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# Fabrications of Fiber Bragg Gratings Written in Photonic Crystal Fibers

Yiping Wang[1,2,*], H. Bartelt[3], M. Becker[3], S. Brueckner[3], J. Bergmann[3], J. Kobelke[3], and M. Rothhardt[3]

[1] *College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China*
[2] *Photonic Research Center, Harbin Engineering University, Harbin 150001, China*
[3] *Institute of Photonic Technology, Albert-Einstein-Str. 9, 07745 Jena, Germany*

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We report a two-beam interference method employing a femtosecond or excimer laser to write fiber Bragg gratings in the pure-silica and Ge-doped photonic crystal fibers (PCFs). The effects of the $H_2$-loading and Ge-doping techniques on the efficiency of grating inscription were investigated by measuring the development of Bragg wavelength and attenuation in the transmission spectra with increasing exposure dose. $H_2$-loading dramatically enhances the laser-induced index modulation not only in Ge-doped PCFs but also in pure-silica PCFs.

**Keywords:** Fiber Bragg Gratings, Photonic Crystal Fibers, FS Laser, Excimer Laser.

## 1. INTRODUCTION

The UV laser exposure is a common technique for writing a fiber Bragg grating (FBG) in a photosensitive photonic crystal fibers (PCFs).[1–6] Recently, the Femtosecond (FS) laser irradiation was developed to write gratings in Ge-doped or pure-silica glass fibers by means of the phase mask methods,[7] the point-to-point methods,[8] and the two- or multiple-beam interferences.[9] For the common phase mask method, the Bragg wavelength of the grating thus generated is directly related to the period of the phase mask employed and cannot be modified in a simple way. In this paper, we report on FBGs written in pure-silica and Ge-doped PCFs before/after $H_2$-loading with a FS or excimer laser and a two-beam interference technique. Such a two-beam interference technique can write FBGs with different Bragg wavelengths by employing a phase grating as a beam splitter in an interferometric setup.

## 2. FBG FABRICATIONS

We written FBGs in two different types of PCFs with a FS laser or an excimer laser and two-beam interference, as shown in Figure 1.[10,11] In the case of FS inscription, FS pulses with a width of 350 fs, a wavelength of 262 nm, a repetition rate of 1 kHz and a pulse energy of 180 $\mu$J were generated by tripling the frequency of the output pulses (130 fs, 786 nm) from a Ti:sapphire amplifier (Quantronix, Titan) seeded by a FS laser oscillator (Coherent, Mira). The FS laser beam with a diameter of 6 mm was focused to a focal line (6 mm × 30 $\mu$m) by a cylindrical lens with a focal length of 335 mm. In the case of excimer laser inscription, nanosecond (NS) pulses with a width of 20 ns, a repetition rate of 1 or 10 Hz, and a pulse energy of 160 mJ were generated by a 248 nm KrF excimer laser (Compex 150T, Lambda-Physics). The laser beam (20 mm × 7.5 mm) from the excimer laser was transmitted through a rectangle window (6 mm × 5 mm) and then focused to a focal line (6 mm × 150 $\mu$m) by another cylindrical lens with a focal length of 500 mm. In both cases, the laser beam behind the lens was diffracted at a phase grating with a grating period of 1065.3 nm (for FS laser inscription) or 1060.9 nm (for excimer laser inscription), the beam thereby being split into two equal parts. About 35% of the transmitted light was diffracted into each of the ±1st order diffracted beams. Then the ±1st orders diffracted beams were redirected and combined via two rotatable mirrors, producing an interference pattern on the fiber. For the excimer laser inscription, the PCFs were placed near the focal plane of a cylindrical lens, rather than on the focal line, in order to prevent the fiber from being destroyed by high local laser energy. The estimated mean flux of both diffracted orders together onto the fiber is about 180 mJ/cm$^2$ for each FS pulse and about 290 mJ/cm$^2$

*Corresponding author; Email: ypwang@szu.edu.cn

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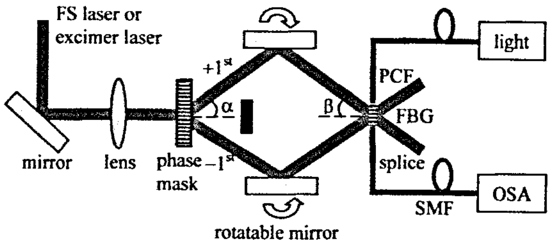


Fig. 1. Experimental setup for writing FBGs with two-beam interference and a FS laser or an excimer laser.

