Single-mode grating reflection in all-solid photonic bandgap fibers inscribed by use of femtosecond laser pulse irradiation through a phase mask

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Single-mode Bragg grating reflection has been achieved in all-solid photonic bandgap fibers by use of femtosecond laser pulse irradiation through a phase mask. The grating created is confined to the all-silica fiber core region and exhibits higher thermal stability than other type I femtosecond-pulse-induced gratings.

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The photonic bandgap (PBG) fiber is an optical fiber that confines the light to the fiber core by use of the PBG of the cladding material, without resorting to total-internal reflection. In recent years, the hollow-core PBG fibers and associated devices have attracted a lot of research interests because of their low level of dispersion and deleterious nonlinear effects and high potentials of low propagation loss, created by the reduced level of scattering and absorption in the empty core [1,2]. However, such fibers are difficult to fabricate and suffer from the drawback of large splicing loss when connected to the conventional single-mode fibers (SMFs). Furthermore, surface modes are excited in the fiber structure [3], which significantly affects the fiber transmission properties. On the contrary, all-solid PBG fibers are easy to fabricate and convenient to splice to the conventional SMFs as no air hole collapse occurs, and the fiber core can be readily doped for Bragg grating inscription or lasing or amplifying system activation. Such fibers are usually composed of a two-dimensional array of high-index rods embedded in a low-index background material [4], with the core formed by omitting one or more rods [5], and have potential applications in compact photonic devices [6].

Recently, fiber Bragg gratings (FBGs) have been inscribed into the Ge-doped cladding rods in all-solid PBG hydrogen loaded fibers by use of KrF excimer laser and the grating resonance coupling to the guided LP_{01} supermodes has been observed, which is much stronger than that between the core modes [7] and as a result, a single-mode grating reflection cannot be achieved, which essentially limits the grating applications.

In this Letter, the FBGs written in nonphotosensitive all-solid PBG fibers by use of femtosecond laser pulses are presented. The gratings are located in the all-silica core region, and as a result, single-mode grating reflection can be obtained. The thermal stability of the FBGs fabricated is better than that of the other type I femtosecond-pulse-induced gratings.

The PBG fiber used in this work is fabricated in the University of Bath by using a modified stack-and-draw process [4], in which a Ge-doped high-index rod lattice of six layers is embedded in pure silica background (with the index difference of 1%), and the core is formed by omitting one single rod (as shown in Fig. 1). The pitch of the high-index rods is 11 μm, and the nominal ratio of the diameter of the raised-index rods to the pitch is $d/\Lambda = 0.4$. The fiber diameter is $\sim$200 μm. In the experiment, a 3 cm length of the PBG fiber was spliced to the conventional single-mode fibers which were well aligned to minimize the insertion loss and to avoid complicated mode couplings between the high-index rods and the fiber core. Owing to the mode field mismatch, the total insertion loss obtained was $\sim$6 dB. After splicing, the fiber was exposed to 800 nm 120 fs laser pulses from a *spectra-physics spitfire* Ti:sapphire amplifier with the repetition rate of 1 kHz and the $1/e$ Gaussian beam radius of 2 mm. The laser system had the maximum pulse energy of $\sim$1.0 mJ, which was attenuated by rotating a half-wave plate followed by a linear polarizer. The laser beam was focused using a cylindrical lens with the focal length of 60 mm before passing through a silica phase mask to illuminate the all-solid PBG fiber. The focal line could be adjusted by moving the cylindrical lens, which was mounted on a three-

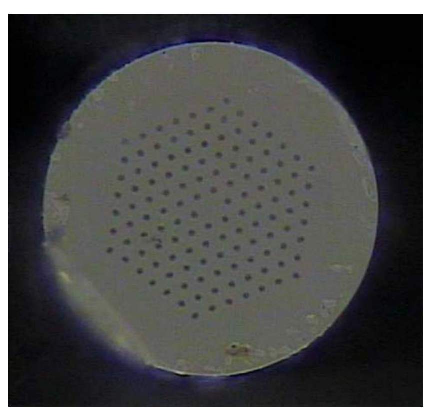

Fig. 1. (Color online) Microscopic photograph of the cross section of the all-solid PBG fiber. The black spots represent Ge-doped rods.

dimensional (3D) precision positioning stage, and the laser beam behind the fiber was monitored with a CCD camera. The focal position could be estimated by the beam shape; however, the actual position was determined by the morphology picture of the grating. Assuming a Gaussian light beam, the width of the focal line on the fiber core is about $2\omega \approx 2\lambda f/\pi\omega_0 = 15.2\ \mu\text{m}$, where λ is the laser wavelength, f is the focal length of the focusing lens, and ω_0 is the incident beam diameter (the focusing effect of the 125 μm diameter fiber cladding has not been taken into account). The phase mask used (Ibsen Photonics) had the grating pitch of 540 nm and the dimension of $10 \times 10\ \text{mm}^2$ was optimized for 800 nm illumination, with the first-order diffraction efficiency of 72.8%. The fiber to be inscribed in was located in a close distance of $\sim$300 μm to the phase mask, which was accurately positioned using a high-precision four-axis translation stage. Since $\sim$20.6% of the zeroth-order diffraction could not be blocked, partial annealing occurred during the growth of the grating.

