Fabrication of strong long-period gratings in hydrogen-free fibers with 157-nm F_2-laser radiation

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Long-period gratings were fabricated in standard telecommunication fiber (Corning SMF-28) by use of what is believed to be record short-wavelength light from a 157-nm F_2 laser. Strong loss peaks were formed without the need for enhancement techniques such as hydrogen loading. The magnitude of the attenuation peak was sensitive to the single-pulse laser fluence, decreasing with increasing pulse fluence as a result of nonuniform 157-nm laser interaction with both the fiber cladding and core. The long-period fiber gratings have good wavelength stability ($\Delta\lambda \sim 7$ nm) under thermal annealing at 150 °C. © 2001 Optical Society of America

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Photosensitivity enhancement techniques such as hydrogen loading[1] are widely applied today to improve the weak ultraviolet laser interaction of standard telecommunication fiber for the fabrication of fiber Bragg gratings, long-period fiber gratings (LPFGs), and other useful photonic structures. Shorter-wavelength laser sources offer an alternative route to photosensitivity enhancement that is especially attractive in terms of access to new absorption channels. Albert *et al.*[2] demonstrated an approximately tenfold improvement in refractive-index modification inside a low-GeO_2 fiber by shifting the laser wavelength from 248 to 193 nm. Two-photon absorption across the GeO_2 bandgap was the inferred photosensitivity mechanism. Our group has further extended such studies to what is believed to be the record short wavelength of 157 nm (Refs. 3–5), with the aim of gaining access to new single-photon processes near the band edge of GeO_2 and fused-silica glasses.

The F_2 laser produces 7.9-eV photons that are known[6] to damage ultraviolet-grade fused-silica glasses in long exposures, possibly through absorption involving three- and four-member silicon-ring structures.[7] In low-GeO_2 (i.e., 5%) glasses, the 157-nm photons directly bridge the ~7.1-eV bandgap,[8] which allows access to strong single-photon photosensitivity mechanisms without the need for traditional enhancement techniques.[3–5] In this Letter we describe, for what is to our knowledge the first time, the formation of strong and good-quality LPFGs in standard single-mode fibers (Corning SMF-28) without fiber pretreatment. The F_2-laser photosensitivity response is comparable with that of 248-nm radiated fibers presoaked in hydrogen.

The 157-nm radiation was provided by a F_2 laser (Lambda Physik LPF 220) operated at 100-Hz repetition rate. The 15-ns pulses passed through an airtight processing vessel that we flushed with 1-atm argon gas to eliminate 157-nm absorption by air. We selected a uniform portion (20 mm × 2.45 mm) of the beam to illuminate a stainless-steel amplitude-grating mask of 304-μm period (152-μm lines and gaps). Standard telecommunication fiber (Corning SMF 28) mounted 2 mm behind the amplitude mask minimized mask contamination. The geometry provided single-pulse laser fluence in the range 1–5 mJ/cm^2 along the full 20-mm exposure length of fiber and produced 66 line-and-space pairs in the LPFG. Single-pulse fluence up to 150 mJ/cm^2 was also applied by concentration of the laser beam with a MgF_2 lens (~6-cm focal length) and translation of the fiber-mask assembly with a motorized stage. The transmission spectrum of each LPFG was monitored *in situ* during the laser exposure with unpolarized infrared light and an optical spectrum analyzer (Ando AQ6531E) set at 5-nm resolution.

The infrared transmission spectrum of a LPFG as recorded at the point of maximum attenuation is shown in Fig. 1. The 17-dB loss peak at 1434 nm was

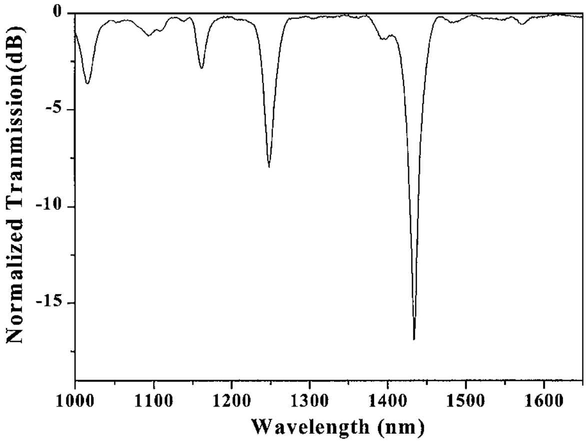

Fig. 1. Normalized transmission spectrum of a 20-mm-long LPFG fabricated in untreated SMF-28 fiber with 157-nm F_2-laser radiation. The single-pulse and total accumulated fluence were 2.7 mJ/cm^2 and 2.7 kJ/cm^2, respectively.

