs and fiber Bragg gratings were formed with several different methods in photonic crystal fibers (PCFs) that consisted of a pure-silica core by introducing a defect or a missing hole at the fiber center and surrounding it with airholes that run along the length of the fiber. Moreover, PCF-based active optoelectronic devices, such as tunable PCF couplers and Mach–Zehnder interferometers, were studied for their potential applications in dense wavelength-division multiplexing networks and sensing systems.

To distinguish the mechanisms of inscription of LPGs by use of versatile techniques, Malki et al. studied the writing mechanism of electric-arc-induced LPGs in SMF-28 fiber by use of Raman and luminescence spectroscopy, finding that the local fiber structural rearrangement and the weak geometrical deformation of glass modified the refractive indices of the fiber core and cladding, whereas Kim et al. proposed an effect of CO₂-laser irradiation on the refractive-index change in traditional fibers by measuring the interference fringe shift formed by a pair of LPGs. Although these researchers depicted the mechanisms of the grating formation in normal fibers by alternative methods, much attention was recently given to the unique characterizations of PCF-based LPGs. Humbert et al. reported the characterization of LPGs in PCF at temperatures from 20 to 1200 °C; however, for sensing technology, the properties of gratings under applied strain also should be probed. Zhou et al. recently performed tensile tests on PCF and confirmed that it has a higher practical strength than traditional fiber, but investigation of the mechanical characteristics of LPGs in PCF has been limited so far.

In this Letter we present a study of strain-insensitive, high-temperature LPGs in an endlessly single-mode photonic crystal fiber (ESM-PCF) obtained by use of a CO₂ laser with periodic stress relaxation and a point-by-point technique. We also characterize, for the first time to our knowledge, these fabricated gratings with respect to their thermal sensitivity in a high-temperature environment as well as their mechanical stability under applied strain. The temperature and strain dependences of the transmission spectra are measured in situ, and this results in an application in which the refractive-index changes of materials surrounding the gratings are detected under harsh conditions.

It is well known that LPGs can be formed in Ge-doped silica fiber by use of UV irradiation with hydrogenation and an amplitude mask technique. However, formation of LPGs is not straightforward in a PCF with a pure-silica core because there is no photosensitivity provided by germanium–oxygen vacancy defect centers, which can be permanently photoinized by UV absorption to cause a refractive-index change through the Kramers–Kronig relation. As was demonstrated by Zhu et al., the LPGs were fabricated in pure-silica PCF primarily by modification of the glass structure. However, any geometrical deformation in a silica fiber causes it to become weak because of flaws or cracks created as stress intensifiers that finally fracture the fiber at low stress levels. A writing technique was presented more recently by which LPGs can be formed in a pure-silica PCF by an arc discharge without physical deformation. Such gratings written by a CO₂-laser beam and their writing mechanism have not been investigated and reported yet, to our knowledge.

During the PCF drawing process a melting preform is drawn to the size of a normal fiber diameter. Tension is accumulated in the fiber core, while compression is generated in the cladding with frozen silica, because
the softening temperature of the cladding with airholes is lower than that of the solid silica core. The tension and compression, which are called mechanically residual stress, influence the refractive indices of the core and the cladding, respectively, by the photoelastic effect. Stress in the fiber can be released at the softening temperature of silica by a focused pulse from a CO$_2$ laser or an electric arc, and the refractive index can be changed as shown schematically in Fig. 1. It is worth noting that, because of the mechanical tension embedded in the core, a change in refractive index ($\Delta n = 8.5 \times 10^{-4}$) is enough to inscribe LPGs in the PCF, and inscription can be achieved by periodic stress relaxation without collapse of the holes. The ESM-PCF used in our experiments was supplied by Crystal-Fibre A/S. The fiber has a hole pitch $\Lambda = 7.4$ $\mu$m and a hole diameter $d = 3.2$ $\mu$m ($d/\Lambda = 0.43$). The core diameter is defined by $D_{core} = 2\Lambda - d = 11.6$ $\mu$m. The diameter of the region of holes is $\sim 60$ $\mu$m, and the outside diameter of the fiber has a typical value of 125 $\mu$m. These fibers are single mode at all wavelengths for which fused silica is transparent. The experimental setup and the grating fabrication procedure are described in Ref. 12.

Characterization of the inscribed LPGs at high temperature was performed with a tubular furnace, whereas the mechanical property of the gratings was demonstrated by direct tension applied along the fiber axes. A superluminescent diode was used to illuminate the fiber, and the output spectra were measured with an optical spectrum analyzer. In thermal experiments, one grating in ESM-PCF (six periods of 530-$\mu$m period length, 1299.59-nm resonance wavelength with isolation loss of $\sim 28$ dB) and another grating in SMF-28 (15 periods of 500-$\mu$m period length, 1252.95-nm resonance wavelength with isolation loss of $\sim 22$ dB) were heated from room temperature (24 $\pm$ 1°C) to 1300°C at an average rate of 10°C/min. We investigated the microstructural rearrangement of fibers by annealing the fiber gratings at 1000°C and 1300°C each for 1 h. The transmission spectra of the gratings at room temperature and at 992°C are shown in Fig. 2. For shifts of resonance wavelength with temperature, the grating in ESM-PCF is much less sensitive than that in SMF-28, because of the unique material in the PCF, and in turn there was no viscoelastic effect between the fiber core and cladding. The inset of Fig. 2 shows an optical micrograph of the fiber's appearance with a LPG, and no physical deformation was observed after the ESM-PCF was treated with a CO$_2$-laser heat source.

![Fig. 1. Diagram of refractive-index change in PCF with mechanical stress relaxation.](image1)

![Fig. 2. Transmission spectra of resonance wavelengths of LPGs in ESM-PCF and SMF-28 fiber at room temperature, before and after 1 h at 992°C. Inset, optical micrograph of the ESM-PCF's appearance with the LPG. No physical deformation was observed after the ESM-PCF was treated with a CO$_2$-laser heat source.](image2)

![Fig. 3. Resonance wavelength shift with temperature variation of LPGs in ESM-PCF and SMF-28. Insets, scanning electron microscope images of the ESM-PCF cross section at (top) 1000°C and (bottom) 1300°C.](image3)
Tension testing of gratings in two fibers was conducted with applied strain from 0.21 to 2.75%\( \epsilon \). The resonance wavelength of the LPG in the ESM-PCF with applied strain shifted toward the blue side, and the strain sensitivity was \(-0.192\) pm/\( \mu \)\( \varepsilon \) up to the maximum strain of 2.74%\( \epsilon \). As the applied strain on the LPG in the ESM-PCF grows, the densification of the glass increases and the refractive index of the core is smaller than its original one, which results in weak mode-coupling strength. As the coupling strength is a sinusoidal profile, the fundamental mode can couple with a higher-order cladding mode and create a new resonance wavelength that is located in another region of the spectrum.

In conclusion, we have experimentally characterized the properties of fabricated PCF-based LPGs at high temperature and applied strain. Compared with the temperature sensitivity of LPGs in SMF-28, which is 119 pm/\( ^\circ \)C at a temperature region from 24 to 992\( ^\circ \)C, a grating in ESM-PCF is more stable at high temperature (10.9 pm/\( ^\circ \)C). Furthermore, the gratings that were formed showed good performance in terms of strain insensitivity (\(-0.192\) pm/\( \mu \)\( \varepsilon \)), making them potential candidates for applications as sensors at high temperature and in harsh environments, such as space aircraft, nuclear power plants, and the chemical industry.

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