Inscription of fiber Bragg gratings by ultraviolet femtosecond radiation

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We report on what is to our knowledge the first fabrication of fiber Bragg gratings by UV femtosecond radiation. The Bragg gratings, with photoinduced refractive-index modulation up to 1.92×10^{-3} in H_2-loaded SMF-28 and up to 1.05×10^{-3} in Nufern GF1 fibers, were written by high-intensity (31–77-GW/cm^2) femtosecond pulses at 264 nm. The dependence of the refractive-index modulation on intensity at equal fluences points to a two-photon absorption mechanism for grating inscription. © 2003 Optical Society of America

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For the inscription of fiber Bragg gratings (FBGs) and long-period fiber gratings (LPFGs), KrF excimer laser radiation at 248 nm and the second harmonic of a cw argon gas laser at 244 nm are widely used.[1,2] Generally, the change in refractive index generated at these wavelengths in fibers is connected with the absorption band of defects in germanosilicate glass and is mainly of a single-photon nature. Recently it was reported that LPFG inscription with deep-UV (157 nm) F_2 excimer laser radiation[3,4] considerably reduces (by more than 2 orders of magnitude compared with that at 248 nm) the necessary light fluences. However, this technique when it is applied to fabrication of Bragg gratings has serious disadvantages such as problems of transporting deep UV radiation through the air, a phase mask, and a fiber cladding.

An alternative approach to inscription is to expose fibers to high-intensity femtosecond radiation and thus to produce the index changes through multiple-photon absorption. In this case the resultant electronic excitation energy can be even higher than in the case of a single deep-UV quantum (7.9 eV), and the problem of transporting the light from laser to fiber core is automatically solved. It should be emphasized that the use of femtosecond pulses allows us to expose fibers with intensities higher by several orders of magnitude than those of nanosecond excimer lasers, without damage. This approach was used for the fabrication of LPFGs by Ti:sapphire laser radiation (800 nm),[5] and by its second harmonic (400 nm).[6] Quite recently, a FBG was written in standard SMF-28 telecom fiber by tight focusing of 800-nm femtosecond radiation through a phase mask.[7]

An even more natural way to inscribe FBGs is to use two-photon absorption to create a refractive-index change in germanosilicate fibers. The two-photon absorption properties of pure and germanium-doped fused silica are well established,[8,9] and this method was recently successfully applied for LPFG inscription in germanium-doped silica fibers by use of 264-nm femtosecond pulses.[10,11] However, to the best of our knowledge no attempts have been made to use femtosecond UV pulses and the common phase mask technique to record FBGs. In this Letter we demonstrate the recording of FBGs in standard and photosensitive commercial fibers by using the fourth-harmonic radiation of a femtosecond Nd:glass laser at 264 nm.

For inscription of Bragg gratings we used a commercial laser (Twinkle, Light Conversion, Ltd., Lithuania).[12] The femtosecond UV pulses [λ = 264 nm, $\epsilon_p \approx 200$ μJ, τ_p = 264 fs (FWHM), w_p = 0.3 cm (FWHM), f = 27 Hz] were directed by a 21.8-cm fused-silica cylindrical lens through a standard 1.07-μm period phase mask (Bragg Photonics, Inc.) onto the fiber. The displacement of the lens with respect to the fiber allowed us to vary the UV irradiation intensity. The relative accuracies of our fluence and intensity measurements were approximately 1% and 4%, respectively.[8] The fiber without the coating was fixed behind the phase mask at a distance of ~100 μm. The phase mask–fiber combination could be aligned three-dimensionally with the laser beam. Movement perpendicular to the direction of light propagation was directed by a 50-mm (1-μm resolution) computer-controlled translation stage (Physik Instrumente, PI 405.DG). Bragg grating transmission was monitored during the inscription by an AQ4222 EE LED source and an AQ6317C optical spectrum analyzer (both supplied by Yokogawa Europe BV). The UV exposure and (or) fiber translation process was computer controlled by LabVIEW software and a PCI-GPIB card (both from National Instruments).

First we tried to inscribe FBGs in H_2-loaded (13 MPa, 80 °C, 2 days) SMF-28 fiber, using the scanned phase mask technique.[1] In this experimental configuration two slits were placed before the fiber. The first (2 mm) was located 5 cm in front of the phase mask to extract the peak intensity region of UV laser pulses. The second (3 mm) was attached to the phase mask holder to limit the length of the grating. In this way the 3-mm region of fiber was scanned with the 2-mm beam through a mask in 100-μm steps, leading to uniform exposure.