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formed with a 2.7-kJ/cm^2 fluence dose (2.7 mJ/cm^2 per pulse). The out-of-band loss of <0.4-dB is similar to what is typically reported for LPFGs fabricated in hydrogen-soaked fibers with ultraviolet-laser sources.[9] To our best knowledge, this is the strongest LPFG formed with an excimer-laser source in low-GeO$_2$ telecommunication fiber without any pretreatment. Although researchers recently applied high-power, high-intensity CO$_2$-laser[10] and femtosecond-laser[11] radiation to hydrogen-free fibers to fabricate strong LPFGs, thermal damage and large out-of-band losses preclude practical consideration of these alternative laser approaches. The present results therefore attest to strong fundamental interaction of 157-nm radiation with low-GeO$_2$ glasses and suggest a practical F$_2$-laser application in the formation of LPFGs.

Figure 2 shows the development of the principal loss peak as a function of the accumulated 157-nm laser fluence for a single-pulse fluence of 2.5 mJ/cm^2. A 50-nm shift of the resonance peak to the longer wavelength evolves smoothly [Fig. 2(a)] over the 4.8-kJ/cm^2 exposure. A peak 16-dB loss is noted at the 1432-nm wavelength, midway through the exposure, before the peak drops to ~2 dB at full exposure [Fig. 2(b)]. These responses are consistent with theory, with the resonance peak intensity following a sinc-squared function of the coupling coefficient between the fiber core mode and the cladding modes.[9]

The maximum attainable transmission loss decreases with an increase in the single-pulse F$_2$-laser, fluence, as illustrated in Fig. 3. Reproduced from Fig. 1 is the 17-dB loss peak at 1434-nm, developed with a total dose of 2.7 kJ/cm^2 when 2.7-mJ/cm^2 single-pulse fluence is used. A total 167-min exposure was required for this 100-Hz exposure. This spectrum is compared with a maximum 8-dB attenuation peak at ~1520-nm wavelength, which was formed by use of an average single-pulse fluence of ~43 mJ/cm^2. A fivefold-larger exposure of ~10 kJ/cm^2 was required. With larger single-pulse fluence of 84 mJ/cm^2, the peak loss decreases to only 4 dB. Such significant decibel falloff in the resonance attenuation points to an important trade-off in 157-nm photosensitivity applications: Low laser fluence provides strong and damage-free photosensitivity responses, at the expense of longer exposure times.

Laser-induced modification of and damage to the GeO$_2$ glasses is principally responsible for a low-fluence F$_2$-laser processing window for fabrication of LPFGs. In photosensitivity studies of GeO$_2$ planar waveguides without cladding,[4] the 157-nm penetration depth in the low-GeO$_2$ (3%) core was inferred to shrink from ~8 to 4 μm during a total 22-kJ/cm^2 exposure at ~7.5-mJ/cm^2 single-pulse fluence. This shrinking points to nonuniform modification of both the 157-nm absorption and the refractive index in the present LPFGs. The planar-waveguide experiments[4] and our laser-grating trimming experiments also predict an ~5×10^{-4} change in the effective refractive index of the LPFG fiber produced at low fluence shown in Fig. 3. The experimental evidence suggests that larger single-pulse fluence (i.e., tens of millijoules per square centimeter) accelerates the glass modification, eventually localizing the refractive-index change to the cladding–core interface. Consequently, energy exchange between the guiding and the cladding modes is reduced, weakening the loss peaks in the LPFG. Further evidence for such nonuniform refractive-index modification is the asymmetric scattering of coupled He–Ne-laser light, which is always strongest when viewed from the F$_2$-laser-exposed side of the LPFG fiber. Further, this scattered light is evident only from within longitudinal slices of the fiber that were exposed to the 157-nm radiation, which is evidence of bulk 157-nm laser damage to the 157-nm-exposed cladding. Such damage is apparently not significant in light of the low, <0.4-dB, out-of-band losses shown in Fig. 1.