for each NS pulse, respectively. The period of the grating is given by[10, 11]

$$\Lambda = \frac{\lambda_L}{2\sin\beta} \tag{1}$$

where $\lambda_L$ is the wavelength of the laser beam and $\beta$ is the half angle of the intersection of the ±1st order diffracted beams (Fig. 1). Given the Bragg condition of $\lambda = 2n_{\text{eff}}\Lambda$, the Bragg wavelength of FBG written in the fiber can be represented as[10, 11]

$$\lambda_B = \frac{n_{\text{eff}} \cdot \lambda_L}{\sin\beta} \tag{2}$$

where $n_{\text{eff}}$ is the effective index of the PCF core. It is obvious that the orientation of the rotatable mirrors defines the spatial frequency of the interference pattern and therefore the Bragg wavelength of the grating. Hence, FBGs with different Bragg wavelengths can be written in the PCFs with only a single phase grating employed in our experiments.

The two different types of PCFs employed are a pure-silica PCF (IPHT-84b1a) and a Ge-doped PCF (IPHT-282b5) from the Institute of Photonic Technology (http://www.ipht-jena.de), as shown in Figure 2. Parameters of the PCFs are listed in Table I. The central region of IPHT-282b5 with a diameter of about 0.8 $\mu$m is doped with a high concentration of germanium. In order to observe the development of transmission spectra with increasing exposure dose, each end of the pure-silica and the Ge-doped PCFs was spliced to a standard single mode fiber (SMF) with a splice loss of 1.5 and 1.0 dB, respectively, by means of arc fusion splicing techniques as reported in the Refs. [12, 13]. The Bragg wavelength and attenuation in the transmission spectrum were

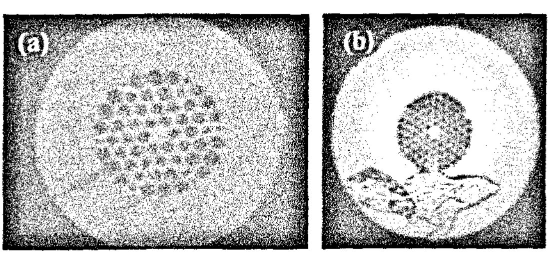


Fig. 2. (a) Cross section images of (a) pure-silica PCF (IPHT-84b1a) and Ge-doped PCF (IPHT-282b5).

Table I. Parameters of pure-silica and Ge-doped PCFs.

| PCF ($\mu$m) | Φ Ge central region ($\mu$m) | Φ Ge socket region ($\mu$m) | Φ core ($\mu$m) | $d$ air hole ($\mu$m) | Λ pitch ($\mu$m) | $d/\Lambda$ | Φ fiber ($\mu$m) |
|---|---|---|---|---|---|---|---|
| IPHT-84b1a | | | 8.8 | 5.6 | 8.0 | 0.7 | 127 |
| IPHT-282b2 | 0.8 | 2.7 | 5.8 | 1.9 | 2.9 | 0.66 | 99.8 |

monitored with a computer-controlled optical spectrum analyzer (OSA) during grating fabrication. For some cases the PCFs were loaded with hydrogen at a pressure of 180 bar and at a temperature of 80 °C during 13 days.

## 3. EXPERIMENTAL RESULTS

We first wrote FBGs in the pure-silica PCF before/after $H_2$-loading with the FS laser. As shown in Figure 3, a FBG with a Bragg wavelength of 1534.88 nm and a peak attenuation of −0.96 dB was achieved in the $H_2$-free pure-silica PCF when the exposure dose increased to 669.78 kJ/cm$^2$, and another FBG with a Bragg wavelength of 1532.60 nm and a peak attenuation of −14.59 dB was achieved in the $H_2$-loaded pure-silica PCF when the exposure dose increased to 495.00 kJ/cm$^2$. It can be found from Figure 3(a) that the Bragg wavelength shifted toward the longer wavelength with increasing exposure dose. It is an interesting phenomenon that, after the exposure was stopped, the Bragg wavelength changed immediately toward the shorter wavelength by about −0.7 nm, and the absolute value of the Bragg attenuation also increased by about 0.2–0.5 dB. Such phenomena were observed for both $H_2$-free and $H_2$-loading PCFs. Further investigation will be done to explain the phenomena.

Then we wrote FBGs in the Ge-doped PCFs before $H_2$-loading with the FS laser as well as with the excimer laser. The repetition rate of the pulses from the excimer laser was 10 Hz. As shown in Figure 4, an FBG with a Bragg wavelength of 1536.98 nm and a peak attenuation of −4.41 dB was achieved with the FS laser when the exposure dose increased to 378.18 kJ/cm$^2$, and another FBG with a Bragg wavelength of 1549.93 nm and a peak attenuation of −2.86 dB was achieved with the excimer laser when the exposure dose increased to 11.31 kJ/cm$^2$. During the FS laser inscription, the wavelength/attenuation also changed immediately after the exposure was stopped. But such a phenomenon was not observed in case of irradiation with NS pulses from the excimer laser.