Figures 1(a) and 1(b) present the transmission spectra for two Bragg gratings recorded in H_2-loaded

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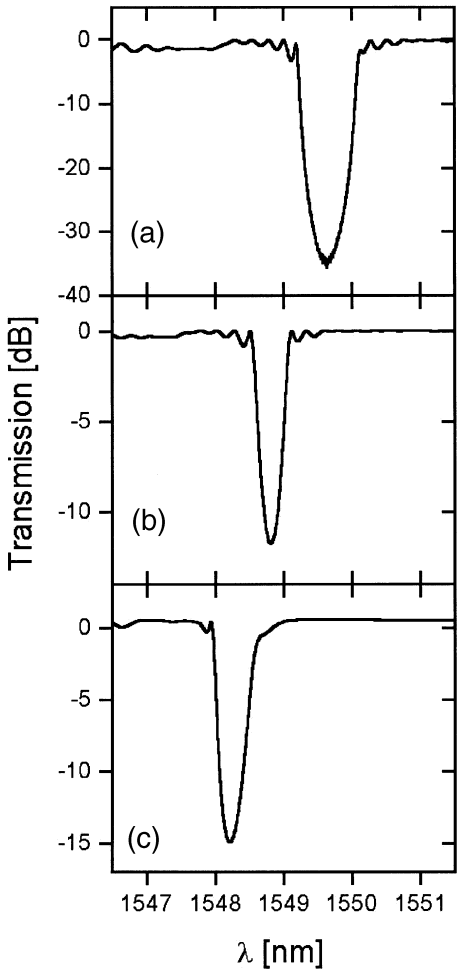

Fig. 1. Transmission spectra of Bragg gratings recorded in (a), (b) H_2-loaded SMF-28 and (c) H_2-free Nufern GF1 fibers with high-intensity 264-nm femtosecond pulses. The irradiation intensities and total incident fluences were (a) 47 GW/cm^2 and 0.68 kJ/cm^2, (b) 31 GW/cm^2 and 0.63 kJ/cm^2, and (c) 77 GW/cm^2 and 4.7 kJ/cm^2, respectively.

SMF-28 fiber with similar fluences (0.68 and 0.63 kJ/cm^2, respectively) but different intensities (47 and 31 GW/cm^2, respectively). The resultant dramatic difference in final peak strength (34 and 12 dB) demonstrates the nonlinear character of the inscription process. As can be seen from Figs. 1(a) and 1(b), the recorded peaks are highly symmetric, with a well-defined spectral shape, and the typical spectral components for uniform gratings can be observed on both sides of the grating peak.[1] Figure 2(a) shows the corresponding dependences of refractive-index modulation[1] on total incident fluence for the uniform gratings depicted in Figs. 1(a) and 1(b). The final refractive-index change values are 1.92×10^{-3} and 0.84×10^{-3} for gratings with 34- and 12-dB peaks. Again, at similar fluences we have a clear difference in the final refractive-index modulation values. It should be emphasized that the ratio of initial slopes for the dependences presented in Fig. 2(a) corresponds to 1.5 and matches well the corresponding ratio of irradiation intensities. As the initial slope of the dependences in Fig. 2(a) is proportional to the irradiation intensity ($\Delta n/E_{\mathrm{inc}} \sim I$), the induced refractive-index change is quadratic with intensity ($\Delta n \sim I^2$), testifying to the two-quantum character of the inscription process [mainly two-photon, as the fiber core material practically does not absorb linearly at 264 nm (Ref. 9)]. Another important point to be mentioned is that at higher irradiation intensities over the range of fluences investigated there is no sign of saturation, whereas at low irradiation intensities the saturation is obvious [cf. Fig. 2(a)].

Next, we irradiated the H_2-free Nufern GF1 fiber with a static beam without slits. As the beam has a Gaussian profile, the exposure was not uniform. We recorded a 15-dB grating with an incident fluence of 4.7 kJ/cm^2 and an intensity of 77 GW/cm^2 [Fig. 1(c)], which corresponds to a refractive-index modulation of 1.05×10^{-3}. The grating spectrum has some asymmetry, probably because of the nonapodized UV beam profile.[1] The refractive-index modulation changed slowly relative to the irradiation fluence, reaching a value of 1.04×10^{-3} [Fig. 2(b)]. However, we did not observe any saturation similar to that reported earlier in experiments with the more-photosensitive fiber Nufern GF1A.[13] This result could be related to the different photosensitivity mechanism in our case.

