PACS numbers: 42.81.Qb; 42.79.Dj; 42.65.Re; 42.70.Gi
DOI: 10.1070/QE2001v031n11ABEH002091

# Fabrication of a long-period grating in a fibre by second-harmonic radiation from a femtosecond Ti:sapphire laser

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***Abstract*. Long-period gratings are fabricated in an optical fibre for the first time by second-harmonic radiation from a femtosecond Ti:sapphire laser without the use of an amplifier. The photosensitivity of different fibres exposed to femtosecond pulses is studied. The estimates of the photosensitivity and the thermal properties of long-period gratings showed that the mechanism of the change in the refractive index induced by the 400-nm second-harmonic radiation differs from the corresponding mechanisms upon exposure to UV radiation from excimer lasers or irradiation by amplified 800-nm femtosecond pulses.**

***Keywords***: *intrafibre refractive-index gratings, femtosecond pulses, photosensitivity*.

## 1. Introduction

One of the most important tasks of fibre optics is the production in single-mode optical fibres of structures that have selective spectral properties. Such structures are periodic variations in the refractive index (gratings) of glass along the fibre. The variation in the refractive index is usually produced by exposing optical fibres to UV radiation in the region of absorption bands of the fibre core glass. The sources of UV radiation are, as a rule, the second harmonic of a cw argon laser or the pulsed excimer lasers. Although refractive-index gratings are widely used in practice, many aspects of their nature are still unclear.

Advances in the development of Kerr-lens self-mode-locked Ti:sapphire lasers stimulated the attempts to use these lasers for producing photoinduced variations in different glasses and glass fibres. Although the emission wavelength 0.8 μm of these lasers lies far away from the UV absorption band of glass, the femtosecond duration of their pulses provides high radiation intensities at which multiphoton effects become substantial, in particular, multi-photon absorption. Variations in the refractive index of glass irradiated by amplified 0.8-μm femtosecond pulses were demonstrated in Refs [1, 2] where it was also shown that these variations were substantially different from those produced by UV radiation.

Because of the high radiation intensity produced by femtosecond pulses, the interaction of radiation with transparent materials exhibits some other features as well. In addition to multiphoton absorption, the multiphoton ionisation can take place, as well as the heating of electrons in a strong electromagnetic-wave field accompanied by the formation of the electron avalanche followed by the breakdown. As a result, a microexplosion can occur inside the glass, followed by the formation of spherical cavities of diameter smaller than the wavelength of light [1]. The formation of such microcavities leads to the glass densification, which is accompanied by a variation in the refractive index. Along with the variation in the refractive index, these defects also cause light scattering, resulting in the undesirable ('out-of-band') losses in fibres.

An electron acquires in the electromagnetic-wave field the breakdown energy, which is proportional to $\lambda^2$ (where $\lambda$ is the wavelength of light). At the same time, the smaller the wavelength, the smaller the number of photons required for multiphoton absorption. Therefore, by decreasing the wavelength of ultrashort pulses, we can obtain the required absorption at the lower intensity, thereby substantially reducing the probability of optical breakdown. The authors of Ref. [3] reported the induction of the refractive index changes by the second harmonic of a femtosecond Ti:sapphire laser without the use of an amplifier. The refractive index was induced in a bulk borosilicate glass sample having a high photosensitivity. We used in our study femtosecond pulses of the second harmonic from a Ti:sapphire laser for inducing the refractive index in optical fibres of different compositions.

Periodic variations in the refractive index photoinduced in the core of a single-mode fibre allow one to produce gratings of two types: Bragg gratings whose period is usually fractions of micrometer and long-period gratings, with a period from 100 to 500 μm. The requirements imposed on the light sources used for writing gratings of these two types are substantially different. Bragg gratings are commonly fabricated using the interference of two light beams to produce a periodic variation in the radiation intensity along the fibre. In this case, a highly coherent radiation source and a high mechanical stability of an optical writing system are required. In the case of long-period gratings, an amplitude mask can be used or step-by-step exposure of the fibre to

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Received 10 August 2001
*Kvantovaya Elektronika* **31** (11) 999 – 1002 (2001)
Translated by M N Sapozhnikov

focused radiation with the modulated intensity. In this case, the coherence is not so important and the requirements imposed on the mechanical stability of the writing system are alleviated. Long-period gratings can be induced not only by exposure to UV radiation but also by irradiating by $CO_2$ [4] and CO lasers [5], by producing fibre microbendings upon heating by an electric arc [6], and by exposure to accelerated ion beams with energies of several megaelectronvolts [7].