Finally we wrote FBGs in the Ge-doped PCFs after $H_2$-loading with the FS laser as well as with the excimer laser. The repetition rate of NS pulses from the excimer laser is 1 Hz. As shown in Figure 5, the absolute value of peak attenuation increased promptly due to the ultra-photosensitivity of the $H_2$-loaded and Ge-doped PCF as soon as the laser exposure started. An FBG with a Bragg wavelength of 1545.23 nm and an peak attenuation

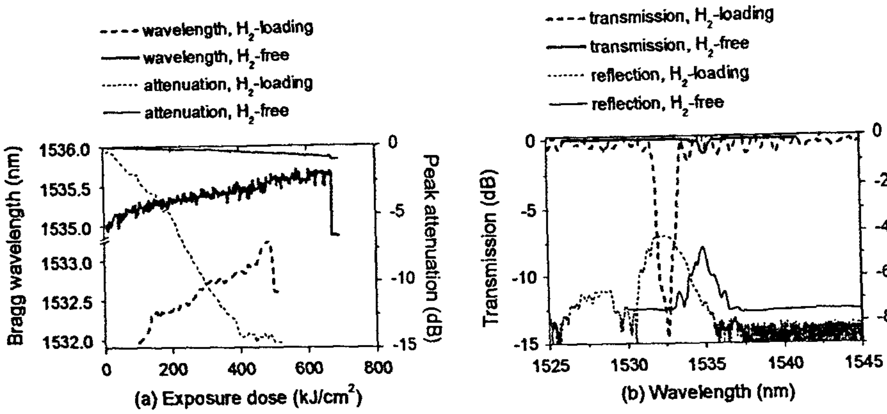


**Fig. 3.** FBGs written in pure-silica PCFs before/after $H_2$-loading with a FS laser, (a) development of Bragg wavelength and peak attenuation with increasing exposure dose, (b) transmission and reflection spectra of the FBGs.

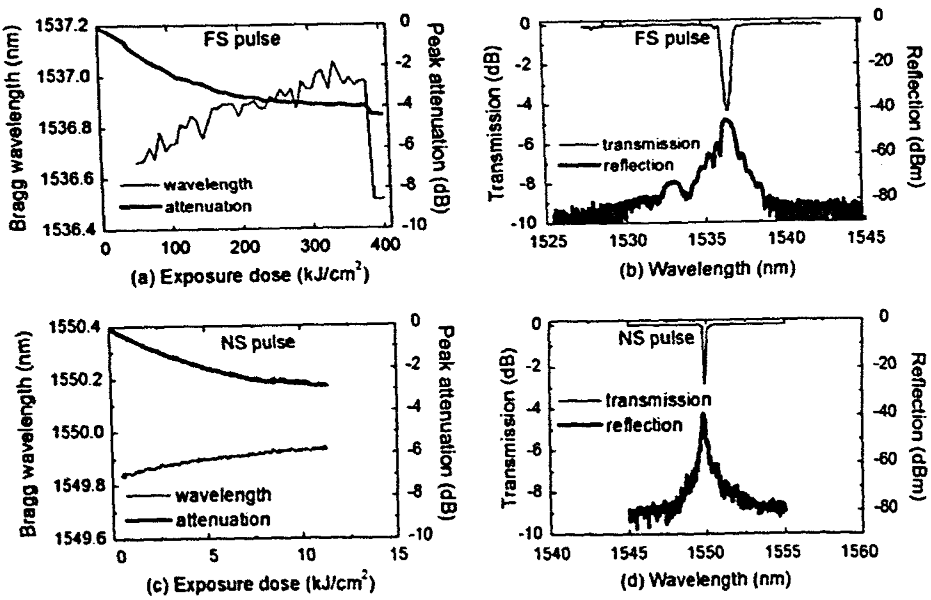


**Fig. 4.** FBGs written in Ge-doped PCFs after $H_2$-loading with (a), (b) a FS laser (FS pulse) and (c), (d) an excimer laser (NS pulse), (a) and (c) development of Bragg wavelength and peak attenuation with increasing exposure dose, (b) and (d) transmission and reflection spectra of the FBGs.