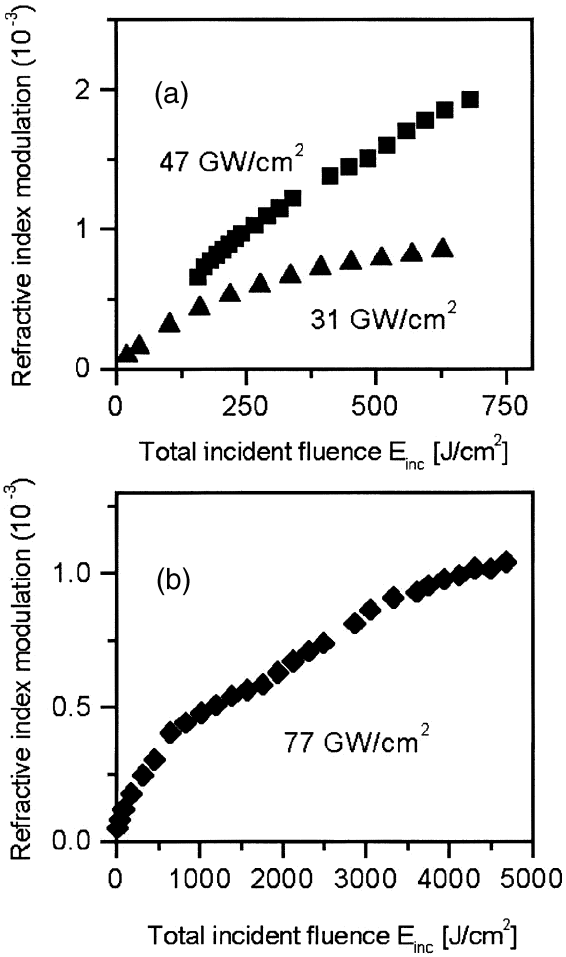

Fig. 2. Dependence of refractive-index changes on total incident irradiation fluence for high-intensity femtosecond UV irradiation of (a) H_2-loaded SMF-28 and (b) H_2-free Nufern GF1 fibers. The accuracy of the calculated refractive-index change is better than 2%.

The off-band losses were insignificant for all inscribed gratings. The difference in exact peak position for two gratings in H_2-loaded SMF-28 is due to the different strain levels that were produced in the fiber while it was installed on the holder and (or) to different average refractive-index changes induced in the exposed region.

Let us compare our results on the efficiency of Bragg grating recording with those in the literature. First we consider the results obtained by single-quantum excitation with 255-nm radiation (second harmonic of a copper-vapor laser; pulse fluence, 0.017 J/cm^2; pulse intensity, 5.7×10^5 W/cm^2; repetition rate, 6 kHz).[13] To induce a refractive-index change of 10^{-3} in H_2-loaded SMF-28 it was necessary to irradiate the fiber for 125 s, which corresponds to a total incident fluence of 12.8 kJ/cm^2. In our case the same refractive-index change was produced with a total incident fluence of 0.27 kJ/cm^2 (irradiation intensity, 47 GW/cm^2), which is ~48 times smaller (cf. Fig. 2). When the Nufern GF1A fiber was irradiated with 255-nm pulses, a refractive-index modulation of 7×10^{-4} was produced in 180 s, which corresponds to a total incident fluence of 18.4 kJ/cm^2. In our case, irradiating a less photosensitive fiber, Nufern GF1, at 264 nm with an intensity of 77 GW/cm^2 yielded the same refractive-index modulation with a total incident fluence of 2.33 kJ/cm^2, which is ~8 times smaller (cf. Fig. 2).

We can also discuss our results with regard to photosensitivity measurements in optical fibers under excimer KrF laser irradiation (248 nm; pulse fluence, 0.35 J/cm^2; pulse intensity, 1.9×10^7 W/cm^2).[14] After a total fluence of 3.3 kJ/cm^2 was attained, the induced refractive-index change in H_2-loaded SMF-28 fiber was 5×10^{-4}, which is ~30 times larger than our fluence value of 0.11 J/cm^2 that was necessary for creating the same refractive-index effect in the experiment with high laser intensity (47 GW/cm^2; cf. Fig. 2).

Let us consider our results with regard to photosensitivity measurements in H_2-loaded SMF-28 fiber under excimer F_2 laser irradiation (157 nm; pulse fluence, 0.04 J/cm^2; pulse intensity, 2.6×10^6 W/cm^2).[15] To reach the refractive-index change of 1.92×10^{-3} an incident (and simultaneously absorbed) fluence of 1.2 kJ/cm^2 was used. To produce the same refractive-index modulation at an intensity of 47 GW/cm^2, we applied an incident fluence of 0.68 kJ/cm^2. We should emphasize, however, that in our case (1) the absorbed (accumulated) fluence is much smaller and (2) the further increase of intensity will decrease the incident fluence (we have no saturation).

Concluding, our two-photon high-intensity UV femtosecond approach allows us to produce fiber Bragg gratings with high efficiency because of the high excitation energy (9.4 eV) that originates from two-photon absorption. An additional advantage is the excellent spatial coherence of Nd:glass femtosecond laser pulses, resulting in extremely good-quality FBGs.

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