A large spectral width of femtosecond pulses and, hence, their low coherence hinder the fabrication of Bragg gratings. For this reason, femtosecond lasers were used for writing long-period gratings. The fabrication of long-period gratings by femtosecond pulses from a Ti:sapphire laser amplified in a regenerative amplifier was reported in Ref. [8]. The grating thus produced features high thermal stability, by retaining its optical properties up to temperature 500 °C. However, upon fabrication of the grating, large 'out-of-band' losses (up to 10 dB) were induced in the optical fibre due to scattering of light by inhomogeneities produced upon irradiation.

Such highly thermostable gratings can be also produced using lasers of other types. They are formed due to strong heating of the optical fibre upon its irradiation. The formation of gratings upon weaker heating is usually related to photochemical reactions taking place in the fibre. Such gratings are, as a rule, less thermostable.

In this paper, we report the first, to our knowledge, fabrication of a long-period grating in a hydrogen-loaded germanosilicate optical fibre by the second-harmonic radiation from a femtosecond Ti:sapphire laser without the use of an amplifier.

## 2. Experimental

Before the writing of gratings, we studied the photosensitivity of various optical fibres irradiated by 400-nm femtosecond pulses. We used the method of measuring the induced refractive index with the help of an intrafibre Mach–Zehnder interferometer consisting of two long-period gratings [9]. The interferometers were produced in fibres under study by their exposure to the 248-nm radiation from an LP EMG103MSC excimer laser operating on a KrF gas mixture through an amplitude mask with period 300 μm. The induced refractive index $\Delta n_{\mathrm{ind}}$ was measured from the shift of the interference maxima according to the relation $\Delta n_{\mathrm{ind}} = \lambda\Delta\lambda(L\Lambda\eta)^{-1}$, where $\lambda$ is the wavelength at which the measurements are performed; $\Delta\lambda$ is the shift of the interference pattern after the fibre exposure; $\eta$ is the overlap integral of the fundamental mode with the fibre core: $\Lambda$ is the period of the interference pattern; and $L$ is the length of the irradiated part of the fibre.

We used fibres of three types:

(1) A germanosilicate fibre (molar content of $GeO_2$ was 4.5 %, the difference between the refractive indices of the core and cladding was $\Delta n = 0.0065$, the cut-off wavelength was $\lambda_c = 0.96$ μm, the fibre was manufactured at Fiber Optics Research Center, Institute of Chemistry of High-Purity Substances, RAS) in the initial form and after hydrogen loading (analogue of a Flexcore Corning fibre);

(2) a standard telecommunication SMF28 germanosilicate fibre (molar content of $GeO_2$ was 3%, $\Delta n = 0.005$, and $\lambda_c = 1.25$ μm) loaded with hydrogen; and

(3) phosphogermanosilicate SMF905 fibre (molar contents of $GeO_2$ and $P_2O_5$ were 10 and 4 %, respectively, $\Delta n = 0.02$, $\lambda_c = 1.02$ μm, manufactured at Fiber Optics Research Center, and Institute of Chemistry of High-Purity Substances, RAS).

The loading of fibres with hydrogen was performed under a pressure of 130 atm at 100 °C for 18 hours.

The gratings were fabricated in the most photosensitive fibre (hydrogen-loaded fibre of the first type) by successively producing individual lines using the experimental setup shown in Fig. 1. The 800-nm, 60-fs radiation pulses from a Tsunami Ti:sapphire laser (Spectra Physics) with an average power of 600 mW and a pulse repetition rate of 82 MHz were converted to the second harmonic by focusing the laser beam into a BBO nonlinear crystal of thickness 2 mm. Because the fundamental-harmonic radiation transmitted by the crystal and reflected from the fibre came back to the laser and destroyed mode locking, a SZS21 optical filter absorbing this radiation was placed behind the crystal. The 400-nm radiation was focused by a $10^{\times}$ microobjective with the numerical aperture 0.30 on the fibre.

