LETTERS

PACS numbers: 42.81.Qb; 42.65.Re; 42.70.Nq
DOI: 10.1070/QE2003v033n08ABEH002486

Fibre-Bragg-grating writing in single-mode optical fibres by UV femtosecond pulses

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Abstract. **Fibre-Bragg-grating writing in single-mode optical fibres by the phase-mask method using 220-fs, 264-nm UV pulses of intensity 31 – 77 GW cm^{-2} is reported for the first time. The achieved degree of modulation of the photoinduced refractive index was 1.9×10^{-3} in an H_2-loaded SMF-28 telecommunication fibre and 1.1×10^{-3} in a H_2-free Nufern GF1 fibre. The dependence of the induced refractive index on the intensity for the same irradiation fluences in the case of the H_2-loaded SMF-28 fibre shows that the refractive index is induced due to nonlinear absorption.**

Keywords: *fibre gratings, femtosecond pulses, photoinduced refractive index.*

Fibre Bragg gratings (FBGs) and long-period fibre gratings (LPFGs) are produced by exposing fibres to UV light, typically from an excimer KrF laser (at 248 nm) or frequency-doubled cw argon laser (at 244 nm) [1, 2]. Absorption of this light in the glass core of the fibre can cause a permanent change in the refractive index of the fibre. Because a standard SMF-28 telecommunication fibre with a low content of GeO_2 (molar concentration is 3 %) has a low photosensitivity, it is preliminary impregnated with hydrogen to increase the induced refractive index [3]. It was shown that the photosensitivity of the H_2-loaded germanosilica fibres increased almost exponentially with the UV photon energy [4] and the photoinduced change in the refractive index was mainly determined by a one-photon process. It was reported that, when SMF-28 fibres were irradiated by an excimer F_2 laser at 157 nm, the irradiation dose required for LPFG writing was substantially lower (more than two orders of magnitude lower than the dose required upon irradiation at 248 nm) [5, 6]. However, problems arise when this laser is used due to absorption of UV radiation in air, cladding glass, and a phase mask (when FBGs are fabricated).

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Received 6 June 2003
Kvantovaya Elektronika **33** (8) 728 – 730 (2003)
Translated by M.N. Sapozhnikov

The effect produced by a decrease in the irradiation wavelength can be achieved by using multiphoton absorption of sufficiently intense light. In this case, the wavelength can be outside the absorption band and the excitation energy can be even higher than the energy of a 157-nm photon (7.9 eV). Femtosecond lasers inherently provide the high intensity due to the short pulse duration. Note also that femtosecond pulses do not damage fibres and do not cause breakdown at intensities a few orders of magnitude higher than in the case of nanosecond pulses from excimer lasers. For example, the LPFG writing by 800-nm femtosecond pulses of intensity $\sim 10^{14}$ W cm^{-2} was reported. Such a high intensity was obtained from a high-power Ti : sapphire laser system containing a master oscillator and an amplifier [7].

By using harmonics of IR radiation from femtosecond lasers, we can reduce the number of photons required for multiphoton absorption, thereby decreasing the radiation intensity. The generation of harmonics occurs efficiently in femtosecond lasers. The LPFG writing by 400-nm femtosecond pulses of intensity $\sim 10^{10}$ W cm^{-2} was demonstrated in paper [7]. Note that unlike [8], no amplifier was used. Also, the efficient PLFG production using the fourth harmonic of a femtosecond Nd : glass laser (at 264 nm) was performed [9, 10].

FBGs (with period of ~ 0.5 μm) can be produced by employing different interferometric schemes, and it is believed that femtosecond lasers are of little use for this purpose because of their low time coherence. However, when phase masks are used, the spatial coherence of a laser beam is important rather than the time coherence. The spatial coherence of femtosecond lasers can be sufficiently high. FBGs were produced quite recently [11, 12] with the help of specially prepared phase masks using intense ($\sim 10^{13}$ W cm^{-2}) 800-nm femtosecond pulses. In this letter, we report the FBG writing with the use of a standard phase mask and the fourth harmonic of a femtosecond Nd : glass laser at 264 nm.

We employed a Twinkle laser (Light Conversion Ltd. Lithuania) emitting 220-fs, 264-nm pulses with a pulse energy of 300 μJ and a pulse repetition rate of 27 Hz. The FWHM diameter of the laser beam was 3 mm. Laser radiation was focused by a fused silica lens with a focal distance of 218 mm on an optical fibre from which a polymer cladding was removed. The phase mask was placed in front of the fibre at a distance of ~ 100 μm from its core. The incident radiation intensity on the fibre was varied by changing the distance between the lens and fibre. The phase mask had a period of 1.07 μm. The transmission spectra of the written FBGs were recorded using a superluminescent diode and an Ando AQ 6317C spectrum analyser with a resolution of 0.05 nm.

