Fabrication of fiber Bragg gratings with 267 nm femtosecond radiation

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Abstract: Strong high-quality fiber Bragg gratings with photoinduced refractive-index modulation of more than 10^{-3} were written in a Corning SMF-28 fiber, a P_2O_5-doped-core fiber and a pure-silica-core fluorine-doped-cladding fiber by third-harmonic radiation (267 nm, 150 fs and 1.2-1.8×10^{11} W/cm^2) of a femtosecond Ti:sapphire laser using a phase mask. We compare the 267-nm photosensitivity responses with the results of irradiation by 193-nm ArF and 157-nm F_2 excimer lasers. The dependence of the refractive-index change on the exposure dose and the annealing characteristics of the fabricated gratings are typical for Type-I UV-written fiber gratings.

OCIS codes: (060.2310) Fiber optics; (230.1480) Bragg reflectors; (320.7160) Ultrafast technology

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1. Introduction

Fiber Bragg gratings (FBGs) are usually produced by fiber exposure to UV radiation with sufficient absorption of the fiber core glass. As a rule, an increase of the UV-radiation photon energy results in higher efficiency of the grating formation. High photosensitivity in the case

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of 157-nm excimer F_2-laser exposure (7.9-eV photon energy) has been reported [1]. However, the use of a F_2 laser for FBGs fabrication has serious disadvantages, such as problems of deep-UV radiation delivery through the air, the fiber cladding and the phase mask.

Another method of refractive index modification is based on multiphoton absorption of high-intensity IR femtosecond pulses. This approach was used for the fabrication of long-period fiber gratings (LPFGs) by 800-nm femtosecond radiation of intensity ~10^{14} W/cm^2 [2]. Recently, FBGs were written with the help of specially made phase masks using high-intensity 800-nm femtosecond pulses [3, 4].

By using harmonics of IR radiation from femtosecond lasers, we can reduce the number of photons required for the multiphoton absorption, thereby decreasing the radiation intensity. The generation of harmonics occurs efficiently in femtosecond lasers. LPFG fabrication by 400-nm femtosecond pulses of intensity ~10^{10} W/cm^2 was demonstrated in Ref. 5. Also, efficient LPFG inscription was performed using the 264-nm fourth-harmonic of a femtosecond Nd:glass laser [6]. Recently, with the help of the 264-nm femtosecond radiation, we obtained strong FBGs in low- and high-Ge-doped fibers [7]. In this paper, we report the fabrication of FBGs in a Corning SMF-28 fiber, a P_2O_5-doped-core fiber and a pure-silica-core fiber by third-harmonic radiation of a femtosecond Ti:sapphire laser.

2. Experimental

800-nm, 45-fs pulses from a Spitfire Ti:sapphire amplifier (Spectra-Physics) with a pulse energy of 1 mJ and a pulse repetition rate of 1 kHz were converted to the third harmonic with the help of a TP-1A Tripler (Uniwave Technology). The 267-nm radiation with a pulse duration of ~150 fs, a pulse energy of 130μJ, and a beam diameter of 2.5 mm was directed on a fiber by a 38-mm fused-silica cylindrical lens through a phase mask. Polarization of the laser beam was perpendicular to the fiber axis. The fiber without polymer coating was fixed behind the phase mask at a distance of about 100 μm. The incident radiation intensity (1-2×10^{11} W/cm^2) on the fiber was varied by changing of the distance between the lens and the fiber. The intensity on the fiber was limited by a two-photon absorption in the phase mask substrate (2-mm thickness). The standard phase mask optimized for 248-nm radiation (Bragg Photonics) had a period of 1.07 μm. The transmission spectra of the written FBGs were measured during inscription with a superluminescent diode and an Ando AQ6317B optical spectrum analyzer with a resolution of 0.05 nm.

We compared the results of the 267-nm irradiation with the refractive index change induced by 193-nm and 157-nm excimer lasers. In the case of the excimer lasers, we used the method of Δn_{ind} measuring based on an intrafiber Mach–Zehnder interferometer consisting of two LPFGs [8]. The 193-nm ArF laser (CL-5000, Physics Instrumentation Center of the A.M. Prokhorov General Physics Institute, Russian Academy of Sciences) generated 8-ns, 30-mJ pulses at a repetition rate of 10 Hz, and the 157-nm F_2 laser (CL-7000, Physics Instrumentation Center), 18-ns, 20-mJ pulses at a repetition rate of 10 Hz.