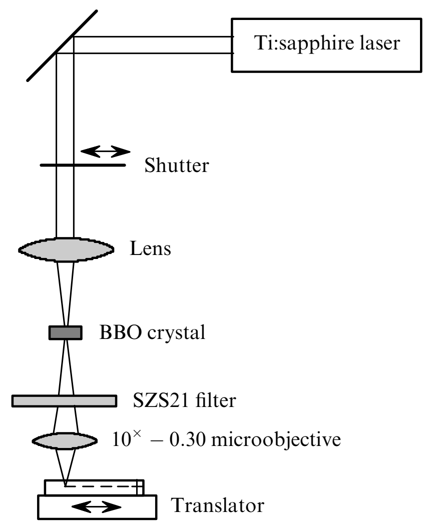


**Figure 1.** Scheme of the experimental setup.

The second-harmonic conversion efficiency in our experiments achieved 50 %. However, taking into account all the losses, the average power of the 400-nm radiation incident on the fibre was 180–210 mW. The laser beam diameter on the fibre core was controlled with the help of an optical microscope by the size of a spot of red luminescence of the fibre core and was of about 15 μm. The fibre was moved perpendicular to the beam by the maximum displacement of a one-coordinate translator with a velocity of 6.3 μm $s^{-1}$, and radiation was blocked with a mechanical shutter. The length of the grating line was 155 μm (half the period), while the size of the intermediate region between the irradiated and nonirradiated regions was of the order of the beam diameter.

The study of the thermal stability of fabricated gratings gives some information on the mechanism of induction of $\Delta n_{\mathrm{ind}}$ in fibres. The long-period gratings produced by femtosecond pulses were isochronously annealed to the temperature 400 °C. The annealing was performed by increasing the temperature of a heater, stabilising the temperature at a specified value for 30 min, fixing the peak of losses, and passing to the next specified temperature.

## 3. Results and discussion

The estimates of the refractive index induced by the second-harmonic radiation from the femtosecond laser for the exposure dose of about 0.2 MJ cm$^{-2}$ gave the value $\Delta n_{\rm ind} \approx 0.5 \times 10^{-4}$ for a hydrogen-loaded fibre of the second type and fibres of the first and third types without hydrogen and $\Delta n_{\rm ind} \approx 1.8 \times 10^{-4}$ for a hydrogen-loaded fibre of the first type.

We studied a fibre of the third type as one of the most sensitive to the 193-nm radiation from an ArF excimer laser. The refractive index induced in this fibre by the 2-kJ cm$^{-2}$ dose of this radiation was $3 \times 10^{-3}$ in the absence of hydrogen, whereas the refractive index induced in the hydrogen-loaded fibre of the first type was $2 \times 10^{-3}$ for the same dose. Therefore, the photosensitivity of these two fibres is different upon irradiation by 400-nm femtosecond pulses and 193-nm nanosecond pulses. This suggests that the mechanisms of the refractive-index induction are different in these two cases.

The loading of the fibre with hydrogen plays an important role in the refractive-index induction. It seems likely that only the formation of defects due to the incorporation of hydrogen into the glass network upon laser irradiation can provide the induction of the refractive index that is sufficient for producing a long-period grating.

The fibre of the first type loaded with hydrogen exhibits the highest photosensitivity. The value of $\Delta n_{\rm ind}$ in this fibre achieved $\sim 4.2 \times 10^{-3}$ for the radiation dose $\sim$ 19 MJ cm$^{-2}$, no saturation in the refractive-index growth being observed. We managed to record long-period gratings only in this fibre loaded with hydrogen using the radiation dose $\sim$ 0.5 MJ cm$^{-2}$. We failed to fabricate gratings in all other fibres at the exposures up to $\sim$ 1 MJ cm$^{-2}$.