**Table II.** Parameters and results of FBGs written in pure-silica or Ge-doped PCFs before/after $H_2$-loading.

| | Pure-silica PCF (IPHT-84b1a) | | Ge-doped PCF (IPHT-282b5) | | | |
|---|---|---|---|---|---|---|
| Laser | FS laser | | F Slaser | | Excimer laser | |
| $H_2$-loading | No | Yes | No | Yes | No | Yes |
| Number of laser pulses | 3721 K | 2750 K | 2101 K | 40 K | 39 K | 503 |
| Exposure dose (kJ/cm$^2$) | 669.78 | 495.00 | 378.18 | 7.20 | 11.31 | 0.15 |
| Bragg attenuation (dB) | −0.96 | −14.59 | −4.41 | −49.77 | −2.86 | −51.80 |
| Reflectivity (%) | 19.79 | 96.52 | 63.78 | 99.9990 | 48.24 | 99.9993 |
| Max index modulation | $9.6 \times 10^{-5}$ | $5.3 \times 10^{-4}$ | $2.3 \times 10^{-4}$ | $1.5 \times 10^{-3}$ | $1.4 \times 10^{-4}$ | $1.1 \times 10^{-3}$ |
| Bragg wavelength (nm) | 1534.88 | 1532.60 | 1536.98 | 1545.23 | 1549.93 | 1552.12 |

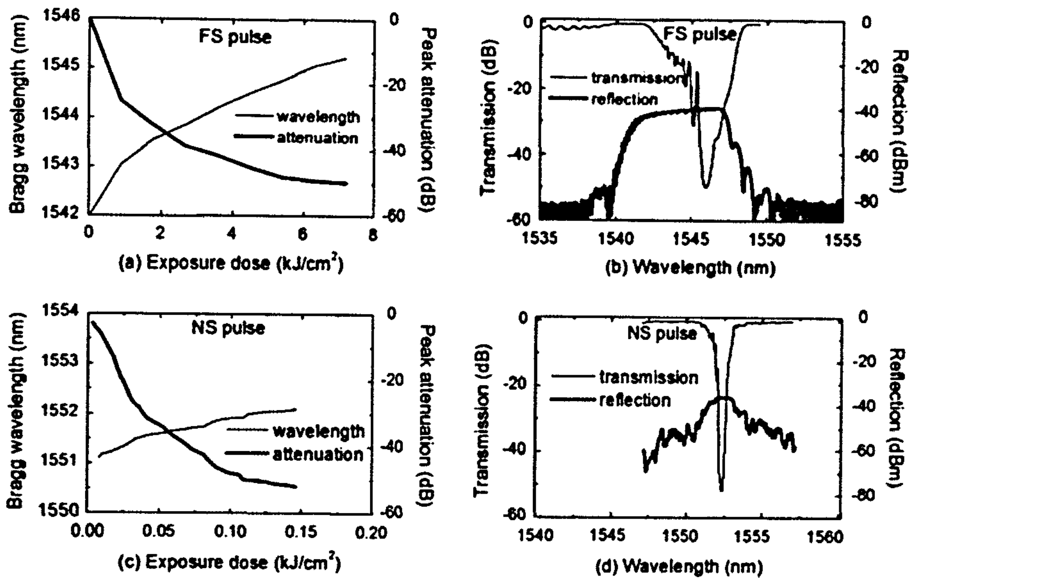


**Fig. 5.** FBGs written in Ge-doped PCFs after $H_2$-loading with (a), (b) a FS laser (FS pulse) and (c), (d) an excimer laser (NS pulse), (a) and (c) development of Bragg wavelength and peak attenuation with increasing exposure dose, (b) and (d) transmission and reflection spectra of the FBGs.

of −49.77 dB was achieved with a FS laser when the exposure dose increased to 7.2 kJ/cm$^2$, and another FBG with a Bragg wavelength of 1552.12 nm and peak attenuation of −51.80 dB was achieved with an excimer laser when the exposure dose increased to 0.15 kJ/cm$^2$.

Additional fabrication parameters and results of our experiments are listed in Table II, in which FBGs with different Bragg wavelengths were fabricated by changing the orientation of the rotatable mirrors in our experiments, which is an outstanding advantage of our experimental setup illustrated in Figure 1. We also measured the reflection spectra of our FBGs, as shown in Figures 3(b), 4(b) and (d), and 5(b) and (d). For FBGs with poor coupling in Figures 3 and 4, the 3 dB-bandwidth of the reflection spectra is about 0.1–0.3 nm. However, it is interesting to observe from Figure 5(b) that the 3 dB-bandwidth was dramatically broadened to more than 5 nm in the reflection spectra of the stronger gratings with a reflectivity of more than 99.99%.