The following fibers were used:

- H_2-loaded and pristine GeO_2-doped telecom Corning SMF-28 fiber (3-mol% GeO_2, $\Delta n_{core\text{-}clad}$ = 0.005, λ_c = 1.25 µm);
- H_2-loaded P_2O_5-doped "P903" fiber (12- mol% P_2O_5, $\Delta n_{core\text{-}clad}$ = 0.01, λ_c = 1.07 µm);
- H_2-loaded and pristine pure-silica-core fluorine-depressed cladding fiber ($\Delta n_{core\text{-}clad}$ = 0.007, λ_c = 0.99 µm).

The fibers were loaded with hydrogen at a pressure of 120 atm, at 80°C during 2 days.

3. Results and discussion

In H_2-loaded SMF-28 fiber, we inscribed a 33.2-dB FBG (Fig. 1) with an intensity of 1.2×10^{11} W/cm^2 and an exposure dose of 0.37 kJ/cm^2 (20-s irradiation time, 20000 pulses). The out-of-band insertion loss of the grating was <0.2 dB. The 33.2-dB FBG peak corresponds to the induced refractive index modulation depth Δn_{ind}=2.4×10^{-3}, assuming uniform 2.5-mm FBG.

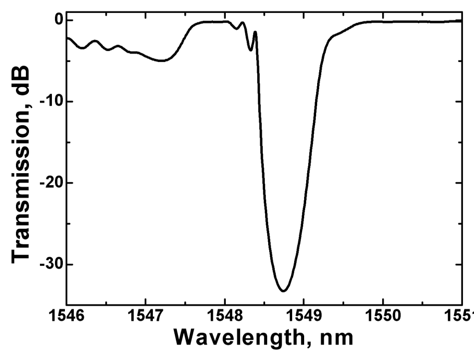

Fig. 1. Transmission spectrum of FBG recorded in an H_2-loaded SMF-28 fiber

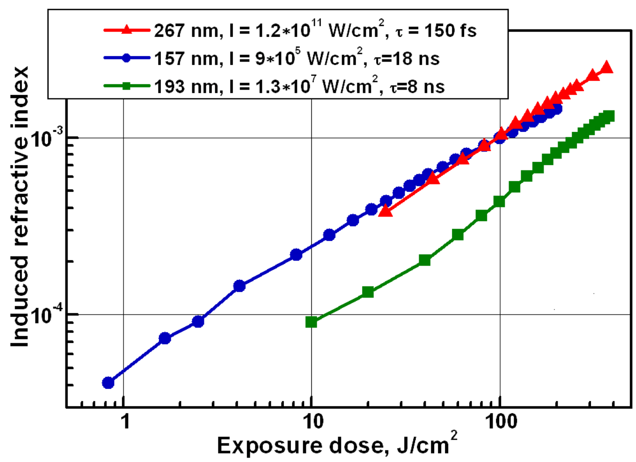

Fig. 2. Dependence of refractive-index change on exposure dose of an H_2-loaded SMF-28 fiber.

We did not observe any saturation of the FBG peak growth. For the FBG in the H_2-loaded SMF-28 fiber, the dependence of the Δn_{ind} on the exposure dose is shown in Fig. 2. The results of irradiation of H_2-loaded SMF-28 fibers by 193-nm and 157-nm excimer lasers are also depicted for comparison. It should be noted that the refractive index changes were induced by uniform UV beams in the case of 193-nm and 157-nm radiation. However, in our experiments with 193-nm ArF laser, Δn_{ind} calculated from FBG peaks was always less (at the same dose) than that measured with the help of a Mach–Zehnder interferometer irradiated by uniform UV beam. It should be noted that strong asymmetry of the induced refractive index in the fiber cross-section was revealed earlier in an H_2-loaded SMF-28 fiber under 157-nm irradiation [1]. As seen from Fig. 2, photosensitivities of the H_2-loaded SMF-28 fiber under irradiation at 267 and 157 nm are comparable. It is also possible to compare the efficiency of FBG inscription in this fiber at 267 and 248 nm (KrF excimer laser) [9]. To obtain $\Delta n_{ind}= 8\times10^{-4}$ with 248-nm nanosecond pulses (pulse fluence of 0.35 J/cm^2, pulse intensity of $\approx2\times10^7$ W/cm^2), the exposure dose of $\approx$7 kJ/cm^2 was used, which is 88 times larger than in the case of 267-nm femtosecond irradiation (80 J/cm^2).

