Strong long-period fiber gratings recorded at 352 nm

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We describe long-period grating inscription in hydrogenated telecom fibers by use of high-intensity femtosecond 352 nm laser pulses. We show that this technique allows us to fabricate high-quality 30 dB gratings of 300 μm period and 2 cm length by use of a three-photon absorption mechanism. © 2005 Optical Society of America

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Long-period fiber gratings (LPFGs, also known as transmission gratings) have existed since the mid-1990s.[1] They were originally fabricated photochemically by UV laser light at wavelengths coinciding with the maximum of the absorption band of defects in germanosilicate glass, and this is the most frequently used way of LPFG fabrication. For this purpose, KrF excimer laser radiation (248 nm; Ref. 2) or the second-harmonic radiation of a cw argon-ion laser (244 nm; Ref. 3) is usually used. Such a conventional low-intensity UV approach leads to a refractive-index change in the Ge-doped fiber core by means of single-quantum photochemical reactions. Recently we used high-intensity 264 nm femtosecond pulses (the fourth harmonic of our Nd:glass laser system[4]) for recording LPFGs in single-mode telecom fibers. Under these experimental conditions, the inscription proceeds by means of a two-photon mechanism.[5]

In this report, we applied 352 nm radiation for LPFG inscription in the hydrogenated single-mode telecommunication fibers SMF-28 and SMF-28e. A schematic of the experimental setup is given in Fig. 1. For inscription of LPFGs we used the third-harmonic radiation of a commercial femtosecond Nd:glass laser (Twinkle; Light Conversion, Ltd., Lithuania), which was generated in a 2 mm long KDP crystal cut for type I interaction ($\theta = 47.6°$, $\phi = 45°$). The method of frequency tripling was similar to that described in Ref. 6. The pulse duration of the resultant 352 nm pulses was 250 fs (FWHM), the beam diameter was 0.27 cm (FWHM), the repetition rate was 27 Hz, and the pulse energy was as much as 150 μJ. The femtosecond UV pulses were focused by a CaF_2 spherical lens, with a 48.6 cm focal distance, through a slit of width 150 μm and onto a fiber (with the acrylate coating removed) that was placed behind the slit at a distance of ~ 100 μm. The movement of the fiber and the control of the light's fluence were accomplished according to the method described in Ref. 5. For LPFG inscription we used the standard telecom fiber SMF-28 (supplied by Elliot Scientific) and the enhanced telecom fiber SMF-28e (supplied by Corning), both with a core diameter of 8.2 μm, a cladding diameter of 125 μm, and a numerical aperture of 0.14. The fibers were sensitized in a hydrogen atmosphere at 160 bars (120 kTorr) at 80 °C for 90 h.

Figures 2(a) and 2(b) present the experimental transmission loss spectra for two recorded gratings in SMF-28 and SMF-28e fibers, respectively. These gratings were fabricated with a 300 μm period, and they were 2 cm in length.

First we want to emphasize that our LPFGs, inscribed by high-intensity 352 nm pulses, are stronger than those produced by other photochemical methods. This statement refers to gratings of the same length and the same period (and, of course, inscribed in the same fiber). By comparing the maximum possible grating strength, we are making a comparison between the coupling coefficients and, consequently, between the corresponding values of refractive-index modulation. For example, the gratings recorded by 248 nm pulses with the same period and the same length in hydrogenated SMF-28 fiber had a maximum transmission loss value of 17 dB,[7] and similarly the LPFGs recorded by 157 nm pulses with the same grating parameters had a maximum transmission loss value of 21 dB.[7] In our group's previous work,[5]

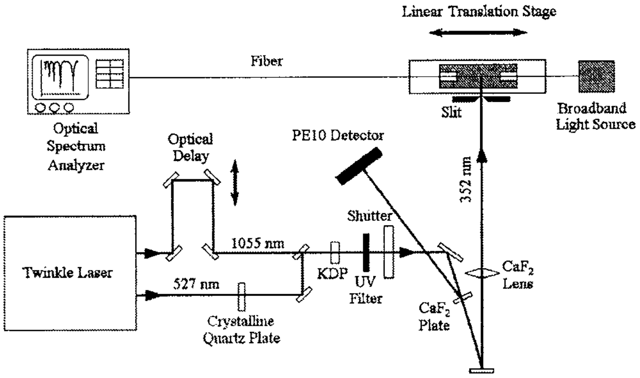

Fig. 1. Schematic of the experimental setup. A 3.3 mm thick crystalline quartz plate was used for a 90° polarization rotation of the 527 nm beam.