First the FBGs were written in an SMF-28 fibre loaded with H_2 (for two days at a pressure of 130 atm and a temperature of 80 °C) using the scanning-beam and phase-mask methods [1]. For this purpose, two slits were placed in the beam in front of the mask and fibre. The first slit of width 2 mm was placed at a distance of 5 cm from the mask to separate the most intense part of the beam for obtaining a sufficiently homogeneous distribution of the radiation intensity over the beam cross section. The second slit of width 3 mm was fixed together with the mask and fibre and restricted the length of the grating being written. The holder of the mask, fibre, and this slit were moved across the laser beam with the help of a computer-controlled translator with a step of 100 μm. In this way, a part of the fibre of length 3 mm was uniformly irradiated by the laser beam focused at a spot of size 2×0.15 mm.

Figs 1a, b show the transmission spectra of two FBGs written at almost identical radiation fluences (0.68 and 0.63 kJ cm^{-2}, respectively) but at different incident radiation intensities (47 and 31 GW cm^{-2}, respectively). A great difference between the loss peaks in the transmission spectra of the FBG clearly demonstrates a nonlinear absorption during FBG writing (probably, two-photon absorption). One can see that the FBG spectra are quite symmetric and have typical spectral components at the edges, which are typical for homogeneous gratings [1].

Then, we made an attempt to write a FBG in a H_2-free Nufren GF1 fibre with an enhanced photosensitivity (this fibre was specially designed for FBG writing). We used the entire beam (slits were removed). Using the radiation intensity of 77 GW cm^{-2} and radiation fluence of 4.7 kJ cm^{-2}, we produced a grating with the 16-dB absorption peak (Fig. 1c). The transmission spectrum of the FBG written in the Nufren GF1 fibre is asymmetric probably due to the inhomogeneous intensity profile over the beam cross section.

Assuming that the grating length is 3 mm, the corresponding modulation of the induced refractive index can be calculated using the theory of coupled modes [1]. The dependences of the degree of modulation of the refractive index in the H_2-loaded SMF-28 fibre on the irradiation fluence calculated for different incident radiation intensities are shown in Fig. 2a. The maximum values of the induced refractive index were 1.9×10^{-3} for the 35-dB peak and 0.85×10^{-3} for the 12-dB peak. This difference for the two intensities indicates that nonlinear absorption of UV radiation takes place during FBG writing. Note that the ratio of the slopes of the initial parts of the curves (about 1.5) agrees with the intensity ratio. It is also important to note that for the intensity 47 GW cm^{-2} no saturation of the induced refractive index occurs even at a maximum fluence, whereas saturation is observed when the incident radiation intensity is 31 GW cm^{-2}.

The calculated dependence of the change in the refractive index on the radiation fluence (assuming that a grating of length 3 mm is homogeneous) for the Nufern CF1 fibre is

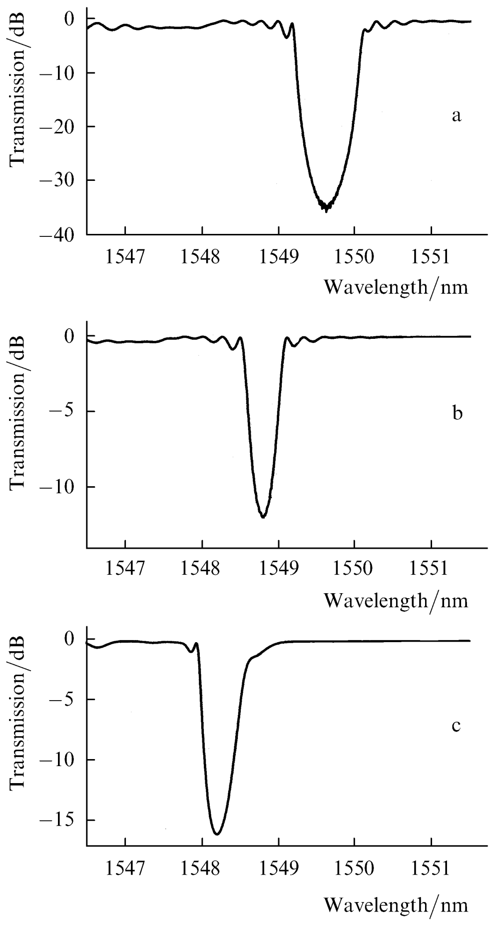

Figure 1. Transmission spectra of the FBG for the H_2-loaded SMF-28 fibre for the pulse intensity $I = 47$ GW cm^{-2}, the total fluence $D_{tot} = 0.68$ kJ cm^{-2} (a) and $I = 31$ GW cm^{-2}, $D_{tot} = 0.63$ kJ cm^{-2} (b) and for the Nufern GF1 fibre for $I = 77$ GW cm^{-2} and $D_{tot} = 4.7$ kJ cm^{-2} (c).