A 14.3-dB FBG (Δn_{ind}=1.3×10^{-3}) was written in an H_2-free SMF-28 fiber with an intensity of 1.6×10^{11} W/cm^2 and an exposure dose of 58 kJ/cm^2 (40-min irradiation duration, 2.4×10^6 pulses). To obtain the same Δn_{ind} in an H_2-loaded SMF-28 fiber, a dose of 0.14 kJ/cm^2 was required, which was $\approx$400 times lower than in the case of an H_2-free SMF-28 fiber. Thus, H_2-loading results in dramatic enhancement of the 267-nm photosensitivity of low-Ge-doped SMF-28 fibers.

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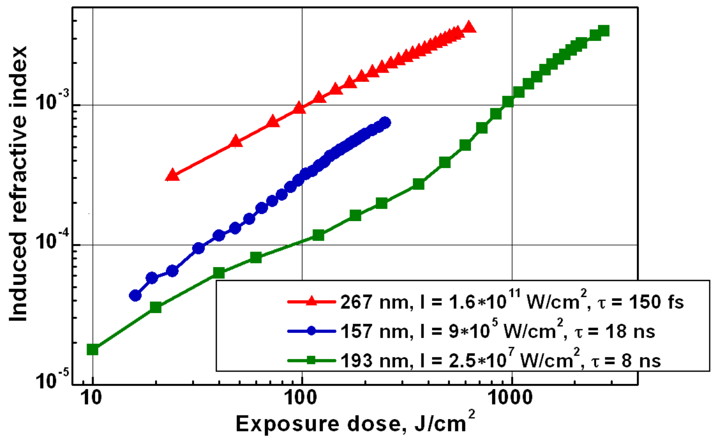

Fig. 3. Dependence of refractive-index change on exposure dose of H_2-loaded P903 fiber.

Strong FBGs were also fabricated in the H_2-loaded P_2O_5-doped-core P903 fiber. A 41.7-dB FBG ($\Delta n_{ind}=3.5\times10^{-3}$) was written with an intensity of 1.6×10^{11} W/cm^2 and an exposure dose of 0.62 kJ/cm^2 (26-s irradiation time, 26000 pulses). In spite of the high Δn_{ind}, there was no saturation of the FBG peak growth. The dependence of the Δn_{ind} on the exposure dose is compared in Fig. 3 with the irradiation results of this fiber by 193-nm and 157-nm lasers. The 267-nm photosensitivity of the fiber is about two times higher than in the case of 157-nm radiation and about ten times higher than in the case of 193-nm radiation. We would like to note that the P_2O_5-doped fiber core has no absorption band at 242 nm (in contrast to Ge-doped fibers), and relatively low $\Delta n_{ind}=3\times10^{-4}$ was induced in other H_2-loaded P_2O_5-doped-core fibers by 248-nm nanosecond radiation with a very high dose of 160 kJ/cm^2 [10]. The high efficiency of FBGs inscription by 267-nm femtosecond pulses is probably explained by the high excitation energy (9.3 eV) which results from two-photon absorption. Another advantage of the femtosecond laser compared to excimer lasers is the excellent spatial coherence of a nearly TEM_{00} laser beam.

We also inscribed strong FBG in the H_2-loaded pure-SiO_2-core fluorine-depressed cladding fiber. A 11.5-dB FBG ($\Delta n_{ind}=1.1\times10^{-3}$) was written with an intensity of 1.6×10^{11} W/cm^2 and an exposure dose of 54.5 kJ/cm^2 (38-min irradiation duration, 2.27×10^{6} pulses). In the H_2-loaded SMF-28 fiber (3 mol% GeO_2 core) the same $\Delta n_{ind}=1.1\times10^{-3}$ was achieved with a dose of only ≈0.1 kJ/cm^2. Without H_2-loading, a very weak FBG (≈0.1 dB) was obtained in the fiber with a dose of >50 kJ/cm^2. To the best of our knowledge, in SiO_2-core fibers the highest Δn_{ind} obtained by UV irradiation without damage was reported to equal 5×10^{-4} [11].