By carefully adjusting the focal line to be located in the fiber core, the grating structure was successfully formed owing to refractive index modulation in the fiber core, induced by the multiphoton absorption. The online measurement of the grating spectrum was implemented by using a superwide-band light source (Amonics ALS-CWDM-FA) and an optical spectrum analyzer (Yokogawa AQ6319) with a resolution of 0.02 nm. The consistency of the results could be observed by fabricating a number of gratings under the same conditions. The fiber was then cleaved at the center of the FBG, and the morphology profile across the fiber section was examined by a Nikon 80i microscope.

Bragg grating with transmission of −8 dB, spectral bandwidth of 0.45 nm, and out-of-band insertion loss of about 1 dB was inscribed in the nonphotosensitive all-solid PBG fiber with the pulse energy of 620 μJ (intensity of $\sim 1.4 \times 10^{13}\ \text{W/cm}^2$). The exposure time was $\sim$30 min because of the slowly grating evolution and the saturation of the FBG peak growth was observed for this type I grating. The transmission and reflection spectra are shown in Fig. 2. Assuming a uniform FBG (of 4 mm length), the refractive index modulation in the fiber core corresponding to the −8 dB transmission at the resonant wavelength of $\lambda_{\text{Bragg}} = 1566.9$ nm was estimated to have $\Delta n_{\text{ind}} = 1.2 \times 10^{-4}$. The supermode reflections were not observed from the spectrum, which may result from the almost uniform index change across the fiber core as can be seen from the optical microscope image of the grating fringes created by the refractive index modulation in the fiber core region (see Fig. 3). Jin *et al.* [7] demonstrated the supermode resonance generated by the phase relationships among the rods in the UV-laser-induced Bragg gratings in hydrogen-loaded all-solid PBG fibers. Hydrogen loading was reported to result in a dramatic enhancement of the photosensitivity of the Ge-doped rods, which leads to a significantly lowering of the grating writing threshold [8], and the gratings obtained were most probably formed in the Ge-doped rods instead of the pure silica core area.

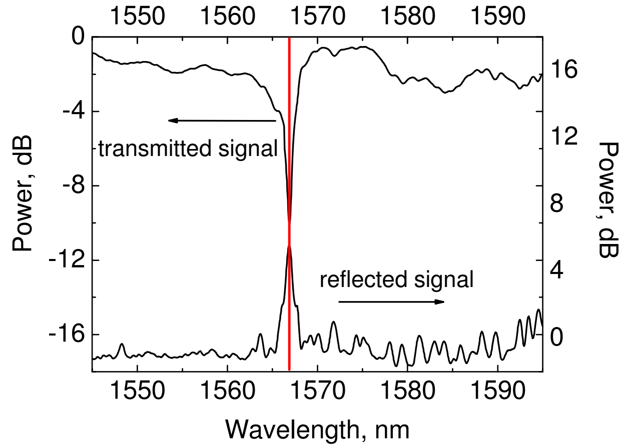

Fig. 2. (Color online) Transmission and reflection spectra of the FBG fabricated in an all-solid PBG fiber with 620 μJ pulse energy.

Since the all-solid PBG fibers used in our work were not loaded with hydrogen, the location of gratings mainly depends on the position and the size of the focal line. By careful alignment, the gratings could be formed merely in the core region; thus, no supermode resonances were observed in our experiment and a clear single-mode grating reflection was obtained.

The femtosecond-laser-pulse-induced grating in all-solid PBG fibers as shown in Fig. 3 has a regular structure with the total length of $\sim$3.5 mm. Such a structure could become irregular in the regions where the Gaussian beam profile tapered to zero, resulting in some missed grating lines. The grating lines were located in the fiber core area as shown in Fig. 3(a), where the laser incident direction was also plotted. The influence area of the femtosecond pulses along the beam propagation direction was approximately rectangular with $\sim 15 \times 65\ \mu\text{m}^2$ dimension as shown in Fig. 3(b), where the cross section of the fiber was cleaved at the center of the FBG. It can be observed that except for the all-silica core area, the Ge-doped rods were not affected by the laser pulses and remained unchanged.

The thermal stability of the FBG is an important issue toward its practical applications, which is characterized by the isochronal annealing approach using an ISOTHERMAL PEGASUS$^{\text{PLUS}}$ 1200 tube furnace. The annealing characteristics of the FBGs written in the nonphotosensitive all-solid PBG fibers have been investigated, and the results are shown in Fig. 4, where the decay in the grating reflectivity is represented in terms of the decay in refractive index

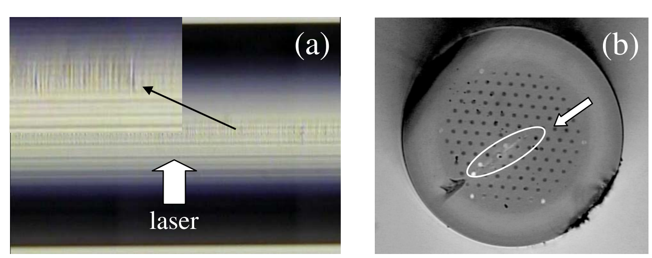

Fig. 3. (Color online) Microscope images of the grating morphology in the (a) longitudinal and (b) the cross section of the fiber.