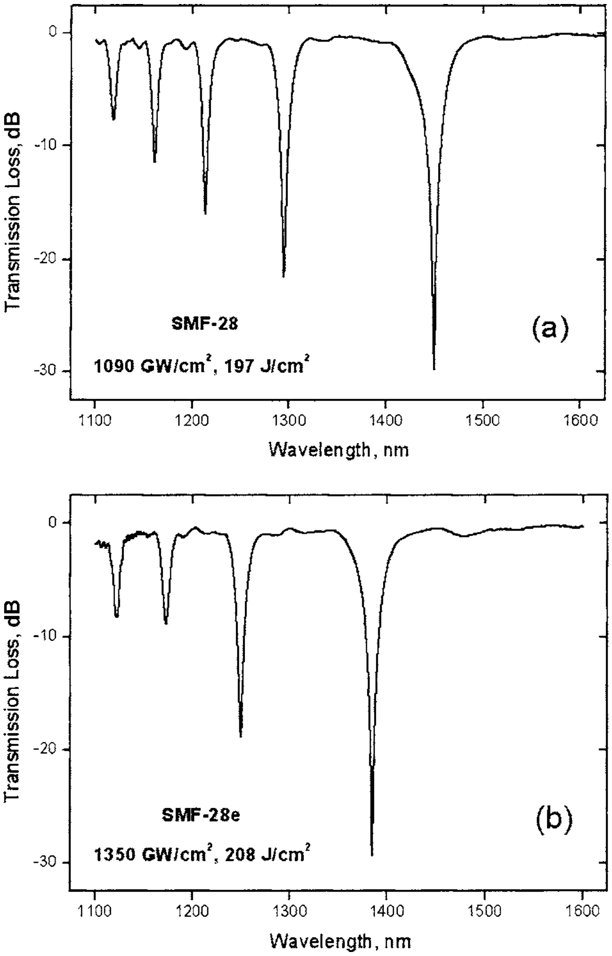

Fig. 2. Transmission loss spectra of LPFGs recorded in (a) H_2-loaded SMF-28 and (b) H_2-loaded SMF-28e fibers by high-intensity 352 nm pulses. The incident irradiation intensity and the incident fluence are shown.

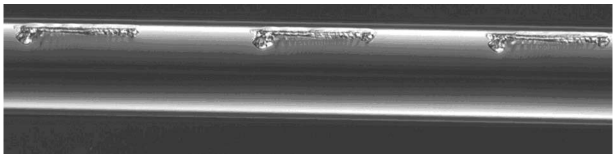

Fig. 3. Photograph of a section of a LPFG recorded in SMF-28e fiber. The longitudinal size of each damaged area is 150 μm.

using high-intensity UV light at 264 nm, we managed to inscribe 24 dB gratings, and, quite recently, using 211 nm femtosecond pulses, we achieved a grating strength of 26 dB (Ref. 8, in both cases, the LPFGs were fabricated with the same parameters in the same fiber). We also made a comparison of the grating strengths of LPFGs produced at 211 nm (Ref. 8) and 193 nm (Ref. 9) for the same grating parameters, and found that LPFGs prepared at 211 nm performed better than the gratings recorded at 193 nm. It follows that the high-intensity 352 nm inscription possesses the highest refractive-index modulation values.

Second, we can clearly distinguish the different wavelength positions of the main transmission loss peak, 1450 nm and 1385 nm, respectively. The linewidth at the 3 dB level is 45 nm and 37 nm, respectively. Third, we note the rather low level of gray losses, especially in Fig. 2(a), for which a smaller intensity value was used for the grating inscription.

Figure 3 presents a photograph of a three-period section of the LPFG recorded in SMF-28e fiber. It shows some regular damage in the cladding area near the incident surface. Two main consequences follow:

(1) The absorbed energy is distributed nonuniformly inside the fiber, similar to that in experiments on LPFG inscription that involved a CO_2 laser.[10] In a separate study,[8] the fraction of absorbed energy in the fiber cladding was calculated with respect to the total absorbed energy (in cladding and in core) at high-intensity 264 nm and 211 nm irradiation. It was shown that with the increase of this fraction from 74.7% (at 264 nm) to 95.5% (at 211 nm) the grating strength increased from 24 to 26 dB. In this investigation we are probably dealing with a larger fraction of energy deposited in the cladding, and hence we obtained a higher grating strength value (30 dB), which outperforms all the grating strength values for all other photochemical inscription techniques. At the same time it is similar to values obtained in experiments with such nonphotochemical recording methods as CO_2 laser irradiation[11] and the electric arc technique.[12] This result is not surprising, as both of these techniques involve energy deposition in the cladding.

(2) The bandgap energy value for 5 mol. % Ge-doped fused silica is 7.1 eV,[13] and the bandgap for pure fused silica is ~9.3 eV.[13] Therefore the bandgap energy value for 3 mol. % Ge-doped fused silica (such a level of doping corresponds to that in the cores of SMF-28 and SMF-28e fibers[14]) is more than 7.1 eV. As one quantum of 352 nm radiation is equal to 3.53 eV, the excitation energy of two quanta (7.05 eV) is not sufficient for the excitation in either the cladding or the core. So our experimental data suggest a three-photon mechanism for LPFG inscription at 352 nm.

In a separate experiment with fused silica and 3.5 mol. % Ge-doped fused silica samples irradiated with high-intensity (up to 2000 GW/cm^2) 352 nm femtosecond pulses, the three-photon absorption mechanism was confirmed and the three-photon absorption coefficients were measured.[15]

In the literature there is only one mention of LPFG inscription by cw near-UV (333–364 nm) light: A weak 3 dB long-period grating with a period of 200 μm and 4 cm length was recorded in an unloaded 10 mol. % Ge-doped fiber.[16] Using high-intensity (~1000 GW/cm^2) 352 nm pulses, we managed to fabricate LPFGs with nearly 3 orders of magnitude higher grating strength in standard telecom 3 mol. % Ge-doped fibers.

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