The results of FBG inscription with 267 nm femtosecond radiation are shown in Table 1. The strong dependence of the 267-nm photosensitivity on H_2-loading and core dopants points to photochemical nature of the induced refractive index, in contrast to "damage FBGs"

Table 1. Results of irradiation with 267-nm femtosecond pulses

Fiber	Transmission loss, dB	Δn_{ind}	Intensity, 10^{11} W/cm^2	Exposure dose, kJ/cm^2	Irradiation time, min
H_2-loaded SMF-28	33.2	2.4×10^{-3}	1.2	0.37	0.33
H_2-free SMF-28	14.3	1.3×10^{-3}	1.6	58	40
H_2-loaded P903	41.7	3.5×10^{-3}	1.6	0.62	0.43
H_2-loaded SiO_2	11.5	1.1×10^{-3}	1.6	54.5	38
H_2-free SiO_2	0.1	0.1×10^{-3}	1.8	50	31

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fabricated by 800-nm femtosecond pulses with an intensity of 2.9×10^{12} W/cm^2 [4]. As mentioned above, the incident radiation intensity on the fibers was limited in our experiments by nonlinear absorption in the phase mask substrate. On the other hand, the laser beam width on the fibers was 100-200 μm and high accuracy of the alignment of the incident beam on the fiber core was not required. Also, we can expect the absence of damage of irradiated fibers owing to a low pulse fluence (<30 mJ/cm^2) used in our experiments.

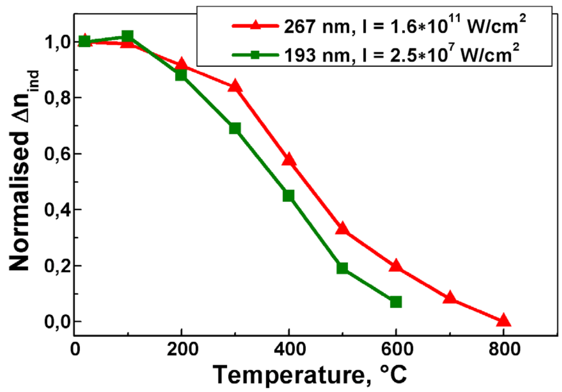

Fig. 4. Temperature dependence of refractive-index modulation of FBGs written in the H_2-loaded P903 fiber during isochronal annealing.

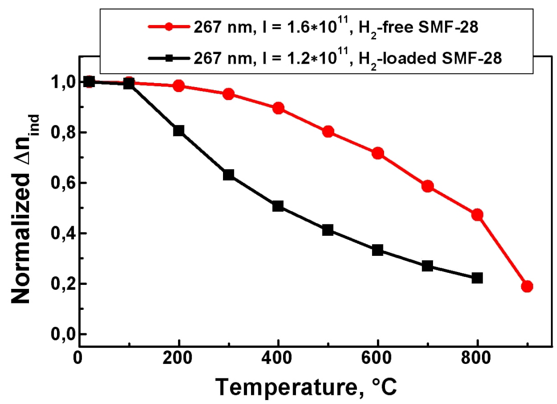

Fig. 5. Temperature dependence of refractive-index modulation of FBGs written in an SMF-28 fiber during isochronal annealing.

Study of thermostability of the fabricated FBGs gives some information on the type of FBGs. Isochronal annealing at each temperature was performed for 20 min, after which the temperature was raised by 100°C. The results of isochronal annealing of the FBG recorded in the H_2-loaded P903 fiber are presented in Fig. 4. The annealing data of FBG fabricated with 193-nm nanosecond pulses are shown for comparison. Thermostability of these FBGs is similar. Annealing characteristics of FBGs written in the H_2-loaded and H_2-free SMF-28 fiber with 267-nm femtosecond pulses (Fig. 5) are also typical for UV-induced Type-I FBGs (significant erasure of the index modulation at T≤500ºC). In contrast, thermostability of "damage" FBGs fabricated by 800-nm femtosecond pulses is similar to that of Type II UV-induced damage gratings [4].

4. Conclusion

The fabrication of FBGs by the 267-nm third-harmonic radiation from a femtosecond Ti:sapphire laser is reported to our knowledge for the first time. Strong high-quality Bragg gratings with photoinduced refractive-index modulation of more than 10^{-3} were written in an

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H_2-loaded and pristine telecom Corning SMF-28 fiber, an H_2-loaded phosphosilicate fiber, and an H_2-loaded pure-silica-core fluorine-doped cladding fiber using a standard phase mask made for 248-nm radiation. The out-of-band insertion losses of the fabricated FBGs are <0.5 dB.

The refractive index change induced by the 267-nm femtosecond pulses was compared with the results of exposure by 193-nm and 157-nm excimer lasers. The 267-nm photosensitivity of some fibers is higher than in the case of the deep-UV 157-nm irradiation. The high photosensitivity in the case of 267-nm femtosecond pulses is probably due to the high excitation energy (9.3 eV) which results from two-photon absorption [7].

The dependence of the refractive-index change on the exposure dose, the annealing characteristics of the fabricated gratings as well as strong dependence of the 267-nm photosensitivity on H_2-loading and the core dopants are typical for Type-I UV-written FBGs.

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