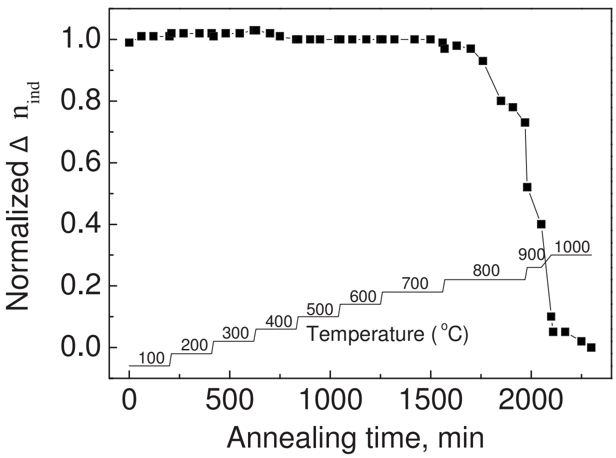

Fig. 4. Thermal degradation of the FBG written in all-solid PBG fiber, with elapsed time over various temperature ranges.

modulation of the gratings written in these fibers [9]. When the gratings fabricated in all-solid PBG fibers were subjected to a series of thermal exposures at 100°C, 200°C, and then progressively to 1000°C with a temperature increment of 100°C, the corresponding variation of the refractive index modulation (Δn_{ind}) was recorded in Fig. 4. It could be observed, as expected that the gratings were more thermally stable when compared with UV-laser-induced samples. The gratings were almost unaffected by the thermal exposure up to 700°C with a value of $\Delta n_{\mathrm{ind}} = 1.2 \times 10^{-4}$, following which a slowly decay occurred at the elevated temperatures. The temperature corresponding to the 50% decrease in the normalized refractive index change Δn_{ind} was 900°C, instead of 650°C for the UV-laser-induced gratings in the H_2-free fibers as reported in [10] (the thermal stability of the H_2-loaded fibers is even worse), even higher than that of the type I femtosecond-laser-induced gratings in Ge-doped SMF-28 fibers (about 800°C as reported in [11]). The gratings in-all solid PBG fibers can sustain a higher temperature than that of the conventional FBGs, which is probably due to the difference in the fiber structure and the fact that the refractive index modulation region is confined within the pure silica core of the fiber.

In conclusion, Bragg gratings have been successfully written in the nonphotosensitive all-solid PBGs by use of femtosecond pulse irradiation through a phase mask. Such gratings support only a single-mode resonance, which is achieved by aligning the laser focal line at the pure silica fiber core area. The annealing test results show that the gratings inscribed by femtosecond laser pulses exhibit higher temperature stability than that of the other type I femtosecond-pulse-induced gratings.

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References

1. J. C. Knight, Nature **424**, 847 (2003).
2. B. J. Eggleton, P. S. Windeler, S. Spalter, and T. A. Strasser, Opt. Lett. **24**, 1460 (1999).
3. K. Saitoh, N. A. Mortensen, and M. Koshiba, Opt. Express **12**, 394 (2004).
4. F. Luan, A. K. George, T. D. Hedley, G. J. Pearce, D. M. Bird, J. C. Knight, and P. St. J. Russell, Opt. Lett. **29**, 2369 (2004).
5. A. Argyros, T. A. Birks, S. G. Leon-Saval, C. M. B. Cordeiro, F. Luan, and P. St. J. Russell, Opt. Express **13**, 309 (2005).
6. V. P. Yuri Logvin, Opt. Express **15**, 985 (2007).
7. L. Jin, Z. Wang, Q. Fang, Y. Liu, B. Liu, G. Kai, and X. Dong, Opt. Express **15**, 15555 (2007).
8. C. W. Smelser, S. J. Mihailov, and D. Grobnic, Opt. Lett. **29**, 2127 (2004).
9. S. Pal, J. Mandal, T. Sun, K. T. V. Grattan, M. Fokine, F. Carlsson, P. Y. Fonjallaz, S. A. Wade, and S. F. Collins, Meas. Sci. Technol. **14**, 1131 (2003).
10. J. Albert, B. Malo, K. O. Hill, F. Bilodeau, D. C. Johnson, and S. Th'eriault, Appl. Phys. Lett. **67**, 3529 (1995).
11. Yuhua Li, C. R. Liao, D. N. Wang, T. Sun, and K. T. V. Grattan, Opt. Express **16**, 21239 (2008).