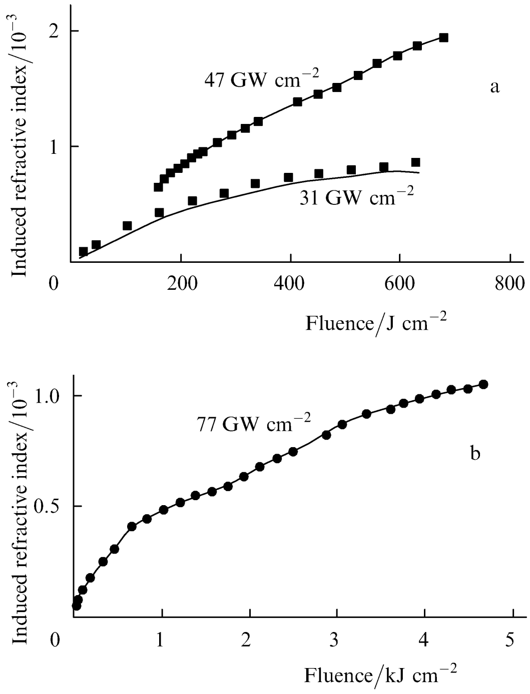

Figure 2. Dependences of the induced refractive index on the radiation fluence for the SMF-28 (a) and Nufern GF1 (b) fibres at different irradiation intensities.

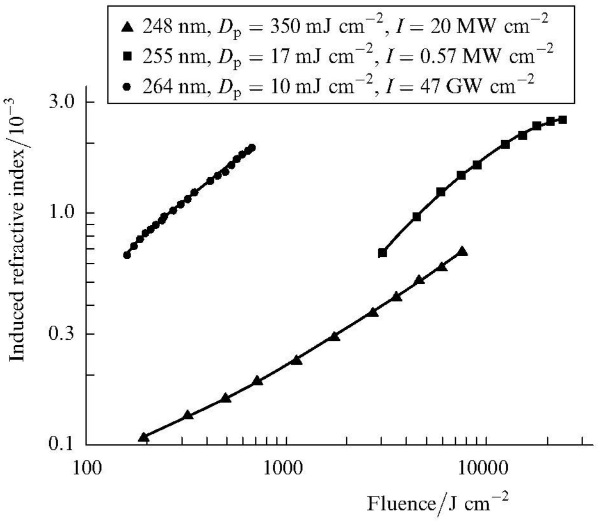

Figure 3. Dependences of the induced refractive index on the fluence in the H_2-loaded SMF-28 fibre irradiated by different lasers (D_p is the pulse energy density).

shown in Fig. 2b. The maximum value of the induced refractive index is 1.1×10^{-3} for the radiation fluence equal to 4.7 kJ cm^{-2}. The FBG writing in a more photosensitive Nufern GF1AA fibre by the second harmonic of a pulsed copper vapour laser emitting 17 mJ cm^{-2} (0.57-MW cm^{-2} peak power density) pulses at 255 nm with a pulse repetition rate of 6 kHz was reported in Ref. [13]. To obtain the induced refractive index, the 8-kJ cm^{-2} radiation fluence was required. In our case, the same change in the refractive index was achieved in a less photosensitive fibre at the 4.2-kJ cm^{-2} fluence, which is almost two times lower. Unlike [13], we did not observe the saturation of the induced refractive index growth, which is probably explained by different photosensitivity mechanisms.

Our results obtained for the H_2-loaded SMF-28 fibre (using the 47-GW cm^{-2} radiation power density) are compared in Fig. 3 with the results of papers where lasers emitting at close wavelengths of 255 nm [13] and 248 nm [14] were used (an excimer KrF laser emitting 350-mJ cm^{-2} pulses with a peak pulse intensity of $\sim$ 20 MW cm^{-2}). To obtain the change in the refractive index 1.9×10^{-3} upon irradiation by the 255-nm laser line, the radiation fluence of $\sim$ 12.5 kJ cm^{-2} was required, whereas in our case, only 0.68-kJ cm^{-2} fluence, i.e., lower by a factor of 18, was sufficient. Upon irradiation at 248 nm, a change in the refractive index achieved 6.5×10^{-4} for the 7-kJ cm^{-2} radiation fluence, which was higher by a factor of 44 than in our case. Therefore, the use of femtosecond 264-nm radiation for FBG writing is more efficient than that of 248-nm and 255-nm radiation. Probably this is related to two-photon absorption.

Thus, we have shown that femtosecond UV radiation can be successfully used for writing high-quality FBGs in single-mode optical fibres using a phase mask. The high efficiency of FBG writing is probably explained by the high excitation energy (9.4 eV) due to two-photon absorption.

Acknowledgements. The authors thank S. Fahy for his attention to this study and Yu.V. Larionov and A.A. Rybaltovskii for useful discussions. This work was supported by the Scientific Foundation of Ireland.

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