## 4. DISCUSSION

The changes of Bragg wavelength/attenuation with exposure dose during the grating inscription give an indication of the increase in index modulation in the fibers. Although the pulse energies of the lasers for exposure are well known, possible effects of the actual beam overlap with the fiber core may differ between the different laser sources and may therefore have some additional influence on the achieved results. Based on the measured Bragg attenuation of our FBGs and the coupled-mode theory, we calculated the laser-induced index modulation with exposure dose in the FBGs,[14] as shown in Figure 6, where the length of gratings written with a FS laser or an excimer laser is

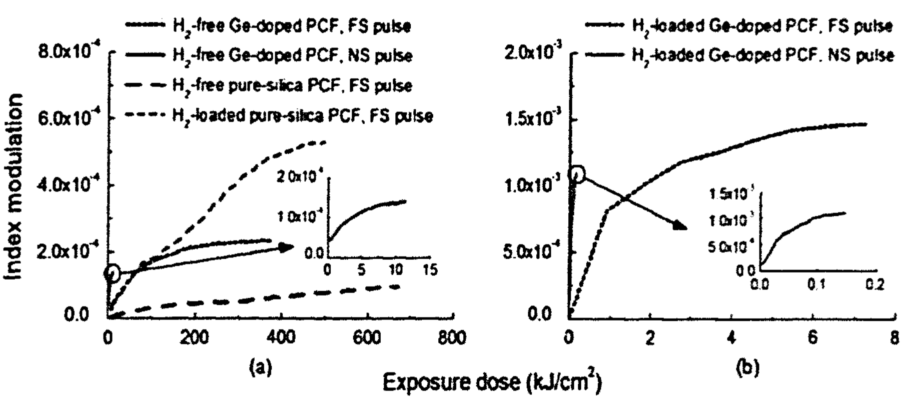


**Fig. 6.** Index modulation with exposure dose in FBGs written in pure-silica and Ge-doped PCFs before/after $H_2$-loading with a FS laser or an excimer laser. Insets in (a) and (b) are sectional magnifications of the nanosecond pulse exposure dose curve.

about 4.3 and 6 mm, respectively. In general, the development of index modulation with increasing exposure dose shows a first region with a fast increase in index modulation (high photosensitivity), and then a second region with slow increase in, or saturation of index modulation (lower photosensitivity). As shown in Figure 6(b), the values for achieving saturation in refractive index was considerably different in the case of $H_2$-loaded and Ge-doped fibers for NS pulses (approx. 0.2 kJ/cm$^2$, red solid curve) compared to FS pulses (approx. 6 kJ/cm$^2$, blue dot curve). In general, with Ge-doped fibers the (initial) photosensitivity is considerably higher for NS pulses than for FS pulse exposure. However, the index modulation finally achieved is similar in both cases.

We also tried to write a FBG in the $H_2$-loaded pure-silica PCF with an excimer laser, but no grating was observed in our experiments. In other words, for pure silica PCFs, only FS pulse inscription produced an index modulation (no photosensitivity observed for NS pulses). FS pulse photosensitivity is lower compared to UV NS pulse photosensitivity in Ge-doped fibers. In the case of hydrogen loading, FS photosensitivity even in pure silica PCFs proved to be extremely increased, and strong index modulations were achieved, as shown by green short dash curve in Figure 6(a). Similar effects have been reported for Bragg grating inscription in solid fibers.[15] Such phenomena for both FS and NS pulses are also known in Ge-doped fibers before and after $H_2$-loading, i.e., $H_2$-loading usually increases the index modulation efficiency of both fs and ns pulses in the Ge-doped fibers. Specifically for pure silica fibers, it seems that hydrogen has a positive effect on the efficiency of the silica network's interaction with the fs optical pulses.

## 5. CONCLUSIONS

High-quality FBGs have been successfully written in two different types of PCFs (pure-silica PCF and Ge-doped PCF) before or after $H_2$-loading with a UV-FS laser and a two-beam interference technique. The achieved gratings have been compared with gratings written with more conventional UV-nanosecond pulses from an excimer laser. A higher efficiency of index modulation was achieved with an excimer laser, rather than a FS laser, in the Ge-doped PCF. In pure silica PCFs only FS pulse inscription achieves an index modulation. $H_2$-loading can greatly enhance the efficiency of grating inscription, not only in Ge-doped PCFs, but also in pure-silica PCFs with fs pulse inscription. The annealing effect on the gratings written by ns and fs pulses will be done in the further investigations. A high temperature seems to be induced in the PCF during FS laser irradiation, as observed in our experiments with a shift of the Bragg reflection wavelength.

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