The fused-silica cladding of the fiber is also photosensitive under F$_2$-laser exposure and is expected to contribute to LPFG efficiency. A F$_2$-laser study[4] of bulk fused silica (Corning 7940) showed a 157-nm penetration depth of ~0.4-mm and a refractive-index response of $\Delta n = 4.6 \times 10^{-5}$ $(NF)^{0.55}$, where N is the

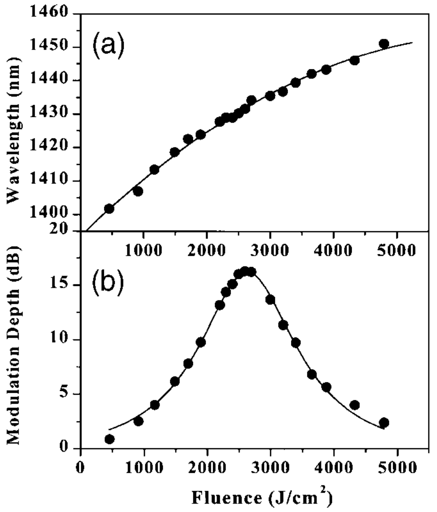

Fig. 2. (a) Center wavelength and (b) transmission loss of the strongest LPFG resonance peak as a function of the accumulated F$_2$-laser fluence. The single-pulse fluence was 2.7 mJ/cm^2.

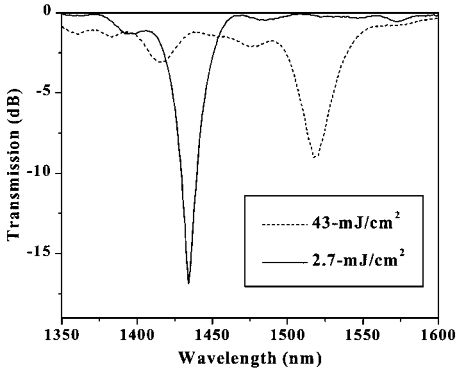

Fig. 3. Transmission spectra of the LPFG resonance peak at the point of maximum attenuation: single-pulse fluences of 2.7 and 43 mJ/cm^2 are shown.

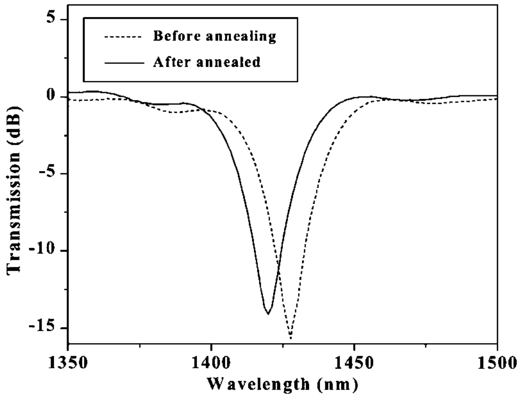

Fig. 4. 7-nm wavelength shift of a LPFG attenuation peak following 24-h annealing at 150 °C. The LPFG was formed with a single-pulse fluence of 2.4-mJ/cm^2 and a 1.9-kJ/cm^2 total dose.

total number of laser pulses and F is the single-pulse fluence in kilijoules per square centimeter. This result indicates that a Δn of $\sim 0.8 \times 10^{-4}$ was induced in the cladding for the LPFG shown in Fig. 1, a value only sixfold smaller than the anticipated refractive-index change in the core.[4]

One important advantage of F_2-laser-formed LPFGs is their intrinsic wavelength stability compared with that of LPFGs fabricated in hydrogen-soaked fiber. Figure 4 shows the resonance loss peak of a F_2-laser-formed LPFG before and after thermal annealing at 150 °C for 24 h. Annealing produces a 7-nm wavelength shift and a 2-dB decrease in the peak strength. These results compare favorably with the ~30-nm wavelength shift and larger drop in strength for thermally annealed (100 °C) LPFGs fabricated in a hydrogen-soaked fiber under 248-nm laser radiation that were reported in Ref. 9.

In related work, we have also shown that the F_2-laser photosensitivity response in SMF-28 fiber is dramatically enhanced by 500 times when hydrogen soaking is applied.[5] Comparison with 248-nm-exposed hydrogen-soaked fibers also revealed a >250-fold enhancement of the 157-nm response. Such strong enhancement by hydrogen of F_2-laser light is only apparent in LPFGs; only threefold enhancement of the 157-nm laser-induced refractive-index change was noted in hydrogen-soaked GeO_2 waveguides (3% GeO_2). The contrasting enhancement is attributed to the strong 157-nm photosensitivity responses in the hydrogen-soaked cladding, which sensitively affect the efficiency of LPFGs.

In conclusion, strong and high-quality LPFGs were formed for what is believed to be the first time without fiber-sensitization techniques by use of what is to our knowledge record short-wavelength 157-nm radiation. The hydrogen-free gratings offer excellent wavelength stability. However, a low-fluence-processing window (~5 mJ/cm^2) appears necessary to avoid fiber damage.

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