Fig. 2 shows the transmission spectrum of one of the written long-period gratings. The grating period is 310 μm and its length is 23 mm (75 lines). The spectrum was recorded with an Ando AQ6317B spectrum analyser with a resolution of 1 nm. The level of 'out-of-band' losses for this spectrum was < 0.5 dB, which is considerably lower than upon writing gratings by amplified 800-nm femtosecond pulses [8] and almost coincides with the level of 'out-of-band' losses upon fabricating gratings by UV radiation.

The spectrum exhibits seven peaks of losses corresponding to the excitation of cladding modes $\mathrm{HE}_{12} - \mathrm{HE}_{18}$, the four right resonances being doublets. Another characteristic feature of the spectra of the induced gratings is great losses for the first peaks (peaks at $\lambda_{\rm r} \approx 1075$, 1110, and 1130 nm in Fig. 2). The first peak in the spectrum of one of the gratings (corresponding to the $\mathrm{HE}_{12}$ mode) was even greater than the last right $\mathrm{HE}_{18}$ peak observed in the spectrum. Usually, peaks of losses in long-period gratings increase with increasing wavelength and, hence, with increasing index $m$ of the cladding $\mathrm{HE}_{1m}$ modes corresponding to these peaks. The problem of the anomalous structure of the transmission spectra of long-period gratings produced in our experiments is an object of further studies. One of the reasons can be the asymmetry of fibres and of the induced refractive index [10].

We found that long-period gratings began to decay upon heating already at 100 °C. This suggests that the refractive-index induction in our experiments is not related to the local melting or heating of the glass, as in the case of amplified 0.8-μm femtosecond pulses [8].

Therefore, our experimental estimates of the photosensitivity of various fibres to the 400-nm femtosecond pulses and the results of annealing of long-period gratings fabricated by these pulses showed that the refractive index is induced due to photochemical reactions. The radiation intensity of $\sim 10^{10}$ W cm$^{-2}$ used in our experiments does not cause strong local heating and melting (the more so, the glass breakdown). Note that the refractive index is induced at least due to two-photon absorption of light because the fibres are virtually transparent at 400 nm. To explain the mechanism of the refractive-index induction in our experiments, further studies are required.

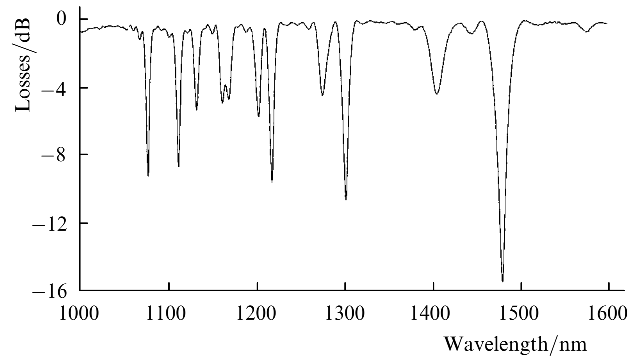


**Figure 2.** Transmission spectrum of the long-period grating.

## 4. Conclusions

Thus, we fabricated for the first time, as far as we know, long-period gratings by the second-harmonic radiation from a Kerr-lens self-mode-locked Ti:sapphire laser. The grating with peak losses up to 16 dB and 'out-of-band' losses not exceeding 0.5 dB was written without the use of an amplifier of femtosecond pulses. This simplifies a laser setup and substantially reduces its cost. Our estimates of the photosensitivity of the fibres and thermal properties of the gratings suggest that the mechanism of the refractive-index induction differs from those in the cases of UV irradiation by excimer lasers or irradiation by amplified 0.8-μm femtosecond pulses.

***Acknowledgements.*** The authors thank S A Vasil'ev and V M Mashinskii (Fiber Optics Research Center, General Physics Institute, RAS) for useful discussions, A V Sharkov (P N Lebedev Physics Institute, RAS) for placing a BBO crystal at our disposal, and O I Medvedkov and I G Korolev (Fiber Optics Research Center, General Physics Institute, RAS) for placing optical fibres at our disposal and their saturation by hydrogen.

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